Green Streets, Highways, and Development 2013

Advancing the Practice

Proceedings of the Second Conference on Green Streets, Highways, and Development

EDITED BY
Adjo A. Amekudzi, Ph.D.;
Sandra L. Otto, P.E.; David J. Carlson;
and Marsha Anderson Bomar

ASCE

TRANSPORTATION & DEVELOPMENT INSTITUTE

GREEN STREETS, HIGHWAYS, AND DEVELOPMENT 2013

ADVANCING THE PRACTICE

PROCEEDINGS OF THE SECOND GREEN STREETS, HIGHWAYS, AND DEVELOPMENT CONFERENCE

November 3-6, 2013
Austin, Texas

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Preface

The T&DI's first Green Streets and Highways Conference was held in Denver, Colorado in 2010. The conference was organized to respond to the rapidly growing interest and activity in sustainable transportation. Over 350 transportation and environmental professionals attended technical panels, workshops and local tours, sharing information on leading edge environmental stewardship and sustainability principles and practices. The contributions of Conference Steering Committee Co-Chairs Hal Kassoff and Neil Weinstein were the foundation of this very successful and well-received conference.

Since that time the interest, knowledge and expertise in sustainable practices has expanded in our industry, leading us to a 2nd Conference on Green Streets, Highways and Development to highlight practical applications and advance the practice. The Conference brought together planners, inventors, designers, suppliers, builders, owners and operators to share their experiences, reveal innovations, and discuss sustainable practices that really work on the ground. The Austin area was an appropriate and exciting setting for the conference. Austin is truly a living laboratory, allowing for a variety of Mobile Workshops and great examples of green principles in action literally out the back door of the hotel. Special thanks go to the conference steering committee, chaired by Marsha A. Bomar, who initiated, developed and fully supported the second conference from start to end.

All papers in the proceedings were peer-reviewed. The conference received almost 100 abstracts. After initial reviews and subsequent invitations for papers, approximately 40 draft papers were received. Through a peer-review process that lasted several months, 35 papers were selected for publication. The steering and program committees as well as subject matter experts provided various types of support for the conference, including soliciting abstracts and papers, organizing sessions and presentations, and managing the peer-review process.

There were a number of volunteers who reviewed the submitted papers. The conference steering committee and the editors appreciate their valuable work. The editors thank them for their important contributions to the conference. The diligent work by committee members and other colleagues was critical for the publisher to meet the deadlines.

Lastly, we would to like particularly thank ASCE and T&DI staff including T&DI Manager Andrea C. Baker, ASCE Publications Acquisitions Editor Donna Dickert and T&DI Director, Jonathan C. Esslinger, P.E., for their support of this conference.

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An Integrated Approach for Designing and Building Sustainable Roads

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ABSTRACT

Recent emphasis on sustainability in the field of transportation has resulted in newly developed sustainability rating systems. However, there is little guidance or industry-wide experience to instruct practitioners on how to integrate sustainability throughout the project lifecycle. The Office of Federal Lands Highway (FLH) of Federal Highway Administration (FHWA) has been evaluating the use of sustainable practices during road design and construction by utilizing rating tools such as Greenroads and INVEST. Based on these evaluations, FLH has identified best management practices to integrate sustainability in road design and construction. This paper first presents the results of evaluations, and then identifies the best management practices, and finally provides an integrated approach for designing and building sustainable roads. The approach is applicable to the project development phases of the project lifecycle, which include project planning, design, and construction. The approach presented in this paper emphasizes interdisciplinary coordination, maintaining accountability of sustainability throughout project development, and appropriately utilizing resources. This paper provides a six-step approach for practitioners to integrate sustainability into the planning, design, and construction of roadway projects. The six steps in this approach are: (1) Develop a Sustainability Vision, (2) Identify Project Context, (3) Define Sustainability Goals, (4) Identify Sustainable Solutions, (5) Assess and Select Sustainable Solutions, and (6) Incorporate Solutions.

INTRODUCTION

The Federal Highway Administration's (FHWA) Office of Federal Lands Highway (FLH) works with a number of federal land management agencies (FLMA) including the National Park Service (NPS), U.S. Department of Agriculture Forest Service (USFS), U.S. Fish and Wildlife Service (USFWS) and Bureau of Indian Affairs (BIA) to deliver roadway projects that provides access to federal lands through Federal Lands Highway Program ($1 billion annually). Many of these agencies place high value on infrastructure sustainability and expect FLH to deliver on this expectation by including the sustainable solutions in their road projects.

The FLH has a number of sustainability initiatives, either recently completed or currently ongoing, to integrate sustainable solutions throughout project development process (planning, design, and constructions) to effectively address the partner agencies' sustainability goals. Recently, the FLH completed a study to identify, disseminate and improve upon its roadway design and construction sustainability practices (Muench et al., 2012). This study identified existing design and construction sustainability best practices by reviewing seven FLH roadway projects using the Greenroads™ Rating System (www.greenroads.org) as a measurement tool (Muench et al., 2011, Anderson 2011). The analysis of results of this study also identified opportunity for improvements in integrating sustainability in roadway projects. In addition, FLH also reviewed a number of projects during pilot and implementation phase of FHWA Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) (www.sustainablehighways.org) (FHWA, 2012).

To further enhance its sustainable solutions offering, FLH developed an integrated approach to integrate sustainability into the planning, design, and construction of roadway projects. The six steps in this approach are:
Step 1 – Develop a Sustainability Vision
Step 2 – Identify Project Context
Step 3 – Define Sustainability Goals
Step 4 – Identify Sustainable Solutions
Step 5 – Assess and Select Sustainable Solutions
Step 6 – Incorporate Solutions

This approach is applicable to the project development phases of the project lifecycle, which include project planning, design, and construction. The successful implementation of this approach depends on proactive project management; an engaged interdisciplinary team led by a project manager or sustainability manager; interdisciplinary coordination; maintaining accountability of sustainability throughout project development by tracking commitments; and finally, reviewing the project by a sustainability rating system.

BACKGROUND

Integrating sustainability on a roadway project does not mean getting a high score in a sustainability evaluation or rating tool, meeting regulatory requirements, or incorporating equal parts of social, environmental and economic solutions. Rather, it means developing an informed vision of sustainability, setting goals that support the vision and are contextually appropriate for the project, and then implementing sustainable solutions that achieve these goals. The result is a project that meets the sustainability vision.

Many current standard practices for project development are in place because of such regulations as the National Environmental Policy Act (NEPA), the Clean Water Act, and the Clean Air Act, and they often contribute to projects being more sustainable. However, the purpose of this approach is to integrate sustainable elements that go above and beyond what is required. Advancing sustainability in this manner can be an innovative and exciting process as projects continue to develop and apply new technologies and processes to maximize sustainability.

Some practitioners may be hesitant to emphasize or encourage sustainability in project development and design due to perceived high cost and expensive maintenance requirements, reluctance to stray from standard design manuals and specifications, and perhaps a lack of understanding of the importance of sustainability. Additionally, while the availability of sustainability technical resources for design and construction continues to expand, little guidance is available to instruct practitioners on how to implement the solutions and ideas in these technical resources into design and construction. This approach aims to increase understanding and change negative perceptions of sustainability and provide a straightforward and manageable approach for integrating sustainability into roadway projects.

This paper provides a step-by-step approach for practitioners to integrate sustainability into the planning, design, and construction of roadway projects that is intended to be integrated with an owner's standard design practices, project development guidance, and technical guidance. The approach presented here should easily fit existing design practices and is not intended to be a separate process.

SUSTAINABILITY DEFINED

The sustainability is often defined by directly quoting or paraphrasing the United Nations 1987 Report of the World Commission on Environment and Development (Brundtland Commission Report) view of sustainable development (United Nations, 1987). Most widely accepted definitions of sustainability are based on achieving a balance of three primary principles: social, environmental, and economic (Figure 1). While it is unlikely to perfectly balance these three principles for a given solution or on a single project, applying the principles of sustainability to a project means at least considering all three of these principles, even if balance is not achieved. As we strive to balance them on each project, we come closer to balancing the three principles on a broader set of projects, and sustainability will be advanced at a programmatic level. The three principles can be further defined as follows:

The **Social** principle: Meeting basic human needs fairly and efficiently. This principle considers solutions based on factors such as human health, safety, access, mobility, mode choice, cultural resources, archeological resources, aesthetics, and recreation.

The **Environmental** principle: Following three natural laws (Robért, 2000):
− Do not extract substances from the Earth faster than they can be regenerated,
− Do not produce waste faster or at a greater amount than it can decompose and reintegrate into an ecosystem, and
− Do not damage or disrupt natural processes or ecosystems with human activities.
Often the easiest of the three principles to understand, the environmental principle considers solutions based on factors such as habitat, ecology, stormwater runoff and quality, air quality, recycling and reuse, energy efficiency, and noise management.

The **Economic** principle: Efficiently and/or productively using public capital, avoiding deterioration of capital assets. This principle considers solutions based on factors such as financial durability, reliability, responsibility, lifecycle costs, benefit-cost-driven decisions, and the use of natural resources.

Figure 1: The Sustainability Principles

The following definitions of sustainability, sustainable development, and sustainable highways have been adopted by FHWA for use in INVEST rating tool:

Sustainability: "Satisfying basic social and economic needs, both present and future, and the responsible use of natural resources, all while maintaining or improving the well-being of the environment on which life depends" (FHWA, 2012).

Sustainable Development: With respect to development, the Brundtland Commission of the United Nations succinctly stated that sustainable development is "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (United Nations, 1987).

Sustainable Highway: "Sustainable highways are an integral part of the broader context of sustainable development. A sustainable highway should satisfy the functional requirements of societal development and economic growth while reducing negative impacts on the environment and consumption of natural resources. The sustainability of a highway should be considered throughout the project lifecycle – from conception through construction" (FHWA, 2012).

INTEGRATED APPROACH FOR BUILDING SUSTAINABLE ROADS

The intent of this approach is to:

- Encourage project teams to develop an informed vision of sustainability that is contextually appropriate for the project.
- Demonstrate to project teams for selecting and implementing solutions that support this vision and go beyond just meeting regulatory requirements.
- Meet the purpose and need of a project, while conserving and protecting the environment and being mindful and respectful of resource limitations. This is what is meant by "balancing the social, environmental, and economic solutions." It does not necessarily mean incorporating equal parts of social, environmental, and economic solutions.

While the end result of this approach may lead to a project that likely scores high on a sustainability evaluation tool, such as FHWA's INVEST, the intent of this approach is to integrate sustainability on every project, no matter the size, type, or location. It is an opportunity to think beyond the design manual and collaborate with other disciplines to achieve a better product. This approach does not have to be an overwhelming task or resource-intensive. It is an approach to do a bit more, without adding too much additional effort. To explain the implementation of this approach, an example problem is illustrated in each step.

Steps 1, 2, and 3 are intended to be completed during project planning. Steps 4 and 5 are intended to be completed during project design and Step 6 is intended to be conducted throughout design and completed during construction. Figure 2 shows both the optimal timing for each step in project development and the window of acceptable timing. The earliest feasible time to accomplish each step is the best time as the opportunities for incorporating sustainable solutions diminish as a project progresses.

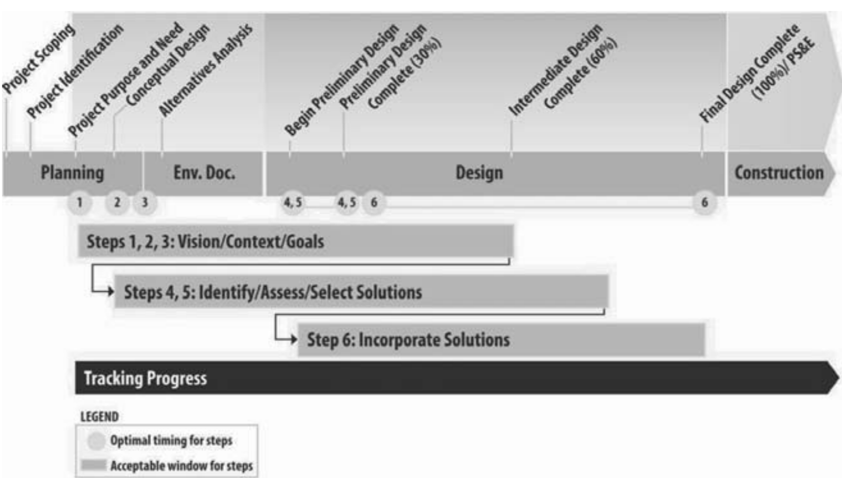


Figure 2: The Timeline of Integrated Approach

Step 1-Develop a Sustainability Vision

The sustainability vision is a brief, well-crafted statement with the purpose of aligning the project team to a desired sustainability outcome and providing them with broadly stated guidance that can be used to develop goals and evaluate performance. This vision is focused on sustainability, specifically on how the project can contribute to the social, environmental, and or economic principles, and therefore it has a different purpose than the project vision that was established in project planning and programming.

The responsibility for developing the sustainability vision for a project depends on where the project is in project development. If the project is still in the planning phase, the sustainability vision should be developed by the owner, community, and stakeholders. If the project is already in design, it may be more appropriate for the owner and project team to develop the sustainability vision.

Developing a sustainability vision is important to ensure the project team understands the desired outcome of a project. Developing the sustainability vision gives the project team and stakeholders an opportunity to start the conversation about what sustainability means to those involved and how sustainability could be achieved by the project team. Ultimately, the agreed-upon sustainability vision will help shape the sustainability goals.

Creating the sustainability vision early, preferably before or during alternatives development, makes sustainability an integral part of the project from day one. There are several points to keep in mind to create a successful sustainability vision:

- The development of the vision should be collaborative with input from the owner, interdisciplinary team, and stakeholders.
- The sustainability vision should be high-level, but not vague. If a vision is too vague, there is a risk of casting the net too wide for the initial set of sustainability goals and solutions.
- The vision should reflect the values and goals of the owner, the partner agencies, affected communities, and the project.
- The vision should be consistent with the project's purpose and need.
- The vision of the project should remain consistent among the project alternatives.
- If a sustainability vision statement already exists for an owner or for a set of projects (for example, if it was included in system-level programming), this step will be an opportunity to review and accept the vision or to adjust the vision based on any project-specific issues.

**Example Project Step 1:
Create a Sustainability Vision**

Basic Information

This project will widen a15 mile corridor of a two-lane scenic byway through rolling mountains to meet current safety standards. There is an existing retaining wall along northern edge and stream along the southern row boundary. Existing ACP needs rehabilitation to depth of at least 4 inches. The project will add trailhead access points and parking in two locations. Scenic byway crosses a wildlife migration route and an historic trail.

Sustainability Vision

The agency is committed to the sustainable development of Scenic Byway X. To achieve this the agency envisions minimizing disruptions to wildlife and to public enjoyment of the historic trail during construction, preserving and/or enhancing the wildlife habitat and the historic nature of the trail, conserving resources and exercising responsibility in a fiscally constrained environment while upgrading the roadway corridor for the safety of the traveling public.

This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.

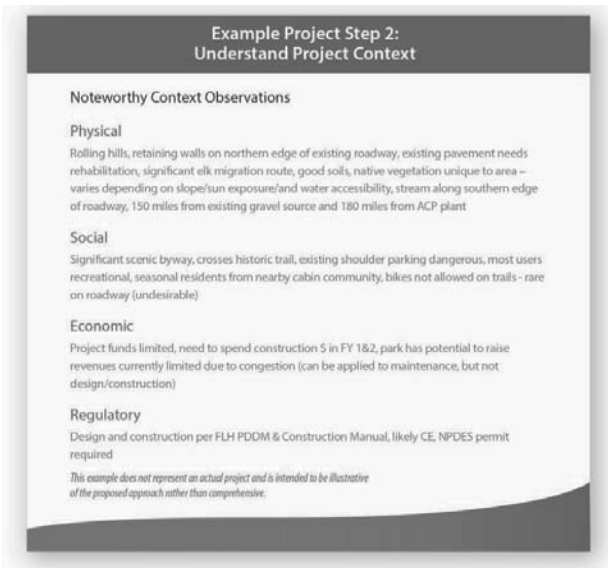
Step 2 – Identify Project Context

Context is unique for every project. The project's context can be broken into four components: physical, social, economic, and regulatory. It is important to identify the details for each. The physical context deals with geography, topography, geology, hydrology, vegetation, and key environmental issue. The Social context addresses demographics, user profile, transportation behavior, historical context, and stakeholder involvement. The economic context focusses on current land-use, operation and maintenance cost, expected budget, and financing. The regulatory context is controlled by design requirement, design criteria, permit conditions, and jurisdiction.

The project context should be identified in the project planning phase with input from the owner, community, and stakeholders. As the project progresses, the project context will continually evolve as more information is collected about the project and its surroundings. As the project enters the design phase, it may be appropriate for the owner and project team to revisit the context to establish any changes.

Understanding the context of the project has several benefits, including understanding the boundaries and constraints of the project as well as the opportunities that the unique project setting can offer. The more information the project team gathers on the current conditions of the area, the more informed the team will be when developing its sustainability goals. Later in the approach, the team will select sustainable solutions; the project context will be important in evaluating which solutions are feasible and relevant and which are not. By having a clear understanding of the project context early in the project development, the team will be able to integrate sustainable solutions into the project early and easily.

The team should strive to understand the context during the project planning phase, as conceptual design begins. However, context is not steady-state; it will evolve as the project progresses and as time passes. Physical context is likely to be more understood once surveys and other field explorations are conducted. Additionally, the social and economic contexts are likely to change if there is a large time gap between conceptual and preliminary design. As the project progresses, the team should review the context when new information comes available and review these context changes for how they may affect sustainable solutions selected for the project.


Example Project Step 2: Understand Project Context

Noteworthy Context Observations

Physical

Rolling hills, retaining walls on northern edge of existing roadway, existing pavement needs rehabilitation, significant elk migration route, good soils, native vegetation unique to area – varies depending on slope/sun exposure/and water accessibility, stream along southern edge of roadway, 150 miles from existing gravel source and 180 miles from ACP plant

Social

Significant scenic byway, crosses historic trail, existing shoulder parking dangerous, most users recreational, seasonal residents from nearby cabin community, bikes not allowed on trails - rare on roadway (undesirable)

Economic

Project funds limited, need to spend construction $ in FY 1&2, park has potential to raise revenues currently limited due to congestion (can be applied to maintenance, but not design/construction)

Regulatory

Design and construction per FLH PDDM & Construction Manual, likely CE, NPDES permit required

This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.

Step 3 – Define Sustainability Goals

A sustainability goal sets an expected standard to be achieved for the project. Accomplishment of the goal will support the sustainability vision and the accomplishment of all of the goals for the project should ensure the sustainability vision is realized. Goals provide the framework for the design phase and for selecting and deciding among sustainable solutions. There is no specific number of goals a project should have; it will depend on the size and type of project.

However, it is a best practice not to exceed five to seven goals. Succinct but well-defined goals will create a strong framework for project development. A small number of concise goals are recommended because it is manageable. This step should be completed by the interdisciplinary team with feedback from project stakeholders.

The objectives that are achieved by clearly defining sustainability goals include organization and prioritization of desired outcomes; means for analyzing and ranking sustainable solutions; connection between sustainability and the NEPA process; interdisciplinary discussions and consensus-building; and measuring progress towards sustainability.

Once the team begins to understand the context in the project planning phase, the interdisciplinary team should have enough background information to begin defining project-level sustainability goals. The team should work to define sustainability goals after the project's purpose and need is documented and as conceptual design and the environmental documentation process begins. It is important to define project-level sustainability goals at this time because the environmental documentation process occurs concurrently with preliminary and conceptual design; therefore identifying sustainability goals after the environmental document is completed is too late for them to drive alternatives and decision-making.

The environmental document outlines potential impacts and in many ways identifies where opportunities exist for implementing sustainable solutions. Additionally, many aspects of the environmental document, such as mitigation measures, can be directly tied into sustainable solutions. Defining sustainability goals at this time will integrate the sustainability goals with the project's overall goals.

Sustainability goals should be more specific than the sustainability vision and should be consistent with it. The project's sustainability vision should be used in forming and evaluating goals to ensure the vision is supported. For example, if the sustainability vision is to build a road while minimizing the environmental impact, the sustainability goals may include improving local water quality, protecting and/or enhancing habitat, and limiting use of energy resources. Eventually the project team will use these goals in identifying sustainable solutions. As goals are identified and discussed with stakeholders, it may also be useful to rank goals in order of importance. This will help later in project development when analyzing the trade-offs for sustainable solutions.

The goals should be consistent with context. There are several types of sustainability goals to consider, and they vary in level of detail (see Figure 3).

Goal Type	Description	Example	Benefits	Weaknesses
PRESCRIBED TOOLS	Identifies a specific sustainability evaluation tool to use on the project. The owner may apply this goal to all projects or selected projects.	Use FHWA's INVEST to monitor and evaluate overall sustainability of project at 30%, 50%, and 100% design submittals.	Rating tools provide lists of sustainable solutions and consistent methods for evaluation (and sometimes implementation). They create an easy framework to work within.	Could potentially limit the types of sustainable solutions applied to a project. Could focus the project team more on the tool and score than the actual sustainability of the project.
PERFORMANCE GOALS	Sets a target rating or score for a project using a specific sustainability evaluation tool.	Obtain a Gold rating using the Rural Extended scorecard in FHWA's INVEST.	Rating tools provide lists of sustainable solutions and consistent methods for evaluation (and sometimes implementation). Targets can set stretch goals for project teams to accomplish.	Targeting a specific score as a goal may focus the project team more on the score than the actual sustainability of the project and could mislead the team into selecting solutions that are not necessarily appropriate for the project.
CATEGORICAL GOALS	Broad sustainability goals that the project team should consider when selecting sustainable solutions for the project, such as improving water quality or reducing greenhouse gases.	Reduce materials and energy use. Reduce water use. Reduce emissions. Optimize habitat and land use.	Categorical goals allow the project to be flexible in selecting solutions because they are generally less specific but still state a clear goal to measure against.	Categorical goals may be too vague to guide a team to sustainable solutions.

Goal Type	Description	Example	Benefits	Weaknesses
SPECIFIC GOALS	Sometimes an owner has a policy in place that is very specific and can be listed as a goal. Or it may have been decided in the planning phase that a certain feature is very important to a project.	Recycle and reuse 100% of existing retaining wall and pavement materials within project limits.	Specific goals are generally clear and easier to implement.	Setting specific goals this early in the project process could be problematic if impacts to the budget and site conditions are unknown.

Figure 3: Types of Sustainability Goals

Step 4 – Identify Sustainable Solutions

Sustainable solutions are specific project activities, features, or processes that contribute to accomplishing one or more project sustainability goals and support the sustainability vision for the project. Step 5 assesses and selects the sustainable solutions for project inclusion. At Step 4, sustainable solutions need only be specific and measurable, relevant to the project context, and consistent with the project sustainability goals.

The interdisciplinary team, with representation from all disciplines, identifies potential solutions. It is important to identify sustainable solutions to determine specifically what opportunities exist to accomplish the sustainability vision and goals from Steps 1 and 3 on the project. This is where the specific sustainable activities, features or processes that will be incorporated into the project are brainstormed.

The team can begin identifying solutions any time after an alternative is selected, preferably as preliminary design begins. It is best to identify, assess, and select the solutions as early in the design phase as possible, as this maximizes number of solutions available to the project. As the project progresses in design, decisions may be made that limit or change the applicability of some solutions. Identifying solutions early in the design process allows the team to actively decide on these trade-offs instead of being forced to accept the remaining solutions. Note that on some projects certain disciplines might progress quicker than others. For example, the drainage design is often further developed in the environmental phase than other elements. In this case, sustainable solutions may need to be identified earlier to incorporate them into alternatives or permit requests.

The purpose of identifying sustainable solutions is to "brainstorm" potential sustainable solutions that would achieve the sustainability goals of the project. Each discipline should review the sustainability goals and then brainstorm solutions, within their discipline, that could be applied to the project to achieve each of the goals. This will provide the team with a manageable and organized set of solutions that will help focus the team and provide ideas that will encourage interdisciplinary collaboration.

This should be viewed as a “big picture” or “brainstorming” activity in which sustainable solutions are identified. The team should strive not too get fixated on subtleties and details of each solution in an effort to determine if it should be accepted or receive further consideration. Additionally, the team should not dismiss solutions because they are not allowed by current standards or specifications. In this brainstorming activity, team members should be encouraged to “push the envelope” and apply analytic thought and problem-solving skills to design tasks within their discipline to develop solutions that fit the context of the project and are in support of the project sustainability goals. It is more important at this step to get the idea on paper. The ingenuity exercised here is valuable for identifying a depth and breadth of solutions for discussion and assessment in the next step. The result of this research is a set of solutions that the interdisciplinary team will assess in Step 5. It is helpful to document these solutions in a tracking system to ensure they are assessed and, if applicable, selected and incorporated into the project.

Example Project Step 4:
Identify Sustainable Solutions

Noteworthy Context Observations

Goal 1: Reduce raw material usage and recycle or reuse 75% of existing structural and pavement materials

Drainage & Landscaping
- Leverage LID to reduce piping and structure needs
- Reuse existing native plantings
- Use RAP as pipe bedding material

Structural & Geotechnical
- Relocate and reuse retaining wall materials
- Use stabilizing techniques to preserve existing structural backfill

Geometric & Pavement
- Cold-in-place recycling of ex. ACP
- Hot-in-place recycling of ex. ACP
- Mill top 4" of ACP
- Use RAP as new shoulder base
- Balance cut & fill

Construction Processes
- Construction waste management plan

Goal 2: Reduce water usage during construction and throughout the lifetime of the project

Drainage & Landscaping
- Use LID techniques to capture greywater
- Greywater irrigation
- Low and no-water plantings
- Plant native species

Structural & Geotechnical
- Greywater in structural concrete mixes
- Use fly ash in concrete mixes to reduce water need

Geometric & Pavement
- Greywater in concrete pavement mixes
- Use fly ash in concrete mixes to reduce water need

Construction Processes
- Closed loop wheel wash
- Monitor water use
- Leverage settling tanks in TESC and reuse greywater for dust control

This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.

Step 5 – Assess and Select Sustainable Solutions

The purpose of assessing the sustainable solutions is to select an achievable set of solutions for the project. It is not reasonable to expect that one project can achieve every solution identified in the previous step as some solutions will be mutually exclusive, some may not be feasible, and others may not be cost-effective. Reaching agreement within the interdisciplinary team and getting buy-in from the owner on which solutions are to be incorporated into the project are critical for achieving success.

The team should begin assessing and selecting solutions soon after the solutions are identified in Step 4, preferably within the timeframe of preliminary design. If additional information is needed or a long list of solutions has been generated, an iterative process may be necessary to assess all of the solutions identified.

How are sustainable solutions assessed and selected?
If Steps 1 through 4 are successfully completed and the transition between steps is well managed, most of the solutions brainstormed in Step 4 should support the sustainability vision, fit the project context, and help achieve the sustainability goals. However, the first step in assessing solutions is to determine the answers to the following two questions for each of the solutions:

- Does the solution fit the project context? and
- Does the solution fulfill one or more project sustainability goals?

Solutions that are found by the team to not fit the project context or the sustainability goals should be removed from the set of solutions. As a best practice, it is recommended that the team document why it decided not to pursue the solution.

Beyond vision, context, and goals, the team should agree upon additional criteria or questions that the team should use to assess and select the solutions. Some examples of criteria or questions that may be used in this assessment are discussed below. These criteria or questions are not exhaustive and should be developed based on what is important and critical to the project's success.

Are there trade-offs? Does the solution conflict with another solution or a sustainability goal?
Examples of trade-offs include two solutions that are both appropriate and feasible for a project but may be mutually exclusive; a solution that has competing principles, such as it benefits of the environment, but at a high economic cost; or the solution has delayed benefits, such as when the initial capital costs are relatively high, but the lifecycle costs are overall lower than a typical design. There is no right answer for these trade-offs. One of the benefits of an interdisciplinary team working together on these solutions is that the "right" answer for the sustainability solution trade-offs usually becomes apparent quickly during discussion.

Feasibility or availability?
Is the solution achievable given the resources and skills available to incorporate this solution and the current state of technology? It may be desirable to identify emerging technologies and solutions on projects, but the implementation of these solutions may not become feasible in time for construction or the owner may decide not to risk the implementation of untested solutions.

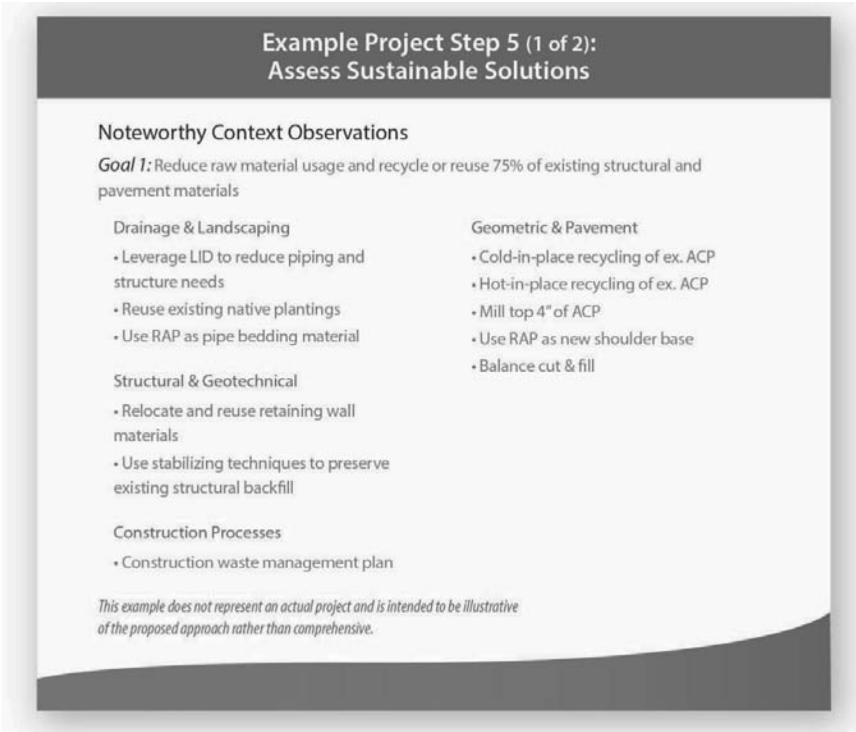
Is the solution cost-effective and does it fit within the project budget?
Here, the team can look at cost in several ways. One way is to look at the total cost of each solution; however, that is cumbersome and may be difficult to estimate early in design. An alternative way of looking at cost is to estimate the relative cost. For example, does the solution cost about the same as, slightly more than, or considerably more than, the traditional method? A relative cost range such as this may be easier to estimate this early in the design phase. Another consideration of cost effectiveness is to examine the initial cost versus the life cycle cost of solutions; some solutions may

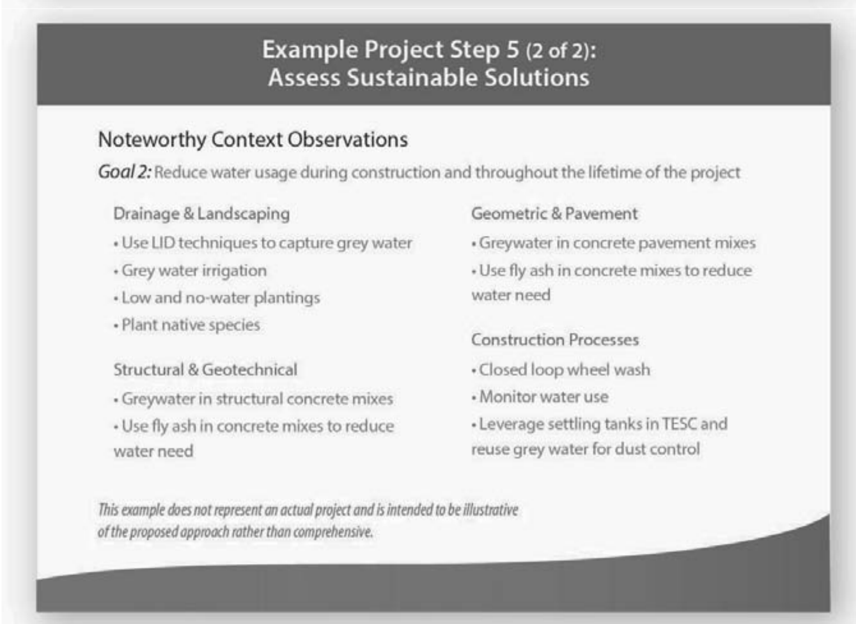
have a higher initial cost than a traditional solution, but have lower replacement or maintenance costs.

What is the sustainable value?
Sustainability is difficult to measure, but the interdisciplinary team may want to measure sustainability on a scale of how significant the sustainable benefit is and how long the benefit lasts, or another method that the team views as appropriate. For example, one might score a solution related to dust control lower than a solution related to habitat restoration because dust control benefits would only last through the construction phase while habitat restoration benefits would last throughout the project's lifetime.

Is the solution relevant to where the project is in project development?
It is important to know where a project is in project development in order to understand which decisions have already been made about a project and which decisions can still be influenced. For example, it is unrealistic for a roadway project that has a 50 percent complete design to go back and implement sustainable best practices in project planning and alternatives analysis, but it is very practical to incorporate recycled materials and a construction waste management plan since decisions regarding those items have yet to be made.

The team should use the questions above to facilitate a discussion about each of the solutions identified in Step 4. As solutions are discussed using the criteria and questions above, the team will identify solutions that are not suitable for the project? These solutions should be removed from the set of solutions. It is recommended that the team document why it decided not to pursue a solution in its range of solutions.


Example Project Step 5 (1 of 2):
Assess Sustainable Solutions
Noteworthy Context Observations
Goal 1: Reduce raw material usage and recycle or reuse 75% of existing structural and pavement materials
Drainage & Landscaping
• Leverage LID to reduce piping and structure needs
• Reuse existing native plantings
• Use RAP as pipe bedding material
Structural & Geotechnical
• Relocate and reuse retaining wall materials
• Use stabilizing techniques to preserve existing structural backfill
Construction Processes
• Construction waste management plan
Geometric & Pavement
• Cold-in-place recycling of ex. ACP
• Hot-in-place recycling of ex. ACP
• Mill top 4" of ACP
• Use RAP as new shoulder base
• Balance cut & fill
This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.


Example Project Step 5 (2 of 2):
Assess Sustainable Solutions
Noteworthy Context Observations
Goal 2: Reduce water usage during construction and throughout the lifetime of the project
Drainage & Landscaping
• Use LID techniques to capture grey water
• Grey water irrigation
• Low and no-water plantings
• Plant native species
Structural & Geotechnical
• Greywater in structural concrete mixes
• Use fly ash in concrete mixes to reduce water need
Geometric & Pavement
• Greywater in concrete pavement mixes
• Use fly ash in concrete mixes to reduce water need
Construction Processes
• Closed loop wheel wash
• Monitor water use
• Leverage settling tanks in TESC and reuse grey water for dust control
This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.

Step 6 – Incorporate Solutions

The interdisciplinary team is responsible for ensuring that the selected solutions are incorporated into the design. The team should begin incorporating solutions as soon as each solution is assessed and selected. Incorporation must be complete by final design and all solutions selected must be incorporated in the Plans, Specifications & Estimates (PS&E). The timing for the activity of incorporating each solution will vary by solution. Some solutions can be included in the plan set as early as the preliminary design submittal or as late as intermediate or final design, while many others will only need to appear in the specifications. For the purposes of tracking progress, it may be helpful to document in the design schedule where (in which design documents) and when each solution should be incorporated.

Each solution should be assigned to a member of the interdisciplinary team or delegated to a discipline lead for design and integration into the PS&E. The assigned discipline lead should be responsible for coordinating with other discipline leads as necessary and ensuring the solution is developed and integrated into the design according to the design schedule. Problems, issues, and coordination needs for sustainable solutions should become part of the regularly scheduled design meetings.

Example Project Step 6: Incorporate Solutions

Responsible Person	Sustainable Solution	When Incorporated	Status
	Leverage LID to reduce piping and structure needs	Intermediate Design	Complete
	Reuse existing native plantings	Final Design	In Process
	Use RAP as pipe bedding material Mill top 4" of ACP Use RAP as new shoulder base Balance cut and fill Relocate and reuse retaining wall materials Use stabilizing techniques to preserve existing structural backfill	Intermediate Design	Complete
	Construction Waste Management Plan	Specifications	In Process
	Use LID techniques to capture grey water Gray water irriation Low and no-water plantings Plant native species	Intermediate Design	In Process
	Closed loop wheel wash Monitor water use Leverage settling tanks in TESC and reuse gray water for dust control	Specifications	In Process

This example does not represent an actual project and is intended to be illustrative of the proposed approach rather than comprehensive.

IMPLEMENTATION OF INTEGRATED APPROACH

The implementation of this approach can be accomplished through an engaged interdisciplinary team that is being led by a project manager and/or a sustainability manager. The interdisciplinary team should maintain continuity in leadership throughout the project development process as membership evolves during different phases. The key responsibilities of the sustainability manager are to guide the interdisciplinary team through the approach presented here; assign responsibility and create accountability within the interdisciplinary team; encourage and facilitate interdisciplinary coordination; track progress of sustainability goals; and finally act as a quality control reviewer to ensure that selected solutions are incorporated.

Coordination within the interdisciplinary team and with the larger project team is critical to the successful integration of sustainability into a project. For example, Step 4 of the approach could be accomplished through brainstorming by discipline and then coming together to assess and select these solutions in a workshop. This has the benefit of providing a depth and breadth of solutions to meet each goal. Discussing the solutions as a group will help identify solutions that likely need assistance from other disciplines to accomplish or that may not be mutually exclusive with solutions identified by another discipline. The sustainability manager can facilitate interdisciplinary coordination through interdisciplinary team meetings and workshops, design meetings, cross-discipline review of design documents, and quality control reviews. All of these methods will encourage regular interdisciplinary discussions.

As progress is made with each of the steps, it is important to maintain a tracking system. A tracking system keeps project information intact and documents the pertinent decision-making related to the incorporation of sustainability into the project. Without a tracking system, there is little or no accountability for meeting the sustainability vision and sustainability goals. By documenting decisions, a tracking system provides continuity between each phase by ensuring that decisions made during each phase are understood by the team in the next phase. It helps teams consider the phases of project development, reminding them that the decisions made in the planning phase will affect those working on the project in future phases.

In addition, the tracking system should be used for the life-cycle of the incorporated sustainable solutions. By tracking the long-term performance, we can learn about the effectiveness of the technology, as well as ways to improve it in the future. This data should include any maintenance activities, repairs, and modifications. The future replacement cost of the solution should also be included if possible. This long-term data will provide a much more effective way of evaluating sustainability from the total life cycle cost perspective.

There is no single appropriate time to begin this approach; there is both an "optimal" time to pursue each step and a window of time in which the step can still be pursued and accomplished. It is important to understand that the opportunities to incorporate sustainability vary and eventually diminish as a project progresses through project development. While it is generally better to consider sustainability as early as possible, there is still some opportunity for practitioners to incorporate sustainability after design commences. Knowing where a project is in its development and what decisions have already been made will help practitioners understand which decisions can still be influenced. If sustainability was not addressed in project planning, the 6-step approach can be modified for projects that are already underway. The interdisciplinary team should simply start at Step 1 and follow the approach with the understanding that some solutions identified in Step 4 may not be feasible due to decisions already made by the project or constraints already added to the project, such as agreements made with the owner's partners and stakeholders.

After a successful implementation of this integrated approach, the effectiveness can be reviewed using available sustainability evaluation tools such as FHWA's INVEST throughout the project life-cycle.

ACKNOWELDGEMEWNTS

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Sustainable Design Practices Result in "More Than Just a Bridge"

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Introduction

The Morgan Street Bridge project is a demonstration of the City of Rockford's commitment to sustainability and the betterment of the community for all of its citizens. From a transportation perspective, replacing an aging bridge results in safety benefits that includes a more sturdy structure and the opportunity to improve traffic flow. These were certainly major considerations back in 2000 when the decision was made to begin planning for the replacement of the Morgan Street Bridge in Rockford, IL. By the time ground broke for construction of the new bridge in the summer of 2012, the list of benefits grew substantially. The bridge project had become a catalyst to unify the community through the revitalization of an impoverished area of town, and a committed effort to identify and implement context-sensitive and sustainable solutions.

The Morgan Street Bridge was originally constructed in 1890, with major upgrades undertaken in 1916 and 1960. A fixture in the community for a majority of Rockford's history, the 900-foot, spandrel concrete arched bridge spanned the Rock River and connected the city's east and west sides. Given its historic and iconic status, it was decided that replacing the structurally-deficient bridge could serve as the rallying point for a regentrification effort to bring new life to the surrounding neighborhoods on the bridge's east end, and revive an abandoned manufacturing development along the west bank that once stood as the center of a thriving industrial river town (see Figure 1).

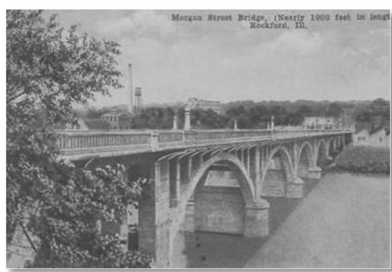

Figure 1. An 1911 painting of the bridge with the city's thriving industrial base in the background. (Source: Rockford Pioneer Historical Society)

The new $30 million Morgan Street Bridge/Corridor project includes a 532-foot, network tied arch structure, along with roadway reconstruction projects on both sides of the bridge. Construction of the bridge is scheduled for completion in December of 2013. Beginning in the earliest stages of planning, a guiding philosophy emerged that this project would be "more than a bridge." The city of Rockford established a list of goals and objectives that included quality of life enhancement, community betterment, neighborhood revitalization, improved access to city landmarks, and the preservation of vital economic generators. (See figure 2.)

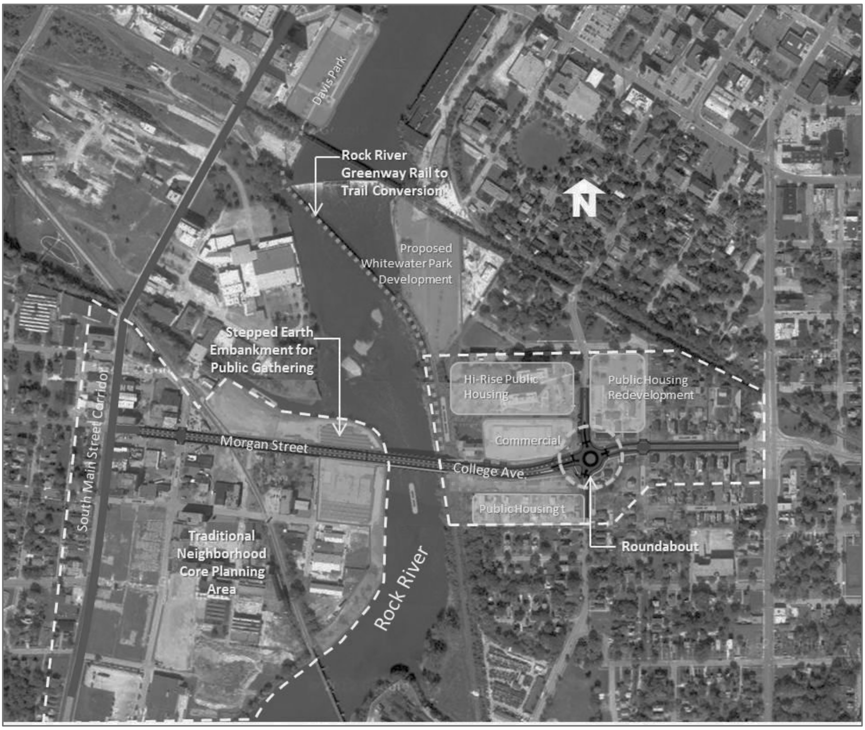

Figure 2. Overall view of the project area.

Community-Driven Design and Integration

Achieving the ambitious and diverse goals attached to the project would not have been conceivable had a people-driven approach not been adopted at the onset. Yet this approach was not limited to the planning stages, where public involvement and stakeholder input efforts are normally concentrated. The extent to which the project goals have been or are expected to be realized could only have been accomplished by continuing to solicit and implement public input throughout the design and onto the construction phases, where new ideas and solutions continued to provide value on this "more than a bridge" project.

A context-sensitive solution (CSS) process was employed to encourage community input throughout the project. It was important to the city's leaders that local citizens be involved, especially those in the immediate project area who would be most impacted by both the eventual construction, and the many permanent improvements that would be designed.

The project team incorporated a variety of methods to solicit the desired input and collaboration. Two focus groups were formed to study bridge-type alternatives and community revitalization opportunities. A Citizens Design Advisory group was also convened. Public meetings were held so that affected citizens could engage the project team on areas of concern. To accumulate data on prevailing concerns and suggestions, surveys and interviews were also conducted. Many of the ideas captured from these efforts, some of which are discussed more extensively later in this paper, were incorporated into the design:

- The community wanted the bridge to retain its iconic status and voiced their preference for a tied-arch bridge for its impressive aesthetic qualities.
- The Morgan Street Bridge has long been known for its regular contingent of fishermen. The design provides accommodations for fishing along the east and west river banks.
- The plans include a park-and-ride area for bicyclists on the west bank, which the city plans to develop. It is hoped that this area will attract water recreational vendors to the riverfront.
- Given the amount of foot traffic over the bridge, a strong preference was voiced for a barrier wall that surpassed the traditional jersey face barrier. Increased safety and protection against snow and rain splash from vehicles were among the concerns. An extensive study into unique barrier wall alternatives was conducted before selecting the eventual alternative.
- A unique, cable-style railing was used to provide an open-air feeling for pedestrians. The stainless steel rails and cables will be given a powder-coated paint finish for aesthetic appeal and to increase the life of the material. (see figure 3.)
- Commemorative, laser-etched plaques will be placed at each quadrant of the bridge and highlight the neighborhood histories at each corner of the bridge.

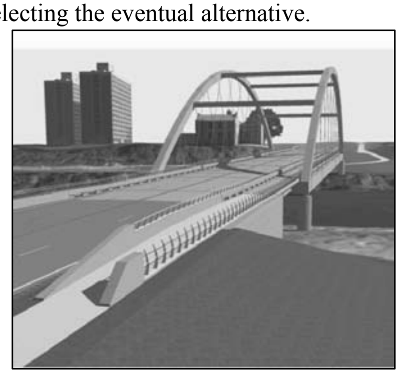

Figure 3. The centerpiece bridge will include several aesthetic enhancements

In addition to seeking input, it was important that the public remain informed of ongoing developments in a timely manner. An informational website was designed and regularly updated to facilitate the CSS process and reach a broader audience. A media outreach plan was developed in partnership with the Rockford Public Information Department, Illinois Department of Transportation (IDOT) and the Rockford Metropolitan Agency for Planning (RMAP.) By maintaining a policy of accessibility for local media outlets, the outreach group was able to both respond to request for information and initiate stories that would serve the public's interest.

This commitment to public participation, which was carried forth throughout the design and construction phases, spanned the administrations of three different mayors. Politics and economics were ever changing, but the public's awareness and participation in the project was consistent.

Since the project exceeded $20 million in projected costs, a value engineering (VE) study was undertaken in accordance with Federal Highway Administration (FHWA) and Illinois Department of Transportation (IDOT) regulations. A value solutions team was formed following the approval of the Phase I project report and concept plans, and prior to initiating detailed design. In addition to satisfying government requirements, this process sought to enhance the project value by identifying design alternatives that would reduce overall life-cycle costs without compromising the essential functions of the project, which included not only improved transportation infrastructure, but the desired community revitalization goals as well.

The VE process was carried out during an accelerated two-day workshop due to schedule and budget restrictions. Significantly shorter than the standard 3-5 day session, the team had a very limited amount of time to understand the unique project challenges and provide lasting value solutions. Advanced information packages, including geotechnical reports, hydraulic studies, and planning documents were assembled and sent to all study participants in an attempt to educate the group on many existing and special conditions prior to attending the workshop. The study combined the collective experience of fourteen industry experts with value team members representing the City of Rockford, IDOT and the consultant, along with key stakeholders representing utility, railroad, and construction companies. A total of 78 creative proposals were generated during the workshop that covered bridge function, roadway function, design suggestions, and general ideas.

Although VE savings yield expectation was low going into the process, given the relatively straightforward nature of the construction project, the results were significant. Of the 11 VE proposals that the group recommended, nine were eventually accepted. This resulted in a six percent reduction in the baseline construction cost of $21.8 million, for a savings of $1.63 million.

While the purpose of the VE process is to identify cost-savings, some of the accepted proposals opened the door to opportunities for environmental improvements and social benefits that would not have been possible had this exercise in creative collaboration not been undertaken. Perhaps the most significant of this value analysis emerged when determining how to address the Illinois Railway (IR) traffic that ran beneath the west end of the Morgan Street Bridge.

Vigilance Reaps Community Benefits and Connections

One of the VE team's recommendations was to eliminate the costs necessary for a railroad flagger during construction by temporary re-routing IR traffic to a track operated by the Chicago, Central & Pacific Railroad (CC&P). By allowing rail traffic to bypass the project site, the overall project costs and duration could be reduced, while also enhancing worker safety. Meeting with representatives of both railroads opened up the discussion for a permanent re-routing of rail traffic. When the decision was made to permanently re-route 0.65 miles of IR rail operations onto CC&P track and open up the abandoned IR right-of-way use for other purposes, an entire new world of potential benefits opened up along with it. Although the design was well underway, the project team remained diligent in identifying opportunities to add value to the project while pursuing engineering optimization.

The permanent railway relocation allowed for the safer construction of a more sustainable highway bridge. Among the benefits were an optimized and shortened bridge span, a lower bridge profile, a more economical Mechanically Stabilized Earth (MSE) wall at the east abutment, the elimination of a retaining wall, and improved construction access through the abandoned railway area. These changes resulted in $815,000 of the VE cost savings.

The environmental impact to the Rock River was also greatly mitigated by allowing the bridge piers to be constructed on the shore line, rather than in the river. This area is a prime habitat for black sandshells (ligumia recta) and gravel chubs (erimystax x-punctatus), both of which are listed as threatened species by the Illinois Department of Natural Resources.

Figure 4. An illustration of the rail to trail conversion.

In recent years, railroad consolidation had been a major goal of the city's. The railway consolidation that resulted from the permanent re-routing also resulted in a more efficient rail network throughout the downtown area. Improvements were made to an existing "diamond" rail crossing intersection, and four highway grade crossings were eliminated, improving safety. This IR relocation resulting from the Morgan Street Bridge Value Study opened the door for conversations to get the process started.

The most far-reaching benefits in terms of sustainability, however, are the plans being developed for the abandoned railroad right-of-way that has been obtained for use by the City of Rockford. (see figure 4.)

The former IR railroad bridge across the Rock River will become a vital connection between the east and west sides of town as part of the Rock River Valley Greenway. The city has applied for a $5.5 million Illinois Transportation Enhancement Grant for the development of the multi-use path to provide sustainable transportation alternatives. The path will connect Davis Park with three other paths on the east and west sides of the river. City officials consider the Rock River among the community's greatest assets and the addition of the greenway will introduce residents to scenic riverfront vistas that were largely unknown due to the area's relative isolation.

In addition to the recreational and sustainable transportation opportunities associated directly with the greenway, the trail will provide access to land that may be developed for recreational purposes. The 6.6-acre site sits alongside the Fordam Dam on the east bank of the river. The land was previously owned by ComEd and was occupied by a combination hydroelectric and coal-fired power plant until it was demolished in 1971. The site is currently under environmental remediation. After clean-up, the city hopes to begin development on some of the numerous proposals being presented for recreational use. (see figure 5.)

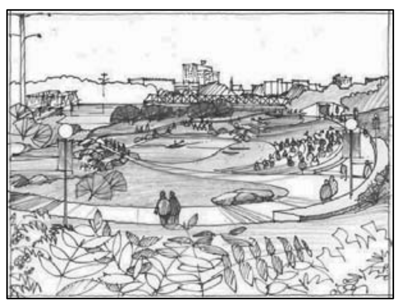

Figure 5. A rendering of a proposed development along the old railroad and east river bank.

Sustainability through Recycled Materials

An initial sustainable solution was the reuse of the demolition material from the existing bridge and a nearby building as fill for the bridge embankment. Approximately 24,000 CY of recycled demolition material was incorporated into the design, yielding a project savings of $220,000. (see figure 6.)

Figure 6. Material from demolished industrial buildings is being reused as fill for the bridge project.

In addition to the project demolition material, several other abandoned buildings to be demolished as part of the city's revitalization efforts were planned as land fill for the bridge project. Five buildings yielded a total of 16,000 CY of recycled material for an additional proposed savings of $250,000. The city provided specifications that required the contractor to crush, sort and stockpile the material for the west bridge approach embankment.

To reduce the amount of fill needed for the roadway approaches, the existing roadway, which would normally be sent off-site, was crushed for use as aggregate backfill and structure embankment. Plans have also been made to recycle material generated from underground utility installation throughout the corridor. Special waste material that included environmentally sensitive solids from the industrial development removals was stockpiled and mitigated on-site to eliminate disposal fees.

Corridor Enhancement Stimulates Neighborhood Re-Vitalization

The Morgan Street Bridge/Corridor project is situated within one of the key areas targeted by the city for re-vitalization. The project's corridor which extends 1,500 feet to the west and 1,800 feet to the east of the bridge has provided an opportunity to develop a complete street that would promote the objectives of making the neighborhoods it traverses more livable, attractive and connected.

On the east, the Morgan Street project extends into an area referred to as the College Seminary Area, one of the oldest parts of town. In recent times this area has been victimized by community decentralization, classic public housing and characterized by declining population and income. Plans for the Morgan Street corridor/bridge improvements were an incentive for the Rockford Housing Authority (RHA) to initiate a bold five-year redevelopment project that would de-densify the housing while creating a more quality based neighborhood.

Figure 7. The Morgan Street Roundabout included lower construction and life cycle costs compared to a signaled intersection.

One of the key opportunities on the east side was at the intersection of College Street (Morgan Street extended on the east side) with Seminary Avenue. The razing of the obsolete public housing properties along one side of the right-of-way provided the needed space to convert that traditional signalized intersection into a modern roundabout. (see figure 7.) The sustainable benefits of the innovative, hybrid roundabout configuration included lower construction ($233,000) and life-cycle costs, elimination of traffic signals, and decrease in Operation and Maintenance (O&M) costs. With traffic counts of 11,000 Average Daily Traffic (ADT) existing and 16,000 ADT proposed, noise and air quality is also enhanced by not having vehicles stopping, idling and starting. An additional benefit is aesthetic improvements through linear landscape enhancements that are adding value to existing neighborhood shopping venues.

On the northeast corner of that roundabout, a three-story, mixed-use development is being constructed through a partnership between the RHA and a private developer that will result in first floor commercial space and multiple housing units above. This first building is an anchor for what is a larger plan to create a mixed-income neighborhood with housing for the elderly and persons with disabilities.

On the west is a sub-planning area referred to as the Traditional Neighborhood Core sub-area of the South Main Business Area, which includes traditional commercial/retail areas, substantial industrial properties, residential neighborhoods and key community institutions. In addition to serving as a new improved gateway to this area, a key design feature is an outdoor seating and viewing area on the northwest quadrant of the bridge. This area features an earth embankment with a unique grass/step configuration to accommodate outdoor pedestrian seating and viewing for river recreational events, including the city's annual firework display for Independence Day. This opportunity was realized following the demolition of abandoned industrial buildings and is now one of the most prized vistas of the Rock River looking toward the central business district. The city has plans to develop the entire west bank into a park-and-ride for bicyclists.

Figure 8. A night rendering of the bridge.

Further neighborhood enhancements include greater mobility through the inclusion of a multi-use path adjacent to the corridor. The bridge itself contains an eight-foot-wide sidewalk on the north side of the bridge and a 12-foot-wide multi-use path on the south side of the bridge allowing pedestrians to have better access and also interact more with the river views. This will also transect with the proposed rail-to-trail conversion that will provide unprecedented pedestrian access to areas along the River and connection to other key neighborhoods.

The aesthetics of the bridge itself provides community value through its highly visible structural design and its ornamental lighting and railing. Sustainable features also include low voltage LED lighting for supplemental bridge accent lighting. (see figure 8.)

Stakeholder Support & Lessons in Reflection

The roundabout intersection at College and Seminary was the city's first. It was important to educate the community about the improved safety and traffic flow that roundabouts offer traditional intersection. The stakeholder outreach campaign during design resulted in overwhelming support during construction. Neighborhood meetings were also held to inform the public of construction activities. This communication proved particularly useful during demolition blasting, utility upgrades and the erection of the structural steel. The impacts from these activities were limited as the result of advanced coordination with utility companies that led to early commitments for extended summer outage times on the high voltage electrical lines.

Continued commitment to the proactive public coordination and Context Sensitive Solutions (CSS) process resulted in revisions made during construction, including the addition of aesthetic coloring of the concrete piers along with a high definition camera installed on a nearby high-rise building to document construction and also provide surveillance for local and federal law enforcement agencies. The camera has provided video evidence in the prosecution of several crimes and is contributing to the city's revitalization efforts in the area by improving public safety.

Conclusion

The Morgan Street Bridge project exemplifies the importance of community engagement and the utilization of methodologies that foster synergy and yield ongoing opportunities and benefits throughout the entire process. The CSS process used for this project was maintained beyond planning and continued into construction.

The use of CSS and VE contributed significantly to the sustainable achievements on this project. CSS promoted involvement and constant visibility of the project in a way that encouraged greater integration of other infrastructure and quality of life opportunities within the proximity of the project. This was a true community-driven project that has and will continue to reap rewards for the community. The utilization of VE provided some surprise outcomes that also contributed to the sustainability value of the project. Both sustainability and VE are compatible in that they both promote the minimization or elimination of waste, and lower life-cycle costs. With community revitalization being a key function of the project, incorporating the VE process early, rather than later in the design process, allowed for some very creative ideas to formulate and eventually blossom into major quality-of-life benefits to the community.

Figure 9. The new Morgan Street Bridge under construction.

PERMEABLE PAVEMENT DESIGN AND CONSTRUCTION
WHAT HAVE WE LEARNED RECENTLY?

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ABSTRACT

Permeable pavements have been gaining popularity throughout North America. Permeable pavements typically consist of pervious concrete, porous asphalt or permeable interlocking concrete block paving units over an open grade base/subbase layer(s). Permeable pavements are designed to infiltrate stormwater, reduce peak flows, filter and clean contaminants in the water stream and promote groundwater recharge. They have become an integral part of low impact design and best management practices for stormwater management. In order to be effective, permeable pavements must be designed to provide sufficient structural capacity to accommodate the anticipated vehicle loadings as well as deal with stormwater flowing into and out of the permeable pavement. While there have been many well designed and constructed permeable pavements, this is a relatively new technology and there have been some "issues" with their performance. This paper describes some of the basics of best practices, design, construction and maintenance considerations for permeable pavement design and construction and focuses on best practices of permeable pavement design and construction in North America.

Keywords: Permeable pavement, permeable interlocking concrete pavement, permeable pavement structural/hydrologic design, case studies, pavement performance, maintenance.

INTRODUCTION

Permeable pavement technologies are an important aspect in sustainable design. Environmental responsibility through green initiatives is being embraced in the transportation industry from grass roots community groups to federal governments. One such tool in the sustainable infrastructure design arsenal is the use of permeable pavement systems.

Traditional pavement surfaces are virtually impermeable and are used in conjunction with ditches and storm drains to channelize precipitation towards storm water management facilities. Permeable pavements provide a different approach. Rather than channelizing precipitation along the surface of the pavement, the water is allowed to infiltrate and flow through the pavement surface where it can be stored and slowly allowed to return into the local groundwater system. Permeable pavements provide runoff reduction and make a significant contribution to on-site trapping, removing and treating stormwater pollutants. National and provincial/state legislation in Canada and the U.S. and other countries regulating runoff has provided increased incentive for use of these pavements by public agencies.

Permeable pavements in some form have been around for centuries, and in the literature since the early 1970s [Ferguson 2005]. Early permeable pavements included a variety of systems that typically retained earth and grass in cells constructed of stone, concrete or plastic materials. While this increased the permeability and permitted some rainwater to enter the pavement, they did not provide substantial structural capacity.

More recently, permeable pavement systems have been designed to accommodate more frequent and heavier loading than those of turf systems. These have included porous asphalt concrete, pervious concrete, and permeable interlocking concrete paver surfaced pavements. Their application has expanded to include walkways, trails, driveways, large commercial parking areas, and roadways.

PERMEABLE PAVEMENT SYSTEMS

Permeable pavement systems consist of a surface with joints and/or openings that will freely allow water to infiltrate the system. The openings allow water from storm events to flow freely through the surface into an open-graded base/subbase where it is collected and stored before it leaves the pavement structure. For low-infiltration rate soils, perforated drain pipes are often placed in the subbase or subgrade to drain excess water, thereby functioning as a detention facility that provides treatment for removal of stormwater pollutants and allows some infiltration. For sites that do not allow for any infiltration, permeable pavement is designed with an impermeable liner that prevents water from entering the soil subgrade; water is detained, treated, and exits via underdrains.

Research has demonstrated that permeable pavements are an effective method for reducing stormwater runoff and pollutants from urbanized areas and can function well with minimal maintenance [Hunt 2009]. Design pollutant removal efficiencies are on the order of 85 percent for total suspended solids (TSS), 35 percent for phosphorus and 30 percent for nitrogen. Permeable pavements has also been shown to work well in cold climates, showing early snow melting qualities with minimal maintenance [Drake 2012].

Like all permeable pavements, the surface will accept sediment thereby decreasing its infiltration rate with time. The rate of decrease depends on sources of deposited sediment typically from ordinary use and unexpected soil erosion from adjacent surfaces. Such reductions from normal use still render a surface that can infiltrate most rain events. Demonstration projects have been completed around North American showing that permeable pavement sedimentation can be addressed through the use of regular vacuum sweeping [Kevern 2011].

General configurations of permeable pavements based on subgrade infiltration are shown in Figure 1. Each of these would be further detailed to achieve the specific goals for an individual installation. These details would include items such as: surface type, curbing and other support features, use of geotextile for layer separation or water filtration, outlet pipe location, downstream water volume and quality treatment, etc.

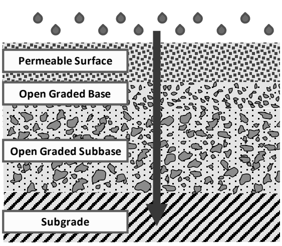

Figure 1a. Full Infiltration

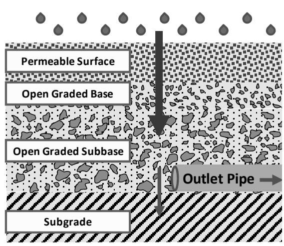

Figure 1b. Partial Infiltration

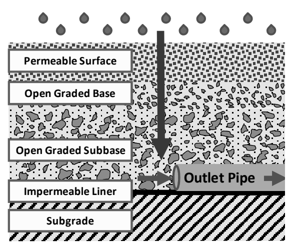

Figure 1c. No Infiltration

Figure 1a shows a full infiltration design. All stormwater is infiltrated into the subgrade below the pavement. This system does not require any additional stormwater features such as catchbasins, outlet pipes, stormwater management ponds, etc. This system is typically only used in areas where the subgrade materials have high infiltration rates.

Figure 1b, shows a partial infiltration design. Water is encouraged to infiltrate the subgrade; however, excess water from higher intensity storms is removed from the pavement structure using outlet pipes to ensure that that the pavement system does not overflow. The outlet pipe under the permeable pavement is typically placed at the bottom of the subbase layer or in a shallow trench near the top of the subgrade layer to prevent it from being damaged during construction. In a partial infiltration design, the elevation of the downstream end of the pipe outlet controls the surface discharge elevation and can be set by the designer based on how much infiltration is allowable and desired for site conditions.

Figure 1c, shows a no infiltration design. This type of system is used for low permeability subgrade where infiltration rates are minimal. They are also used for applications where infiltration would be undesirable, such as:

- Water harvesting applications where water is stored for subsequent use;
- "Brownfield" sites where it is not desirable to have water flowing through contaminated subgrades;
- Areas where the subgrade is susceptible to frost heaving or swelling due to moisture content variations; or
- Where subgrade exposure to saturated conditions would result in a reduction in subgrade strength requiring a very thick pavement structure to accommodate traffic loading.

The three primary permeable pavement surface types as designated by their industry associations include porous asphalt, pervious concrete and permeable interlocking concrete pavement. These surface layers are typically underlain by open graded aggregate layer(s). These aggregate layers provide structural capacity to accommodate the traffic loading and act as a reservoir to store and release stormwater as required by the designer. As a design variation to increase load carrying capacity, the pavement industry in the United Kingdom has published a guide to the design and construction of permeable pavements that includes a layer of asphalt concrete beneath the permeable surface [Interpave 2012]. To maintain permeability, holes are drilled in the asphalt concrete and filled with open graded aggregate. The asphalt concrete layer provides additional strength and stability to the permeable surface while the aggregate filled holes provide positive drainage to the underlying aggregate base/subbase.

STRUCTURAL AND HYDROLOGICAL DESIGN

The design of permeable pavements requires the consideration of both structural and hydrological components as shown in Figure 2. The structural design of the pavement is completed to determine the thickness of the various pavement components that are necessary to support the intended design traffic while protecting the subgrade from permanent deformation. The hydrological design determines the key design elements necessary to infiltrate rainwater and surface runoff into the pavement hold and/or detain and filter the water to achieve the stormwater management objectives. An optimal pavement design is one that is just strong enough to accommodate the design traffic and has the minimum hydrological features to provide water quantity and quality management.

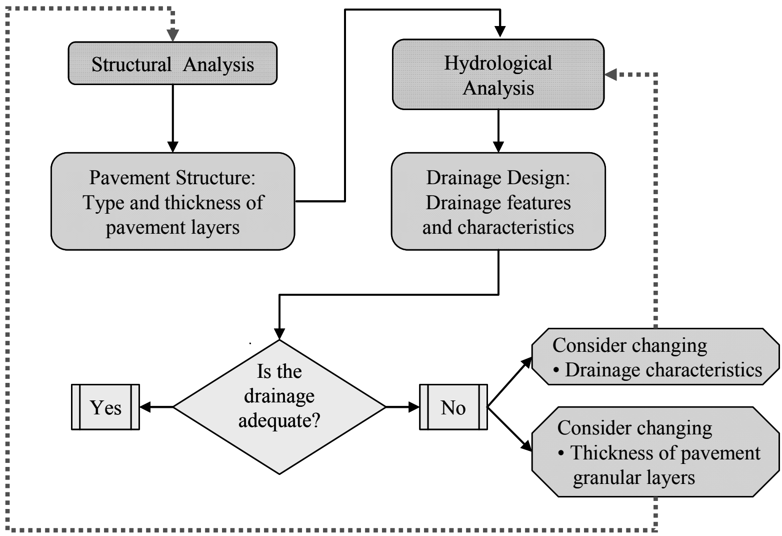

Figure 2. Structural and hydrological design flowchart [Swan 2009].

The most common structural analysis procedure for porous asphalt and permeable interlocking concrete pavement follows the requirements of the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures [AASHTO 1993, Smith 2010]. Pervious concrete structural design is based on the StreetPave system as modified by the American Concrete Paving Association (ACPA) [ACPA 2012].

There are numerous stormwater models that could be used to complete the hydrological design for permeable shoulder pavements. Depending on the hydrologic design goals, appropriate models may include:

Simple volumetric runoff estimation methods. These models generate an estimated runoff volume for a specified design storm depth, but do not assign a hydrograph "shape" to this runoff volume. Examples include the NRCS Curve Number method [NRCS 1986], the volumetric runoff coefficient method, and others.

Event-based hydrograph estimation methods. These models generate an estimated runoff hydrograph for a specified design storm. Examples include the Watershed Hydrology Program (WinTR-20), Small Watershed Hydrology (Win TR-55), Santa Barbara Unit Hydrograph (SBUH), HEC-1 Flood Hydrograph Package, HydroCAD Stormwater Modelling (HydroCAD), and others.

Continuous simulation modelling programs. These models generate long term runoff hydrographs from multiple storms based on a continuous rainfall record and other hydrologic inputs; many also have the capability to route the hydrograph through stormwater management facilities that conduct continuous analysis of transient inflows, outflows, and storage levels. Examples include the USEPA Stormwater Management Model (SWMM), the Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS), Source Loading and Management Model for Windows (WinSLAMM), Integrated Design Evaluation and Assessment of Loadings (IDEAL), others.

In general, the hydrological analysis assesses if the design runoff volumes or hydrographs can be infiltrated, stored and released by the pavement structure provided. The quantity of water in the pavement system is described as a water balance [NRCS 1986].

The design of underdrain and outlet structures is a function of the hydrologic design goals for the project. Some agency specifications require detention of stormwater for a certain time (i.e., a minimum drawdown time, e.g., 72 hours) to ensure adequate retention time for treatment. For flow control purposes, outlet configurations should be designed to meet the specific flow control objectives of the project. For example, for control of the 10 year peak runoff flowrate to match pre-development peaks, a relatively large outlet may be appropriate to provide "peak shaving" (i.e., functioning similar to a peak flow control detention facility). In contrast, to provide flow duration control from 50 percent of the pre-development 2-year peak to the 10 year peak, a very small low-flow outlet control may be needed, with supplemental outlets at higher elevations to effectively manage flows and durations to pre-development levels across a broad range of storm events.

PERMEABLE PAVEMENT SUITABILITY

To determine the suitability of a project for permeable pavement, the key factors specific to the project should be considered. Based on their importance in overall decision making, these factors can be divided into primary, secondary, and other considerations which may impact the decision to use permeable pavements for a particular project. Primary considerations (i.e., fatal flaws or major design challenges) are those that would have an overriding influence on the decision to move forward with the project. Secondary considerations are those that have a lesser influence and usually are taken into account as part of the design process when there are no overriding considerations. These factors may diminish the performance or acceptability of permeable pavement or may require additional design provisions (and associated costs) to avoid risks. Other considerations may have some influence on the decision to include permeable pavements for a particular project. The primary considerations should generally be weighted the highest to reflect their importance in moving forward with the project, while secondary and other considerations are useful to prioritize between sites and inform design, but are not generally fatal flaws.

A. Primary Considerations
- Availability of funding
- Status of environmental approval
- Safety
- Significant grades (>5 percent)
- Depth of water table
- Geotechnical risks
- Groundwater contamination risk

B. Secondary Considerations
- Stringent receiving water quality standards
- Sand use for winter maintenance
- Low soil infiltration rates
- Target design volumes and runoff rates
- Risk of flooding
- Mandates for stormwater quality control
- Mandates for drainage and peak flow control
- Maintenance protocols

C. Other Considerations
- Interest in innovation
- Presence of utilities
- Impact of unknown site conditions
- Risk of accidental chemical spill

This list of considerations reflects typical needs and expectations. Other constraints and project-specific considerations should be added or deleted as necessary. Each of these criteria is discussed in more detail in Table 1.

Table 1. Permeable Pavement Use Considerations.

Importance Level	Description
Primary Considerations	
Availability of funding	The initial capital construction cost of permeable pavement is typically higher than for conventional pavement. Overall long term life-cycle costs can be very competitive if consideration is given to stormwater quality and quantity benefits.
Status of environmental approval	In some jurisdictions, permeable pavement may not be permitted or may require additional environmental approvals.
Significant grades	Grades of more than 5 percent may pose significant design challenges. It may be necessary to bench the subgrade to promote water infiltration and/or to slow water to prevent channelization or scouring.
Depth of water table	Permeable pavements should not be used in areas where the water table is within 0.6 m of the top of the soil subgrade.
Geotechnical risks	Geotechnical risks may introduce added design complexity and may necessitate the use of an underdrain and/or impermeable liner.
Groundwater contamination risk	A variety of factors influence the potential for stormwater sources to contaminate groundwater, including soil characteristics, depth to groundwater, existing soil contamination, and application of salt for deicing.
Secondary Considerations	
Stringent receiving water quality standards	While the presence of and need to protect nearby aquatic resources may provide incentives for the use of permeable pavements in cases, for some protected watersheds, cold water streams, and other receiving waters with stringent water quality standards, the level of treatment provided by permeable pavements (for water discharged from underdrains) may not provide adequate protection from stormwater quality impacts.
Sand use for winter maintenance	Winter sand may clog permeable pavement systems resulting in reduced system permeability.
Low soil infiltration rates	Low soil infiltration rates may need to be supplemented with an underdrain to provide adequate drainage, which tends to reduce performance and increase costs.

Importance Level	**Description**
Target design volumes and runoff rates	Due to geometric factors, permeable pavements may be limited in terms of how much volume they can store. It may be necessary to include supplementary storage features to achieve water storage and infiltration goals.
Risk of flooding	Permeable pavements may not be capable of conveying flows from peak storm events. Areas subject to frequent flooding may require supplemental drainage features to ensure that the surface is drained.
Mandates for stormwater quality control	Permeable pavements may contribute substantially to water quality improvement. Where regulations require stormwater quality management, this may significantly incentivize the use of permeable pavement.
Mandates for drainage and peak flow control	Permeable pavements provide stormwater management alternatives to more costly practices to provide drainage and peak flow control.
Maintenance protocols	Permeable pavement systems require mandatory non-traditional maintenance practices such as vacuum sweeping, which may influence their applicability and desirability for a project.
Other Considerations	
Interest in innovation	Utilizing traditional impermeable surfaces for stormwater management provides opportunities for innovation.
Presence of utilities	The design and construction of permeable pavements may be problematic or require additional design features, such as cutoff walls, in areas where utilities are present.
Impact of unknown site conditions	Variability of soil conditions, presence of organics, potential for frost heave, etc. may impact pavement performance.
Risk of accidental chemical spill	While spills are relatively uncommon and tend to occur at low volumes that can typically be retained in the permeable pavement.

KEY DESIGN CONSIDERATIONS

The design of permeable pavements must consider both the structural and hydrological situation and conditions. Some key design considerations are provided in Table 2.

Table 2. Key Permeable Pavement Design Considerations

Feature	Description
Site Characterization	
Drainage Path	In order to assess the suitability of a site for potential use for permeable pavement, the drainage patterns in the area surrounding the permeable pavement should be evaluated to determine its possible impact on the permeable pavement.
Traffic Type and Patterns	Assess traffic type and composition. Avoid using permeable pavements in high traffic areas subjected to traffic such as buses or heavy trucks. Avoid use where traffic will contaminate the pavement surface with dirt, oils and grease.
Winter Maintenance	Avoid the use of winter sand which may clog the pavement. Limit use of deicing chemicals if water is to be captured and re-used.
Groundwater Depth	Do not use permeable pavements in areas where the groundwater is within 0.6 m of the bottom of the pavement.
Subsurface Conditions	Underground utilities, presence of bedrock etc. may require special considerations.
Surrounding Land Use	Avoid use downstream of high sediment and/or contaminant generating activities.
Structural Design	
Traffic	Complete structural design suitable for the intended traffic. Consider current and future expected traffic types and frequency.
Subgrade Characteristics	Carefully evaluate subgrade structural capacity. Consider to be in "soaked" condition. Determine infiltration capacity. Assess need for compaction to uniform density.
Surface	Determine structural capacity of surface layer. Typically less than that of conventional pavement surfacing. Carefully assess impact of construction conditions and techniques on the stability of the surface.

Feature	Description
Base/Subbase	Determine structural capacity. Typically less than that of conventional materials. Select durable and crushed materials to maximize structural capacity and porosity for water storage. Select clean materials with very low fines contents.
Reliability	Assess design reliability and select appropriate value for intended traffic and maintenance activities.
Hydrological Design	
Design Storm	Determine expected storm duration, frequency and intensity.
Surface	Determine surface infiltration capacity both initially and long-term if subject to contaminant loads.
Surface Slope	Avoid surface slopes of > 5 percent. Design for runoff for permeable paver surfaces at higher slopes.
Subsurface Slope	Avoid subsurface slopes for infiltration designs. Consider berms and weir structures for sloped pavements.
Contributing Area Runoff	Determine runoff volume, speed, etc. from contributing areas. Consider potential contaminant loads.
Supplemental Surface Drainage	Design supplemental surface drainage for high intensity storms that may limit surface infiltration at times.
Subgrade Infiltration	Determine potential for subgrade water infiltration based on soil type, density, permeability, etc.
Underdrains	For partial or no infiltration designs, determine the type, location and need for underdrains. Specify outlet details and clean out provisions.
Outflow Details	Design outflow from underdrains to meet detention goals. Ensure
Geotextile	Assess the need for geotextile separators to prevent fines migration and layer intermixing.
Liner	Determine the need and type of impermeable liners for no-infiltration designs.

KEY CONSTRUCTION CONSIDERATIONS

While the construction of permeable pavements is generally straight forward, it is necessary to ensure that everyone involved in the construction is fully aware of the ‘special’ considerations necessary to ensure that the pavements are constructed to the highest level of quality to ensure a long life. Some of the key construction features are summarized in Table 3.

Table 3. Permeable Pavement Construction Considerations.

Feature/Pavement Type	Description
All Permeable Pavements	
Construction Timing	Do not schedule construction during cold weather or raining conditions. Site subgrades may be susceptible to moisture weakening.
Pre-Construction Meeting	Hold a pre-construction meeting to ensure that everyone is cognisant of the permeable pavement requirements and need to keep the site clean.
Subgrade Compaction	Avoid construction equipment traversing the subgrade resulting in compaction and a reduction of permeability.
Underdrains	Place underdrains in shallow trenches on top of 50 mm layer of base aggregate. Cover and protect from compaction damage. Connect and fit outlets.
Base/Subbase Placement	Place the base/subbase materials in lifts. End dump and push to prevent subgrade compaction if desired. Compact using appropriate compaction equipment. Start with 2 passes using vibrator roller then switch to non-vibratory compaction to avoid crushing of base/subbase materials.
Construction Protection	Avoid contamination with fines. Provide "Texas Gates" to dislodge dirt or wash stations for construction equipment as necessary.
Permeable Interlocking Concrete Pavement	
Paver Selection	Select appropriate paver types, thickness and placement orientation commensurate with the expect site use.
Bedding Layer	Select bedding layer to ensure that it is "choked" into the underlying layer. Ensure consistent thickness. Avoid excessive layer thicknesses.
Joint Filler	Select the appropriate joint filler material for the paver type. Ensure high frictional properties to promote friction between paves and joint filler while maximizing infiltration capacity.

Feature/Pavement Type	Description
Pervious Concrete	
Mix Design	Ensure mix design addresses maximum structural capacity and permeability. Utilize admixtures and fibres to promote curing and appropriate cement film thickness.
Placement	Utilize admixtures to promote cement hydration. Ensure adequate compaction to maximize layer uniformity.
Curing	Take steps to ensure adequate cement hydration, curing compounds, admixtures, surface moisture loss provisions, etc.
Porous Asphalt	
Mix Design	Ensure adequate asphalt cement film thickness but asphalt cement type selection, use of fibres, fillers, etc.
Placement	Utilize adequate compaction equipment, pay attention to temperature/viscosity during placement/compaction.

CONCLUSIONS

The use of permeable pavement for stormwater management has gained rapid acceptance across North America. They provide the ability to utilize a traditional contributor to stormwater problem as a solution to both detain and "clean" stormwater. While the addition of water to a pavement can have detrimental effects on the structural capacity of a pavement, the careful design of permeable pavements can ensure that they can provide both long life and be effective in accommodating stormwater. Careful consideration of design features and construction techniques are necessary to ensure their success.

Key design features include a careful assessment of the permeable pavement site and its surrounding land use to ensure that the pavement surface does not become contaminated with sand/dust or vegetative matter. A rational assessment of the traffic to which the pavement will be exposed including truck, bus and other heavy vehicles will permit the designer to ensure that the pavement has sufficient structural capacity for its design life. A hydrological design taking into account rain water landing on the pavement and water shed from the surrounding area can be accommodated into the permeable pavement and then properly treated for water quality improvements and permitted to exit the pavement either through infiltration into the subgrade or controlled through underdrains. Construction processes and techniques should consider the protection of the permeable pavement from contaminants during construction and to ensure that the pavement is able to accommodate both vehicle loading and water infiltration and exfiltration in accordance with the pavement design. Finally, with all pavements, maintenance practices should including occasional vacuum sweeping to ensure the longevity of the permeable surface with repairs completed to address any localized deficiencies such as settlement and ravelling etc.

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Benefits and Applications of Utilizing Agency Asphalt Mixture Design Historical Records

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ABSTRACT

Advancement of the practice of building sustainable highway networks can be furthered by effective use of historical records. To this end, this paper presents analysis of a historical record of approved asphalt mixture designs maintained by the Mississippi Department of Transportation. Distributions of mixture properties are analyzed and discussed; properties of the reclaimed asphalt pavement (RAP) materials in the dataset are compared to total asphalt mixture properties. The data highlights the materials diversity that occurs within the jurisdiction of an agency. Benefits and applications of such an analysis of historical records are discussed. Applications for the data include re-use of RAP in plant mixed asphalt, in place recycling, and educating the next generation of pavement materials engineers. The data collection and analysis techniques are straightforward, easy to perform, and low cost, while the potential benefits to an agency are high.

INTRODUCTION

In recent years, applying sustainability concepts has become a focus for the transportation profession. Transportation infrastructure desperately needs attention, though funding levels are challenged. Improved methods to renew and recycle highways are being studied nationwide. One approach that should be considered by agencies is to advance their practice and improve the future of their highway network by looking into their past for guidance on how to rehabilitate aging pavements and to educate the next generation of pavement materials engineers.

The objectives of this paper are to describe a historical record maintained by the Mississippi Department of Transportation (MDOT), to present techniques used to extract and organize the information, to analyze historical distributions of asphalt mixture properties, and to discuss applications for the data that could improve transportation infrastructure sustainability. Ideally, this paper will serve as a model for other agencies since the analysis techniques presented are straightforward and have a wide range of potential uses that could extend beyond those presented. It is anticipated that most agencies maintain records of their approved mix designs, so the approach presented could be directly applied by those entities. The analysis also highlights the diversity of materials that reside within an agency's records that should be considered in the context of large scale recycling.

Use of the data presented is mostly aimed at recycling the pavement materials represented in the MDOT database, though some consideration is given to items such as education and reasonableness checks. Broadly speaking, recycling asphalt (flexible) pavements can be performed in two manners: in-place, or re-introduced into a mixture off-site at a plant. Applications of the MDOT database are broadly divided herein into these two categories.

MDOT ASPHALT MIXTURE DESIGN HISTORICAL RECORD

All asphalt mixes used on MDOT projects are submitted for review and approval through the Materials Division Central Testing Laboratory, where data for each design is entered into a standard formatted Excel template with a unique file name, making it feasible to retrieve data for analysis. The standard data handling procedure provides MDOT the ability to use straightforward programming in Visual Basic to extract any design parameter of interest from the entire database. To accomplish this task, the search program is directed to a specified folder that houses the Excel files for all mixes. It then opens each file, copies the designated data, pastes it in a new Excel file, and closes the mix design file. This process continues until the selected data has been copied from all mix files in the specified folder and pasted to the new file. The user then has a summary file that can be sorted and filtered to organize data and analyze statistics of all approved asphalt mix designs.

Properties of all mix designs approved by MDOT between January 2005 and March 2010 were extracted from the historical record and became the dataset used for analysis in this paper. Data retrieved for each asphalt mixture included combined aggregate blend properties, design compactive effort, asphalt binder grade, and mixture volumetric properties. Also included were individual aggregate stockpile proportions, aggregate types, aggregate water absorptions, and stockpile gradations. For mixtures that contained RAP, the RAP total asphalt content, extracted aggregate gradation, and extracted aggregate water absorption were also included.

Raw data was arranged by nominal maximum aggregate size (NMAS) and design compactive effort (i.e., 50, 65, and 85 gyrations). The dataset contained a total of 837 mixtures; however, not all 837 mixtures were unique in terms of volumetric properties. In a number of cases there were two mixtures with identical aggregate and volumetric properties. In most instances these duplicate cases resulted from re-approvals of existing mix designs with different binder grades or different binder sources. The duplicate cases were removed from the dataset as they do not represent unique volumetric mixture combinations, which reduced the number of mixes to 590.

The majority of mixtures contained combinations of gravel, limestone, sand, and RAP although not all mixtures contained all these aggregate types. Twenty-two mixtures (3.7% of the total) were removed from the dataset because they contained other unique or unusual aggregate types. The aggregate types for the 22 mixtures removed were: granite (19 mixes), slag (1 mix), sandstone (1 mix), and crushed concrete (1 mix). Removal of these 22 mixtures left 568 for use in analysis. Overall, 529 of the 568 mixtures, or 93%, contained RAP. The resulting dataset of 568 mixtures was considered to be the population of typical asphalt properties in Mississippi for analysis of the historical distributions of mixture properties. This is a reasonable approach with all the approved mixtures statewide over a period exceeding five years.

HISTORICAL PROPERTIES OF MISSISSIPPI MIXTURES

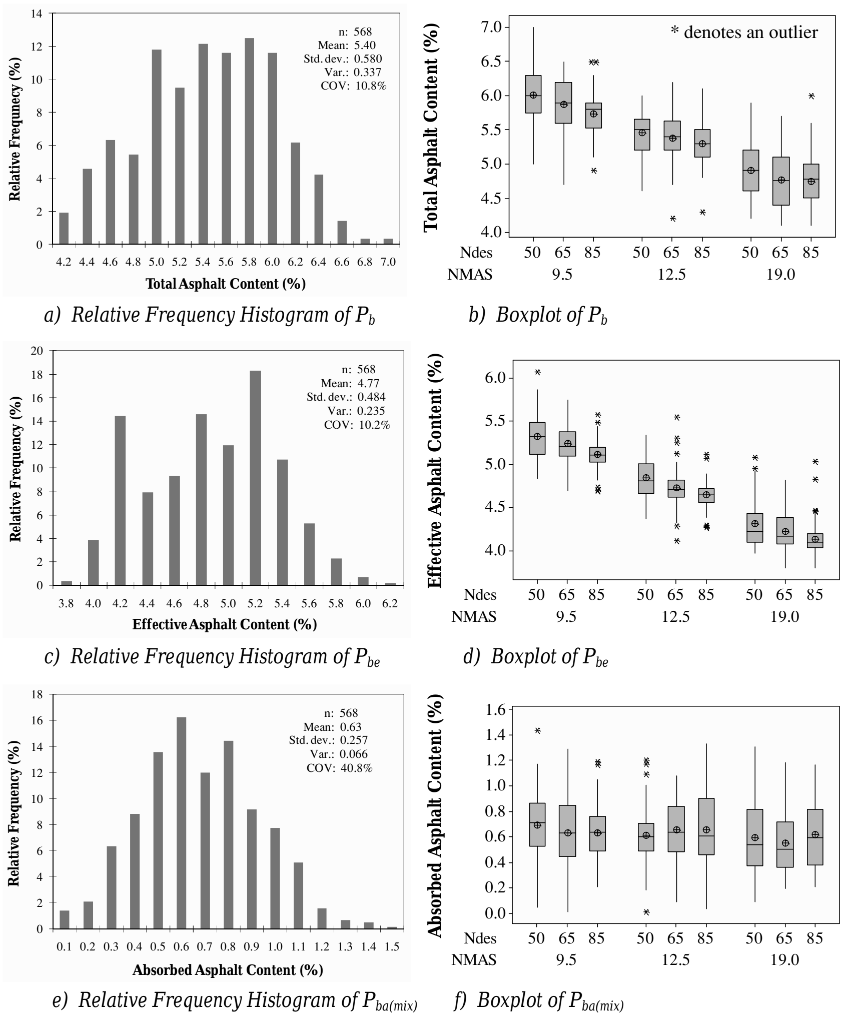
Asphalt Contents

Figure 1 presents relative frequency histograms and boxplots of total, effective, and absorbed asphalt contents for the mixtures. Examination of the total and effective asphalt content relative frequency histograms (Figure 1a and Figure 1c) reveals a relatively wide spread of values and no clearly defined peak. The effective asphalt content standard deviation is lower than the total asphalt content standard deviation. The coefficients of variation (COV) for the two populations are nearly the same (approximately 10%). From the boxplot of total asphalt content (Figure 1b) it can be observed that as the NMAS of the aggregate gradation increases, the total asphalt content decreases, as expected.

The same observation can be made from the effective asphalt boxplot (Figure 1d). It is evident that an increase in compactive effort during mix design results in a decrease in effective asphalt content. This is expected since a greater compactive effort during mix design requires less effective asphalt to achieve target air voids.

Examination of the absorbed asphalt relative frequency histogram (Figure 1e) indicates a general peak and an approximately normal distribution that is in contrast to the distributions of total and effective asphalt. The COV is approximately four times higher for the absorbed asphalt distribution. The effective asphalt contents boxplot (Figure 1f) reveals little difference in mean absorption values with changes in compactive effort. The lack of change in the mean absorbed asphalt content for changing compactive effort is expected since compactive effort does not affect aggregate absorptive capacity. It is interesting to note that the differences in absorbed asphalt content for different NMAS are quite small. One reason for the differences could be crushing the same base aggregate source to produce different gradations, since absorption is a general characteristic of the gravel or stone source.

A few observations are indicated in the boxplots of total and effective asphalt content as potential outliers. While unusual, these extreme observations were left in the dataset, because they represent real mixtures and are part of the population of asphalt mixes in Mississippi. The total asphalt content range over the five year period covered by this dataset was 4.1 to 7.0%. A wide range in absorbed asphalt content was observed of 0.03 to 1.33% (extreme values were excluded). MDOT defines absorbed asphalt for their mix designs as a percentage of the total mixture, $P_{ba(mix)}$; total asphalt content is therefore the sum of absorbed and effective asphalt contents.



a) Relative Frequency Histogram of P_b

b) Boxplot of P_b

c) Relative Frequency Histogram of P_{be}

d) Boxplot of P_{be}

e) Relative Frequency Histogram of $P_{ba(mix)}$

f) Boxplot of $P_{ba(mix)}$

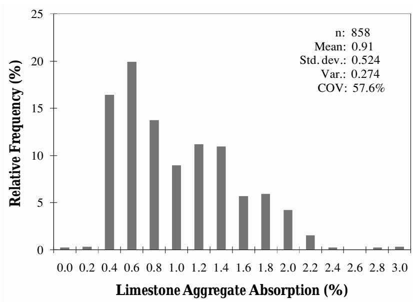
Figure 1. Summary Asphalt Content Results

Water Absorption of Aggregate Sources

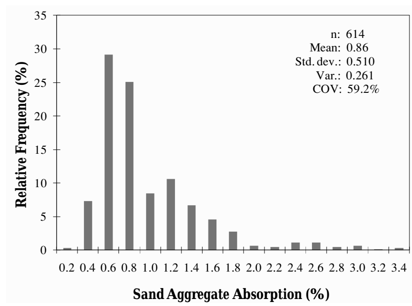
Aggregate stockpile data were sorted into limestone, sand, and gravel categories based on identifying information collected from the mix designs. Water absorption (Abs) relative frequency histograms for the three aggregate categories as well as the combined aggregate blends are provided in Figure 2.

The limestone histogram (Figure 2a) has a distribution with a mean of 0.91%, no clear peak value, and a slight right skew. A possible explanation is that

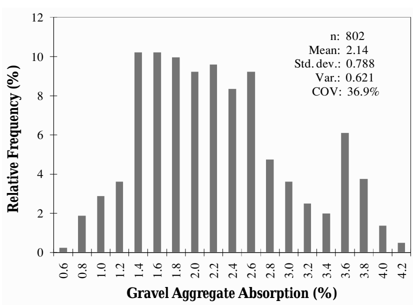
Mississippi has no substantial native sources of limestone, so essentially all limestone aggregate is imported from adjacent areas such as Kentucky and Alabama. The data could be a reflection of important quantities from different locations as they likely have different absorption properties. Overall, 80% of the limestone water absorption values fall in the range of about 0.35 to 1.75%.



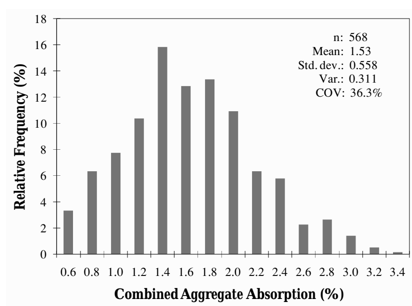
a) Limestone



b) Sand



c) Gravel



d) Combined Aggregate Blends

Figure 2. Summary Water Absorption Results

The sand distribution in Figure 2*b* has a peak that is near the mean value of 0.86% but is severely right skewed. The MDOT mix design data does not clearly define what constitutes sand, which could explain some of the skew. The aggregate identified as sand could be a naturally occurring aggregate (i.e., clean but un-crushed) or contain manufactured materials (i.e., crushed aggregate) that could have very different water absorption values. Overall, 80% of the sand water absorption values fall in the range from 0.40 to 1.55%, which is similar to limestone data.

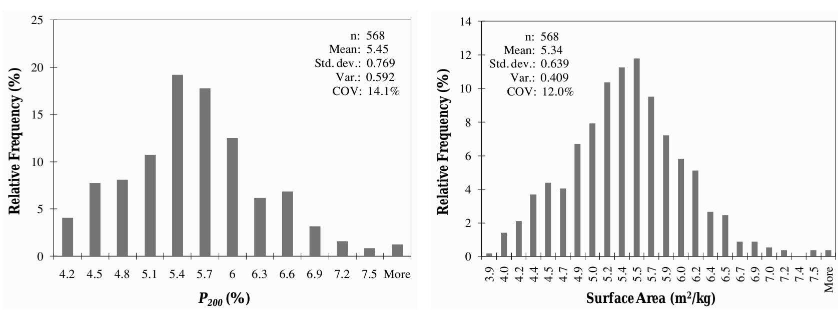
The crushed gravel histogram (Figure 2*c*) reveals a wide distribution with no clear peak. This is likely due to variations in geology between aggregate sources. There are three general geologic source types of gravel deposits in Mississippi, each with different mineralogical composition (Russell 1987). Gravel is located in alluvial beds and also in terrace deposits; it is generally composed of several types of siliceous chert and is frequently mixed with quartz sands (Russell 1987). Overall, 80% of the gravel water absorptions fall in a range of about 1.25 to 3.45%.

Figure 2*d* plots composite aggregate blend water absorption results. In contrast to the individual aggregate sources, the distribution is approximately normal with a peak near the mean value of 1.53%. Overall, 80% of the aggregate blend water absorption values fall in a range of about 0.80 to 2.25%.

Gradation of Aggregate Sources

Of the 568 mixture dataset; 228 gradations were 9.5 mm NMAS (40% of total), 167 were 12.5 mm NMAS (30% of total), and 173 were 19.0 mm NMAS (30% of total). Aggregate gradations are classified by AASHTO M 323 as either fine or coarse based on the percentage passing the primary control sieve (PCS). For 9.5 mm NMAS gradations, 208 of the 228 (91%) are classified as coarse-graded (less than 47% passing the 2.36 mm PCS). For 12.5 mm NMAS gradations, 97 of the 167 (58%) are classified as coarse-graded (less than 39% passing the 2.36 mm PCS). For 19.0 mm NMAS gradations, 53 of the 173 (31%) are classified as coarse-graded (less than 47% passing the 4.75 mm PCS).

Figure 3 plots percent fines and surface area (SA) for all aggregate blends. The percent fines (P_{200}) distribution appears generally normal in shape, with a mean of 5.45% but with a slightly higher proportion of values below the mean than above. The SA distribution appears normal in shape with a mean of 5.34 m^2/kg and a few extreme values to the far right of the distribution.



a) Gradation Passing 0.075 mm Sieve *b) Surface Area*

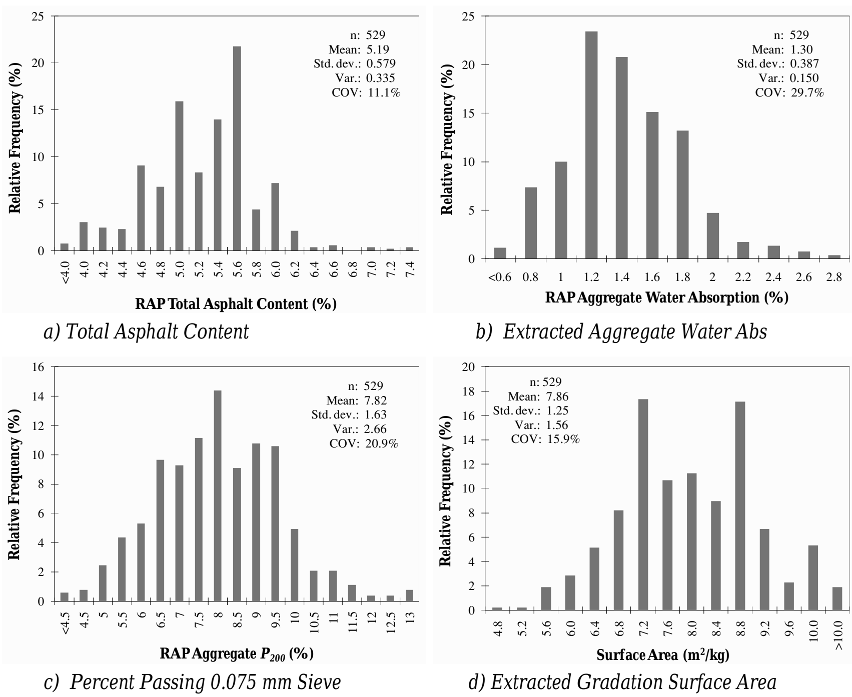
Figure 3. Summary Aggregate Blend Results

RAP Properties

Figure 4 plots RAP properties used in new mixtures. The total RAP asphalt content distribution (Figure 4*a*) is generally normal in shape but contains several values that are outside the central distribution. High values are likely due to testing error, since they are above the highest total asphalt content of 7.0%. Potential errors that would over estimate RAP asphalt content include aggregate degradation in an ignition test, loss of fine material, or incomplete recovery of mineral fines from extraction solvent. Low values may be due to testing error, from RAP sources with stripped aggregate, or from RAP mixed with base material during reclaiming.

The water absorption histogram (Figure 4*b*) is fairly normal aside from one abnormally low value that is likely testing error. The RAP fines histogram (Figure 4*c*) is also fairly normal and has a wide distribution with a range of 3 to 13% and a relatively high standard deviation. The extracted RAP aggregate surface area distribution (Figure 4*d*) has a mean value of 7.86 m^2/kg and two peaks on either side of the mean value. In a few cases, surface area exceeded 10.0 m^2/kg, and these cases were those in Figure 4*c* with a high fines (i.e., passing 0.075 mm sieve) content.

Since RAP was formerly new asphalt, it is interesting to compare the distributions of RAP and current MDOT mixes. Table 1 presents the results of unequal variance *t*-test comparisons between RAP and current mixture properties. The mean RAP total asphalt content is significantly lower than the mean total asphalt content for new MDOT mixtures; the difference is 0.21%. The standard deviations of the two distributions are nearly identical, which suggests that the distributions are quite similar except for their mean values. Possible reasons for the lower RAP asphalt contents include testing error resulting in lower total asphalt contents (e.g., incomplete extraction of RAP asphalt), loss of asphalt volatiles during service life, or actual loss of asphalt during the reclaiming process (e.g., during milling and handling). Another potential explanation for this result is that mixes were designed according to earlier versions of MDOT specifications (i.e., more design compaction) and resulted in generally lower asphalt contents than current specifications.



a) Total Asphalt Content

b) Extracted Aggregate Water Abs

c) Percent Passing 0.075 mm Sieve

d) Extracted Gradation Surface Area

Figure 4. Summary RAP Results

Mean water absorption of extracted RAP aggregate is significantly lower than the mean combined aggregate blend water absorption values of current MDOT mixes; the difference is 0.24%. Lower aggregate absorption values for RAP imply that values of RAP aggregate G_{sb} values are also lower. The mean percent passing the 0.075 mm sieve (i.e., fines) for RAP aggregate is significantly higher than for current MDOT mixtures; the difference is about 2.4%. Also mean SA of RAP aggregate is significantly higher than for current mixes; the difference is about 2.5 m^2/kg. Increased fines are likely due to aggregate degradation (milling in particular).

Table 1. Unequal Variance *t*-test Comparison of RAP to Mixture Properties

Category	Material	*n*	Mean	Std. Dev.	*t*-stat	*t*-crit	Significantly Different?
Asphalt Content	RAP	529	5.19	0.580	5.82	±1.96	Yes
	Mixtures	568	5.40	0.579			
Abs	RAP	529	1.30	0.387	-8.19	±1.96	Yes
	Mixtures	568	1.54	0.558			
P_{200}	RAP	529	7.82	1.632	30.49	±1.96	Yes
	Mixtures	568	5.45	0.769			
SA	RAP	529	7.86	1.248	41.64	±1.96	Yes
	Mixtures	568	5.34	0.639			

Note: Significance testing performed at the 95% confidence level.

PLANT MIXED APPLICATIONS

RAP Characterization

A particularly useful application for the MDOT historical record was as part of a prediction method for RAP absorbed, inert and effective bituminous components. Historical property distributions from the dataset of mix designs analyzed in the previous section were a key component in development of the prediction method. The analysis was presented in Doyle et al. (2012) and is only summarized herein.

A key component of Doyle et al. (2012) was the assumption that the raw materials (i.e., binder and aggregates) used for asphalt placed within the last five years represent the raw materials being in RAP being used in the present day. For example, an asphalt pavement placed fifteen years ago that is milled for RAP has the same aggregates and asphalt absorption of a mix that was placed within the past five years and is in the MDOT dataset. This was a reasonable assumption for Mississippi materials within the jurisdiction of MDOT based on the data in this paper, although fines content of RAP materials is higher than for new mixture as seen in Table 1.

A regression equation was developed from the mixture property data set to predict aggregate bulk specific gravity (G_{sb}) from effective specific gravity (G_{se}) of RAP coated with virgin binder. Predicted G_{sb} and RAP total asphalt content were then used to estimate RAP absorbed asphalt content. The regression was shown to provide better estimates of RAP absorbed asphalt than conventional methods.

In addition, parameters defining normal distributions of effective asphalt content were developed from the MDOT mixture properties dataset for each category of NMAS and design compactive effort. For desired mixture properties, confidence interval estimates for effective asphalt content were used within a statistical approach to estimate ranges of effective and inert RAP asphalt. The approach indicated that RAP effective asphalt content was sensitive to temperature.

Education and Reasonableness Checks

The mixture property distributions and the Visual Basic program described previously allow MDOT to quickly obtain typical values for any mixture parameter. This could prove to be a useful tool for identifying mix properties that are outside typical ranges during the mixture approval process; i.e. a reasonableness check. For example, if a 12.5 mm mix design was submitted that required 7.5% total asphalt content, it would immediately be recognized as unusual and could be investigated.

Another reasonableness check for MDOT is to assess typical values. For example, Newcomb et al. (2007) recommended using an assumed value for RAP asphalt absorption of 1.5% when using a back-calculation procedure to estimate RAP properties and no known properties are available. It is evident from the absorbed asphalt distribution that that the recommended assumed value is questionable for MDOT. Such a high value for absorbed asphalt was only approached a few times over a time span exceeding five years even for relatively high absorption aggregates (Abs in combined gradation as high as 3% or more in several cases).

Properties of the dataset could be used as an educational tool in technician training or classroom education of civil engineering students (this has occurred in two classes at Mississippi State University) as a first exposure to typical values encountered in asphalt mix design (e.g., asphalt content, absorption). If desired, total asphalt content distributions could be used to estimate initial trial asphalt contents for mix design. Availability of mixture properties could be useful to asphalt producers, as they could see how their asphalt mixtures compare to trends in their region.

IN-PLACE RECYCLING APPLICATIONS

Asphalt mixture property distributions could potentially be used to better inform agency wide planning efforts over the medium and long term; for example, estimation of the long term costs associated with an agency wide adoption of full depth reclamation (FDR) as a rehabilitation strategy. A few representative FDR candidate materials could be selected based on the historical record, mixes be designed from the materials and used to develop a general idea of material costs (e.g., estimate typical cement or emulsion contents needed for FDR).

Another example is evaluating merits of hot-in-place recycling (HIPR) and cold-in-place recycling (CIPR) as a function of virgin asphalt binder prices. Howard and Doyle (2010) documented asphalt binder prices over many years, and when virgin binder prices spiked a few years ago, the relative economics of HIPR and CIPR could change. They would be at least somewhat affected by the total asphalt content of pavements within the charge of the responsible agency.

Another application for in-place recycling is aiding in determination of a suitable reference density for design and quality control purposes. Note that MDOT is currently sponsoring an in-place recycling project for high traffic applications where these issues are being investigated. A regression equation to predict maximum mixture specific gravity (G_{mm}) within a region using parameters such as aggregate percentages (e.g. limestone versus gravel and sand) and total asphalt content could be useful. Doyle and Howard (2010) present a sorting procedure that can provide a very reasonable total limestone content of a RAP sample.

SUMMARY AND CONCLUSIONS

The ability to capture volumetric and component material properties of asphalt mixtures produced within an agency domain has proven to be a useful tool. The effort and cost to collect and analyze the data is minimal, especially when all the potential benefits are considered. Specific benefits could vary, but the approach herein could easily be used by other agencies if they maintain accessible records of asphalt mix designs.

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Cool and Long Lasting Pavements with Geosynthetic Reinforced Chip Seals

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ABSTRACT

Pavements absorb a large amount of solar radiation. High pavement temperatures in warm climates cause problems such as rutting and accelerated aging of the mix, the urban heat island effect, and deterioration of air quality. This paper discusses, with models and experimental results, the concept of using an insulation layer, such as a geotextile, and aggregates with higher reflectivity in chip seals, to reduce the conduction of heat through an asphalt pavement and increase the reflectivity of the surface, respectively. Reductions of temperature in the range of 8-10 °C were noted at the surface and 75 mm below the surface with the use of a 2.4 mm thick Petromat geotextile with chip seal. The study showed that a significant improvement in temperature reduction can be achieved with the use of a thicker insulation layer and/or an insulation of lower conductivity.

INTRODUCTION

High quality roads are critical for the smooth functioning of our society, as they constitute the primary mode of transportation of people and freight. The performance of roads or pavements (including those used at airports) is primarily affected by two factors: loading and environmental effects, such as temperature fluctuations and the presence of moisture due to rain or snow. A pavement is designed and constructed such that the effects of the environment can be mitigated, therefore the cost of a pavement generally increases with an increase in the range of temperature fluctuation. In this context, the increased cost generally coincides with an increased environmental impact in the form of energy consumed and gases emitted during the construction of the pavement [Sakulich, 2011]. Furthermore, the ability of the pavement to resist the effects of the environment is not always guaranteed because of the enormous variability in predicting factors, the stochastic nature of the design process, and the unavoidable variations in material properties and construction quality.

In a conventional asphalt pavement, higher ambient temperatures generally increase the likelihood of rutting in the hot mix asphalt (HMA) layer [Van de Loo, 1978, Brown and Cross, 1992, Monismith et al, 1994]. Repairing pavements consumes a significant amount of time (resulting in wasted time and fuel as vehicles move inefficiently) and energy (most of which comes from non-renewable resources). If the service life of a pavement can be extended, avoiding such repairs (or at least making them less frequent), then a significant amount of energy, driver time, and fuel could be saved while reducing CO_2 emissions. That is, extending the life of the pavement is a step towards achieving true sustainability. Reducing high temperatures in the pavement will therefore extend service life.

In this study, the use of an insulating layer near the surface of the pavement and a highly reflective layer at the surface has been investigated. Examples of available insulation materials are polypropylene (commonly used in geotextiles; K= 0.2 W/mK) and polystyrene (K= 0.03 W/mK) (The Engineering Toolbox, 2013). Other materials that are being researched include nano-insulation materials (K= 0.002 W/mK, Jelle et al, 2010). Work with insulation layers in the asphalt mix layer part of asphalt pavements has not been conducted. However, researchers have investigated the use of thermal insulation to prevent frost damage in soils (for example, Kestler and Berg, 1992, Wen et al, 2007, Humphrey and Blumenthal, 2010, and Field et al, 2011,) and the use of asphalt mix layer as insulation over concrete pavements (Khazanovich et al, 2012).

OBJECTIVE

The objective of this paper is to present the results of a theoretical simulation and experimental validation of the concept of the reduction of pavement temperature.

SCOPE

The scope of work consists of modeling the effects of temperature (due to ambient air temperature, solar radiation, etc.) on a full depth asphalt pavement with and without insulation, and determining the effect of the variation in insulation type and insulation layer thickness.

MODELING AND SIMULATION

Houston, TX, was selected as a case study of a locale with high average temperatures. The hourly air temperature for the most recent year for which data is available (2007) was extracted from NOAA (NOAA 2012) database and the highest temperature was determined. Next, data were analyzed to determine the last time at which the temperature was recorded as 25 °C – data starting from this point to the end of the day at which the maximum temperature occurred were then extracted for further analysis. Solar radiation data (the total amount of statistically modeled average direct and diffuse solar radiation received on a horizontal surface during the 60-minute period ending at the timestamp) were obtained for the latest year available (2005) from the National Solar Radiation Database from the National Renewable Energy Laboratory (NREL) site (NREL, 2012). Radiation data relevant to the period in question were extracted. Radiation and temperature data were used for the modeling and simulation of the pavement in the next step.

One rectangular layer (sub-domain) was created for the control HMA only model (Table 1). The HMA layer contains 462 triangular mesh elements and 979 degrees of freedom. Three rectangular layers (sub-domains) were created for the HMA with insulation model with the relevant thermal properties (Table 1). The insulation layer was inserted and placed between two HMA layers. The entire geometry contains 1,047 triangular mesh elements and 2,174 degrees of freedom.

Table 1. Thermal properties (Chen *et al.* 2008)

	Thermal conductivity k, W/m^2	Heat Capacity C, J/kg	Density ρ, kg/m^3
HMA	1.2	1200	2350
Insulation #1	0.17	904	1963.5
Insulation #2	0.02	904	1963.5
Insulation #3	0.002	904	1963.5

Evaluation of the effect of temperature

First, a full-depth asphalt pavement was modeled using the finite element modeling (FEM) technique (using COMSOL Multiphysics 'general' and 'heat transfer' modules, COMSOL, 2012). All sides except the top were considered to be insulated. The air temperature was used in the model as a time-dependent parameter. A model was next created for a pavement with insulation, and identical FEM analysis and simulation were conducted. The model consisted of a 6 mm layer of HMA over one of three different insulation layers, ranging in thickness from 2.4 mm (typical thickness of a geosynthetic layer) to 24 mm, atop a standard HMA pavement. The three insulation materials examined had thermal conductivities of 0.17 W/mK (polypropylene), 0.02 W/mK (polystyrene) or 0.002 W/mK (nano insulation materials, NIM, Jelle et al, 2010). A surface layer of relatively high reflectivity (50%) was used in this step along with the environmental data from Houston. Both solar radiation and high temperature were utilized for simulation, which was conducted for a total time period of 161 hours (approximately 7 days). Temperatures vary at different depths of the pavements (Fig. 1), whereas the maximum temperatures (Fig. 2) do not occur at the same time at the different depths.

Observations

The simulation shows the presence of insulation to be effective in lowering the temperature at the lower layers to different extents. The 2.4 mm thick insulation layer of K= 0.17 W/mK is marginally effective; however, the change in thickness from 2.4 mm to 24 mm seems to have a significant effect on the reduction in temperature. The insulation layers with K= 0.02 or 0.002 W/mK reduce the temperatures significantly, at the cost of also significantly increasing the surface temperature. The best result seems to be from the 2.4 mm thick insulation layer with K= 0.17 W/mK and a highly reflectivity surface – temperatures at all layers including the surface are reduced significantly, obviously due to the effect of the high reflectivity, and hence low absorption of heat.

The presence of a high reflectivity surface by itself is highly effective in reducing the temperature of all layers (Fig. 3). Such a highly reflective surface could be achieved with the use of a thin or ultra-thin layer of fresh portland cement concrete, for example.

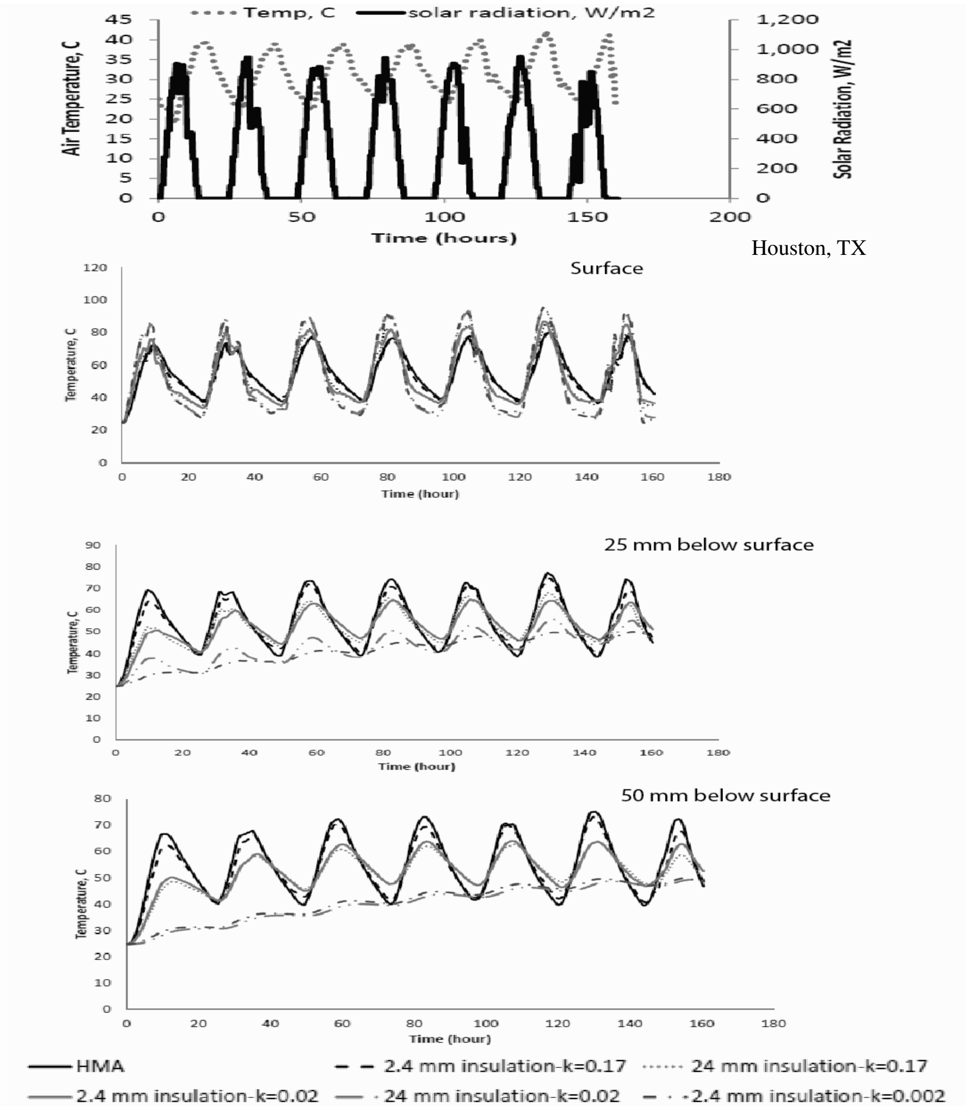


Figure 1. Air temperature and solar radiation, and results of simulation for Houston

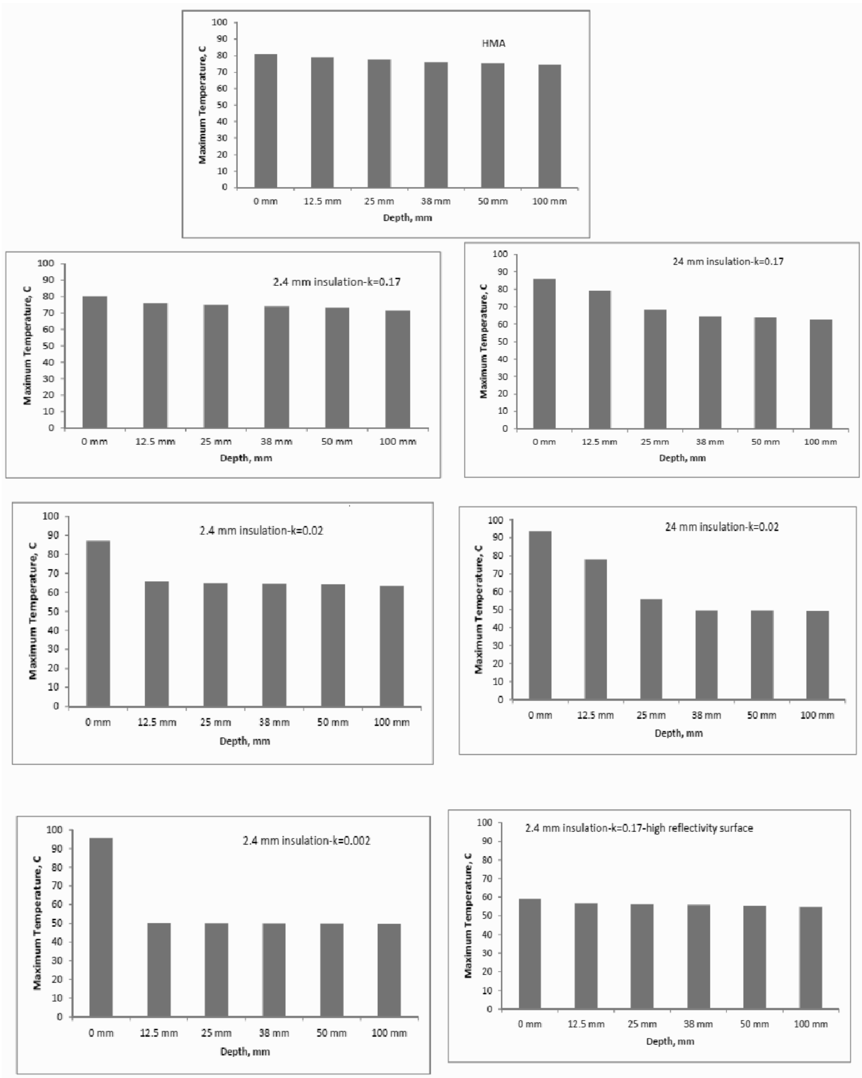


Figure 2. Predicted maximum temperatures at different depths for different cases

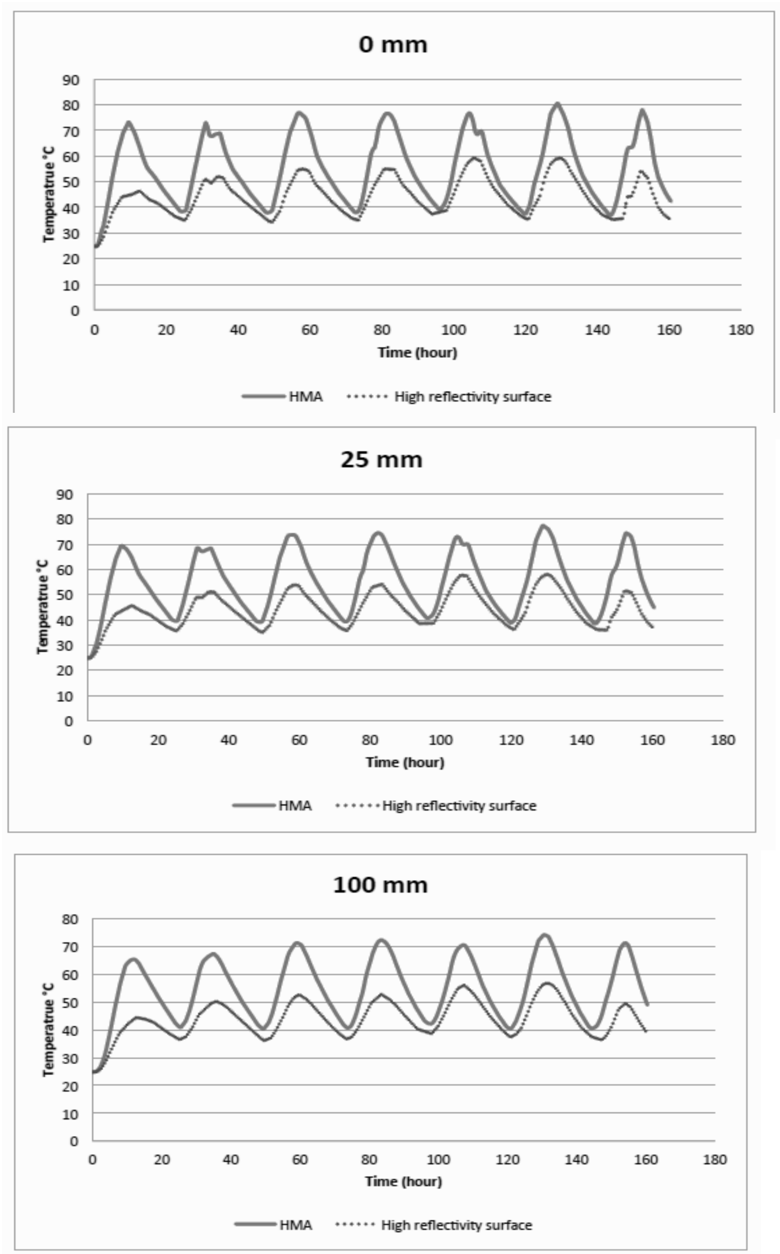


Figure 3. Effect of high reflectivity surface on the temperature

Discussion

The use of an insulation layer can be effective in reducing temperature extremes in asphalt pavements, and hence extending service life by reducing the impact of the environment. The use of a highly reflective surface is also feasible; however, such layers could lose the reflectivity over time, and may not be cost effective. Some issues with the durability of ultrathin portland cement concrete (PCC) layers have also been noted in the literature. Furthermore, the presence of an insulation layer (such as in the form of a geosynthetic layer) could contribute as a protective membrane against moisture ingress. Table 2 shows the reduction in maximum temperature that can be achieved with different insulations. While a very low thermal conductivity could be achieved only through the use of specialized products such as the nanoinsulation materials, it is quite possible to use existing polypropylene geosynthetic layers to achieve a significant reduction in maximum temperature (such as 9 °C for a thickness of 24 mm).

To determine the effect of this reduction of temperature fluctuations on service life, MEPDG/MEPDS (MEPDG, 2007) software can be used to predict rutting damage in conventional and insulated pavement systems. To do this, the weather database in the MEPDS was utilized. For this example, four cities were selected to consider a range of maximum pavement temperatures, from 70 ^{o}C to 52 ^{o}C. These are, in decreasing average temperatures: Houston, TX; Raleigh-Durham, NC; Chicago, IL; and Portland, ME. A pavement located in Houston was simulated, using the climatic information for the above four cities, to determine the rutting damage over the years, and the years to failure, for the range of temperatures from 70 ^{o}C to 52 ^{o}C. It can be seen (Fig. 4) that for the same traffic loading and the same materials, the life of the pavement can be extended by 5 years for a 5 ^{o}C drop in maximum temperature. The drop in temperature is more effective in extending the life of the pavement at higher temperatures. It is evident from the data presented earlier that such extension in service lives is quite feasible with the use of insulation layers with K= 0.17 W/mK (for example, polypropylene/geosynthetic layers).

The surface layer that is above the insulation layer will experience a higher temperature for warmer climates and lower temperature for cooler climates. It will therefore need to be of such a nature that its load bearing capabilities remain relatively unaffected by changes in temperature. For example, a thin polymer modified binder layer (6 - 12 mm thick) or a polymer modified chip seal would be ideal for warmer climates. Such thin layers are not likely to fail by rutting.

Similarly, highly modified polymer binder layers can also be utilized for the surface layer in the case of cooler climates; the presence of layers such as geosynthetics underneath the surface layer will most likely be more forgiving of thermal cracking potential than a conventional base layer. The use of a high reflectivity surface is also another option, provided that it is durable, can retain the reflectivity for sufficient length of time, does not cause visual distress to drivers, and is cost effective. Therefore, the most desirable cross section of a pavement is one with insulation and a moisture-resistant layer near the top, with a highly durable surface (and preferably one with high to moderate reflectivity, such as a chip seal or an ultrathin PCC layer, Fig. 5). Also, at this time, with the existing insulation materials that are currently available, it seems that this application is more appropriate for hot than for cold climatic conditions.

Table 2. Reduction in maximum temperature (at a depth of 25 mm)

Case	Maximum temperature, °C	Reduction in temperature, °C
HMA	77.5	---
HMA + 2.4 mm K= 0.17 W/mK	74.8	2.7
HMA + 24 mm K= 0.17 W/mK	68.1	9.4
HMA + 24 mm K= 0.02 W/mK	55.8	21.7
HMA + 24 mm K= 0.002 W/mK	34.5	43.0

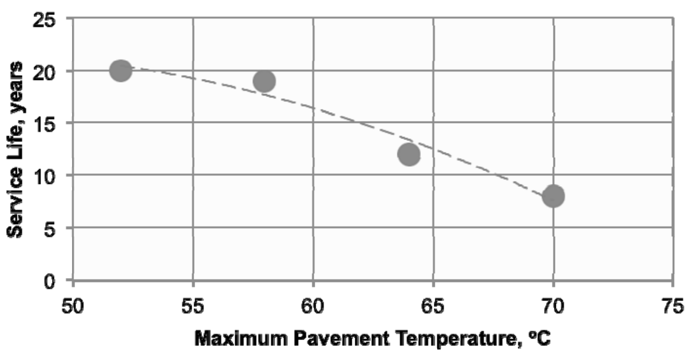


Figure 4. Service life versus maximum pavement temperature

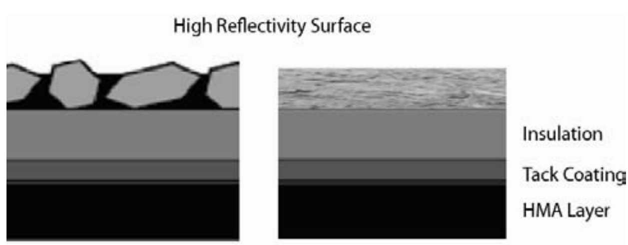


Figure 5. Desirable combination of high reflectivity surface and insulation near the surface

VALIDATION OF THE CONCEPT WITH LABORATORY EXPERIMENTS

Experiments were carried out with samples of HMA with and without geosynthetic reinforced chip seals with light colored aggregates (Fig. 6). The samples consisted of Massachusetts Highway Department 12.5 mm nominal maximum aggregate size (NMAS) gradation with 6% PG 64-28 asphalt binder. The conditions during the tests were as follows: Air temperature: 19.7 - 37.84 °C; Solar radiation: 41 - 887 kW/m^2, and wind speed: 0.2 - 12.7 km/h. The samples were subjected to solar radiation outdoors, and temperatures at different depths were collected over a time period of 12 hours during the daytime. From the results (Fig. 7) it is evident that the temperatures are significantly reduced at different depths. To separate the effects of the light colored aggregates in the chip seal and the geosynthetic layer, similar experiments were carried out with a geosynthetic layer with and without aggregates, as well as a control sample (air temperature: 24 - 29 °C, solar radiation: 74 - 1007 kW/m^2, wind speed: 2 - 9 km/h). It can be seen (Fig. 8) that both the geosynthetic layer and the light colored aggregates are separately contributing towards the reduction in temperature. Furthermore, experiments with one (2 mm) and three (6 mm) geosynthetic layers also show the positive effect of increasing the layer thickness (Fig. 8; air temperature: 23 - 28 °C, solar radiation: 166 - 930 W/m^2, wind speed: 3 - 12.5 km/h).

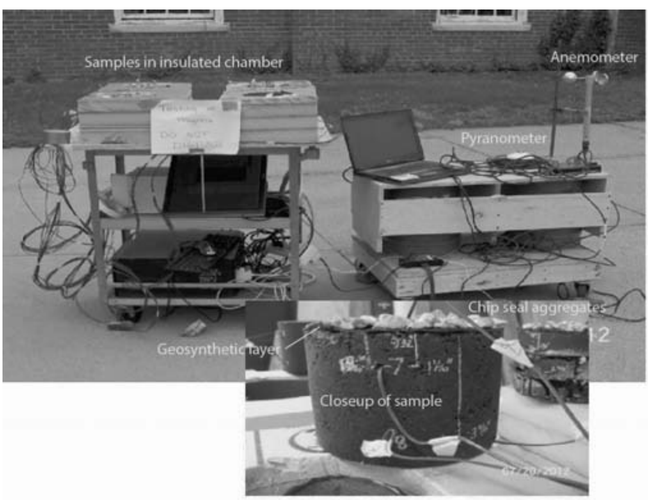


Figure 6. Close-up of HMA sample with geosynthetic layer and chip seal aggregates, and test set-up

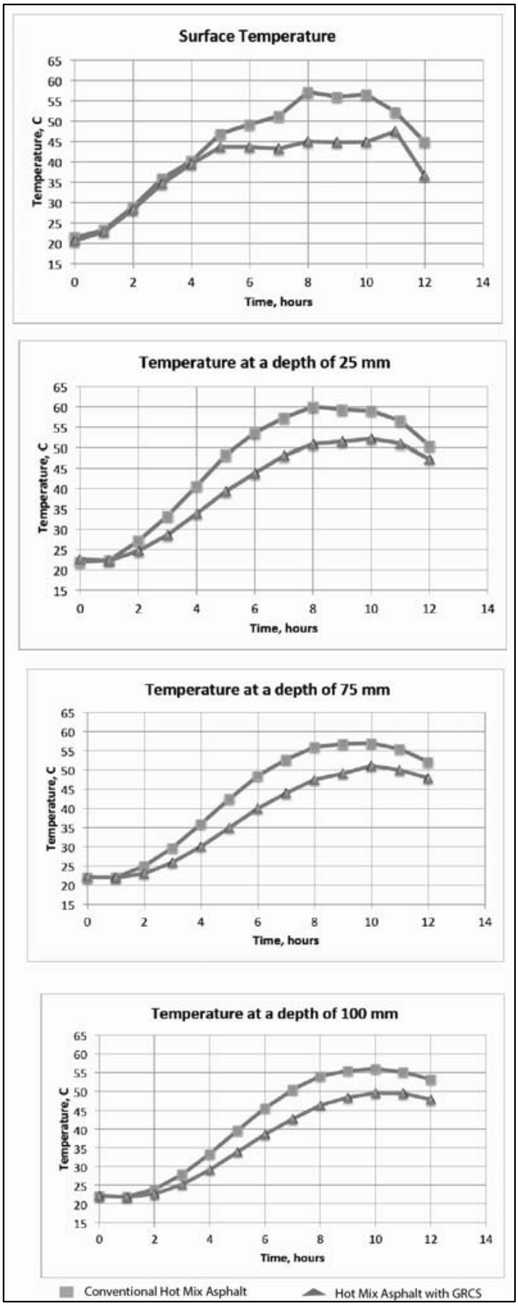
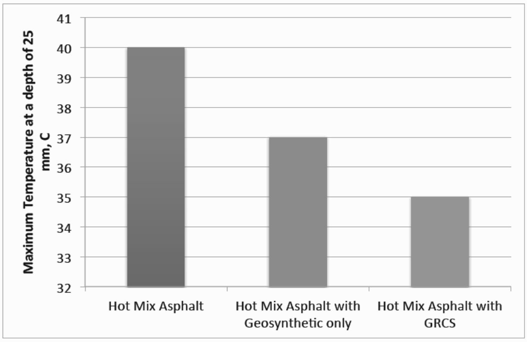


Figure 7. Plot of temperature versus time data from experiment



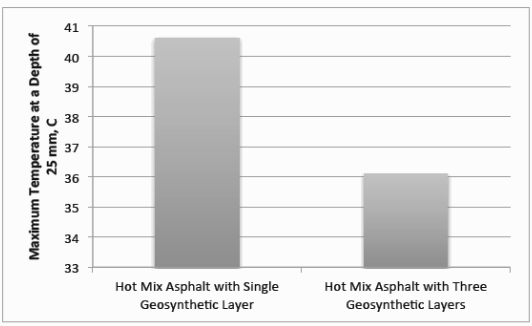


Figure 8. Results of experiments showing effect of chip seal and geosynthetic layer and thickness of geosynthetic layers

PRACTICAL APPLICATION AND POTENTIAL APPLICABILITY

The concept of geosynthetic reinforced chip seal (GRCS) is not new, but its application for reducing pavement temperature is new. GRCS is used in many areas (for example, Myers, 2012), as a pavement preservation treatment. However, the temperature reduction potential opens up a new application of this treatment, and should be researched further.

One important point that should be noted is that asphalt binder itself is as good an insulator as polypropylene (almost similar K); however, in general its insulating effect is not pronounced since it is present in only about 10% (by volume) in commonly used HMA. The use of geosynthetic layer provides a way of absorbing and retaining a good amount of asphalt binder, which can effectively lower the thermal conductivity. Hence, it is the combined action of the geosynthetic and the asphalt binder (with which it is saturated) that provides the insulation effect.

The applicability of GRCS needs to be investigated with different types of binder for chip seal. While chip seals with commonly used asphalt binders can be sufficient for low or medium traffic volume rural roads or those with slow traffic, the use of polymer modified binder to resist raveling in high-speed roads or at urban intersections (or turning areas) could be necessary.

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Binder and Mixture Testing to Assess Rutting Performance of Warm Mix Asphalt (WMA)

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ABSTRACT

Warm mix asphalt (WMA) technology is steadily gaining popularity due to the environmental, energy, and cost savings it offers as a sustainable alternative to conventional hot mix asphalt (HMA). However, adoption of WMA for commercial and military airfield pavements has been slow due to lack of documented good performance on airfields and concerns about potential rutting problems. This paper presents testing results for 11 WMA technologies, compared to traditional HMA. One unmodified base binder and one aggregate gradation were utilized throughout. Both laboratory full-scale plant-produced materials are tested. Binder performance grade (PG) data and Asphalt Pavement Analyzer (APA) mixture rutting data are presented. Relationships between laboratory and plant produced binder data and APA rutting are explored. The overall conclusion is that WMA is a viable alternative to HMA to improve the sustainability of airfield pavements.

INTRODUCTION

Warm mix asphalt (WMA) has been defined by Bonaquist (2011) as asphalt mixture that is produced at temperatures at least 28°C (50°F) cooler than conventional hot mix asphalt (HMA). WMA technology offers numerous environmental, energy, and cost savings over traditional hot mix asphalt (HMA) for asphalt pavements (Prowell and Hurley, 2007). As a result, WMA is increasingly being used to improve the sustainability of asphalt concrete for highway pavement applications (NAPA, 2009). However, use of WMA for commercial and military airfield applications has been limited (Su et al., 2009; Rushing et al., 2013). The primary reason for this is the lack of documented design and performance data for airfield use and rutting performance concerns; the use of WMA for airfield paving applications will likely increase if these concerns can be alleviated. Therefore, the specific objectives of this paper are to: 1) investigate the effects of WMA additives and processes on binder properties in the laboratory and the asphalt plant; and 2) evaluate the relationship of binder data to rutting performance test results.

There are at least 30 WMA technologies available as of 2012 (Mejías et al., 2012); however, they can all be classified into one of three general categories: chemical additives, organic additives (e.g., wax), and asphalt foaming additives/processes. For this paper, 11 WMA technologies for testing were selected from each general category and included 6 chemical additives, 3 organic additives, 1 asphalt foaming process, and 1 foaming additive.

EXPERIMENTAL PROGRAM

A two component experimental program was developed as part of a larger research effort to accomplish the objectives of this paper. The first component involved laboratory testing of binder properties and rut testing performed as part of the mix design process. The second component involved full-scale plant production of a subset of the laboratory mixtures. Plant produced material was sampled and used for binder and rut testing; rut testing was performed on both laboratory-compacted and field-compacted mixture.

Asphalt binder performance grade (PG) testing was conducted to assess the effects of different WMA technologies on the base binder. Mixture specimens were prepared at the design asphalt contents and tested in the Asphalt Pavement Analyzer (APA) to assess rutting potential using test conditions intended to simulate heavy airfield traffic. Three of the WMA technologies were then selected (one from each category) along with the HMA for production at an asphalt plant. Plant-produced material was sampled, and binder was extracted, recovered, and PG testing performed. APA testing was also performed on laboratory-compacted and field-compacted specimens of plant-produced material.

Materials Tested

A total of eleven warm mix technologies were evaluated in the laboratory testing component and compared to the HMA control. One unmodified base binder (PG 67-22) produced by Ergon Asphalt and Emulsions in Vicksburg, MS was utilized throughout. An unmodified base binder was selected to avoid any secondary interactions between the WMA additives and asphalt modifiers. The high PG temperature of this binder is uncommon, but is specified for use in several southeastern U. S. states, including Mississippi. This binder grade will also meet the requirements for a PG 64-22. Table 1 explains the nomenclature used in this study to identify each binder and provides details of the warm mix technologies evaluated and their respective dosage rates. Warm mix dosage rates were selected based on manufacturer's recommendations. When a range of dosage rates was recommended, the median dosage rate was selected.

For laboratory testing, all the warm mix additives were pre-blended with the base binder prior to use with the exception of the foam process (Binder 4) and the foaming additive (Binder 12). Each additive was mixed into the base binder with a high shear mixer for 10 minutes. For Binder 4, the laboratory asphalt foaming device described in Doyle et al. (2011) was used to produce foamed asphalt from the base binder; the binder temperature was set to 160°C (320°F) and the binder discharge temperature was set to 149°C (300°F). For the foam additive WMA mixture (Binder 12), the correct dosage of additive was weighed out for each material batch and added just before mixing.

For plant production, the base binder (Binder 1) was the standard binder used by the asphalt plant and was used directly from the plant's binder storage tank. Binder 2 was produced by introducing pellets of the wax product into the mixing drum through the fiber feed port located near the base binder injection point. For Binder 3, the additive was pre-blended with the base binder at the asphalt terminal and the binder was pumped directly from the transport truck into the asphalt plant's feed line. Foamed asphalt (Binder 4) was produced with a Gencor Industries, Inc. Ultrafoam GX2™ system that was bolted into the base binder feed line just ahead of the injection point.

Table 1. Warm Mix Additives Tested

Binder ID	Product Name	Manufacturer	WMA Category	Dosage Rate[a] (%)
1	PG 67-22 Base Binder	Ergon	---	---
2	Sasobit®	SasolWax	organic wax	1.5
3	Evotherm™ 3G	MeadWestvaco	chemical additive	0.5
4	Foam (water)	---	foam process	2.0
5	SonneWarmMix™	Sonneborn	organic wax	0.6
6	Asphaltan B	Romonta	organic wax	2.5
7	QualiTherm™	QPR®	chemical additive	0.2
8	Rediset WMX-8017A	AkzoNobel	chemical additive	1.5
9	Cecabase RT Bio 10	Ceca Arkema Group	chemical additive	0.4
10	Licomont BS 100	Clariant	chemical additive	3.0
11	Bitutech PER	Engineered Additives	chemical additive	0.6
12	Advera®	PQ Corporation	foam additive	0.25[b]

a) Dosage rate by percentage of binder weight unless otherwise specified.
b) Dosage rate by percentage of mixture weight.

For mixture testing, a single aggregate blend was used for both the laboratory and plant production components (Figure 1). During plant production, there were some slight deviations from the Job Mix Formula (JMF) blend used for mix design testing, but deviations were within acceptable limits for plant production. Asphalt mixtures were designed to meet the specifications of UFGS 32-12-15 for asphalt used on airfields. The design compactive effort was 75 gyrations in the Superpave gyratory compactor (SGC) and the design asphalt content was selected to produce 4% air voids (V_a). A two hour short term oven aging period was used during mix design. Theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) of the mixtures were determined according to AASHTO T 209 and AASHTO T 331 (vacuum sealing), respectively. Laboratory mixing and compaction temperatures for the HMA were based on data provided by the supplier and were 160°C (320°F) and 146°C (295°F). For the WMA, both mixing and compaction temperatures were dropped by 30°C (55°F). Table 2 summarizes the designed volumetric properties of mixtures made with Binders 1 to 12 in the laboratory and provides results of testing the plant produced mixtures made with Binders 1 to 4. Actual plant production temperatures varied but were approximately 143°C (290°F) for the HMA and 121°C (250°F) for the WMA mixes, respectively. Additional plant production details are provided in Rushing et al. (2013).

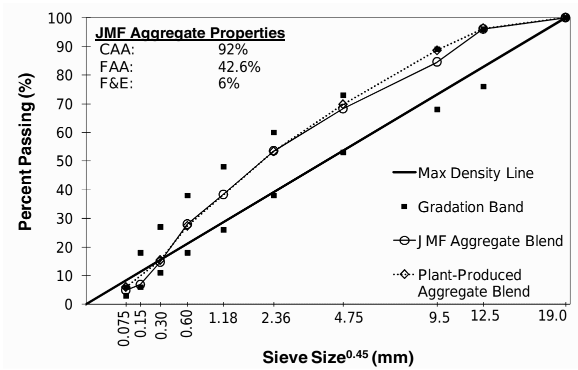


Figure 1. Aggregate Properties

Table 2. Mixture Volumetric Properties

Binder ID	P_b	P_{be}	V_a	VMA	VFA	D/B
1	5.3	4.48	4.0	14.3	72.0	1.04
2	5.2	4.40	3.9	14.0	72.2	1.06
3	5.2	4.40	3.9	14.0	72.1	1.06
4	5.1[a]	4.29[b]	4.0	13.8[b]	71.1[b]	1.08[b]
5	5.2	4.48	4.0	14.2	71.9	1.04
6	5.2	4.45	4.0	14.2	71.8	1.04
7	5.1	4.45	3.8	14.0	72.9	1.05
8	5.2	4.46	3.8	14.1	73.0	1.04
9	5.2	4.46	3.7	13.9	73.4	1.04
10	5.2	4.44	3.6	13.8	73.9	1.05
11	5.1	4.41	3.9	14.0	72.1	1.05
12	5.1[a]	4.47[b]	3.7	13.9[b]	73.4[b]	1.04[b]
1-QA[c]	5.3	4.58	2.3	12.9	82	1.16
2-QA[c]	4.9	4.33	3.1	13.1	76	1.21
3-QA[c]	4.9	4.27	2.0	12.0	83	1.61
4-QA[c]	4.8	4.11	4.7	14.1	67	1.50
Target	**---**	**---**	**4**	**min 14.0**	**65-78**	**0.8-1.2**

Note: An asphalt binder G_b = 1.03 was assumed and used for all volumetric calculations.

a) Total asphalt content was adjusted to account for the water added to the binder. Nominal asphalt contents for mixtures 4 and 12 with water included were both 5.2%.
b) Calculated using the adjusted total asphalt content.
c) Average results of researcher's Quality Assurance (QA) testing.

Test Methods

Properties of the base binder and all WMA binders with organic or chemical additives were tested to determine the continuous performance grade (PG) in accordance with AASHTO M 320. Asphalt binder from samples of plant produced mixture was trichloroethylene extracted according to AASHTO T 164 Method A.

Binder was then recovered by rotary evaporation according to AASHTO T 319. Recovered binder was then tested and graded according to M 320 except that the Rolling Thin Film Oven (RTFO) test (AASHTO T 240) was not conducted and the binder was graded based on post production properties only.

Asphalt Pavement Analyzer (APA) wheel track testing was performed to assess rutting performance of the laboratory and plant produced mixtures. Typical APA loading conditions are intended to approximate the truck traffic; so loading conditions were modified to better represent aircraft traffic. Specifically, the APA testing used a tube or hose pressure of 1724 kPa (250 psi) and a wheel load of 1113 N (250 lb) as recommended by Rushing et al. (2012) for aircraft conditions. The test temperature was 64°C (147°F) as ordinarily used for the base binder grade. For the laboratory mix design testing component, test specimens were made by trimming the specimens compacted to N_{des} gyrations used to verify volumetric properties (i.e., target V_a = 4%) to 75-mm thickness. For the plant produced mixture component, two sets of specimens were laboratory-compacted to a 75-mm thickness with target air voids of 4% and 7%; the purpose of two air void levels was to bracket the anticipated air voids achieved by field compaction. A third set of specimens were cores taken from field-compacted material and trimmed to a 75-mm thickness.

RESULTS AND ANALYSIS

Binder Data

Table 3 provides binder test data at a consistent set of test temperatures and the continuous PGs of the binders. The original foamed binders (4 and 12) were not tested since asphalt foaming is a transient effect and the water does not remain in the binder. Foamed Binder 4 plant-produced material was tested. Figure 2 presents the continuous PG data for original Binders 1 to 12 with data grouped by WMA type.

On the low temperature side (Figure 2), the base binder 1 was graded at -23.9°C which slightly exceeds the specification of -22°C. Low PG temperatures for the WMA binders fall into two groups. The first group did not change much from the base binder and still meets the desired specification; this group includes one organic wax (binder 6) and three chemical additives (binders 3, 8, and 11). The second group changed markedly from the base binder with a temperature increase on the order of one full binder grade (i.e., 6°C increment). This group includes two organic waxes (binders 2 and 5) and three chemical additives (binders 7, 9, and 10). Overall, five of the nine WMA binders tested had a noticeable increase in low PG temperature which could be indicative of reduced low temperature performance. However it is important to note that the Rolling Thin Film Oven (RTFO) component of binder testing, which is intended to simulate the effect of HMA mixture production temperatures, was not modified to address the differences in temperature between HMA and WMA mixture production temperatures. Therefore it is not certain from these data alone if the final mixture low temperature performance would be detrimentally affected. Previous work has not indicated a significant reduction in low temperature mixture performance for WMAs made with the same modifiers as binders 2, 3 and 4 in this study (Doyle et al., 2011).

Table 3. Summary of Binder Test Data

	Original	RTFO Residue	PAV Residue			Continuous PG Temps	
Binder ID	$G^*/\sin\delta$ (kPa)[a]	$G^*/\sin\delta$ (kPa)[a]	$G^*\sin\delta$ (kPa)[b]	Stiffness (MPa)[c]	m-value (---)[c]	High (°C)	Low (°C)
1	0.766	1.68	4640	233	0.319	67.8	-23.9
2	1.51	2.62	5600	215	0.284	71.4	-18.3
3	0.811	1.63	4800	219	0.310	67.7	-22.9
4	Foam process WMA was not tested, data for the base binder was substituted as needed						
5	0.689	1.46	4930	202	0.292	66.9	-18.6
6	1.52	2.39	5800	256	0.321	70.7	-23.4
7	0.760	1.27	5080	200	0.281	64.9	-16.3
8	1.14	1.94	4830	207	0.343	69.0	-24.7
9	0.691	1.64	5050	212	0.280	67.0	-17.6
10	2.75	5.88[d]	5890	217	0.279	81.9	-18.1
11	0.667	1.48	4890	232	0.322	66.7	-24.2
12	Foam additive WMA was not tested, data for the base binder was substituted as needed						
1-RB[e]	---	2.24	3600	147	0.324	70.2	-25.1
2-RB	---	2.85	4230	184	0.288	71.9	-20.7
3-RB	---	1.51	3500	150	0.338	67.1	-26.3
4-RB	---	2.90	3820	149	0.317	72.2	-23.8

a) Tested at 70°C.
b) Tested at 25°C.
c) Tested at -12°C.
d) Extrapolated from test data.
e) RB is recovered binder from samples of plant-mixed material.

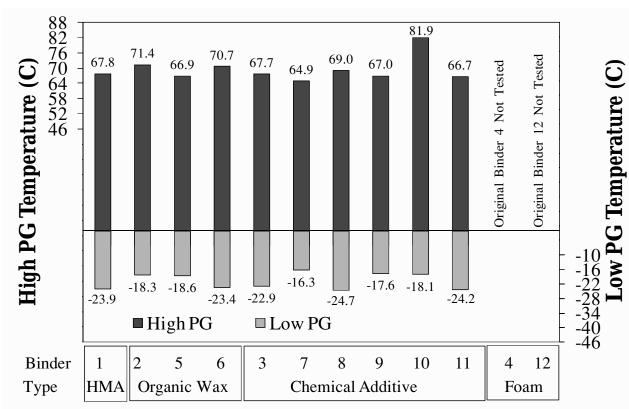


Figure 2. All Original Binder Continuous PG Data

On the high temperature side (Figure 2), the base binder 1 was graded at 67.8°C which slightly exceeds the specification of 67°C. All of the WMA binders except for binders 7 and 10 did not change appreciably from the base binder and generally still meet the desired specification. The high PG temperature for binder 7 dropped about 3°C from that of the base binder, but it would still meet requirements for a PG 64 binder, so a major reduction in rutting performance would not be expected. The high PG temperature for binder 10 increased dramatically compared to the base binder, over two full binder grades and it essentially grades as a PG 82, which would typically be a polymer-modified binder. No apparent problems with the test data were observed and project resource constraints prevented the binder from being re-tested to verify the results. Overall, the high PG binder data do not indicate that a big reduction in rutting performance should be anticipated with WMA; however the change in temperatures during mixture production previously discussed could affect final rutting performance.

Figure 3 compares the continuous PG data for Binders 1 to 4 as original binder and as recovered binder from plant produced mixture. When interpreting the recovered binder data, it must be kept in mind that the solvent extraction and recovery process likely changes the binder properties. On the low temperature side, the recovered Binders 1, 3, and 4 all grade similarly to each other and meet the requirement of -22°C. On the other hand, recovered Binder 2 does not quite meet the requirement. On the high temperature side, all recovered binders meet the 67°C requirement. Though Binder 3 is a few degrees lower than the others, major differences in rut performance of plant produced material between the HMA and WMAs would not be anticipated based on these data.

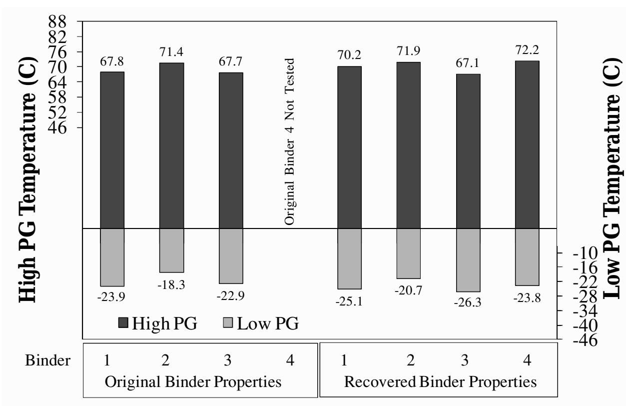
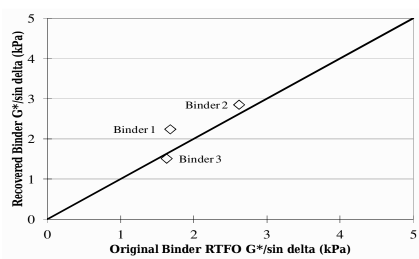


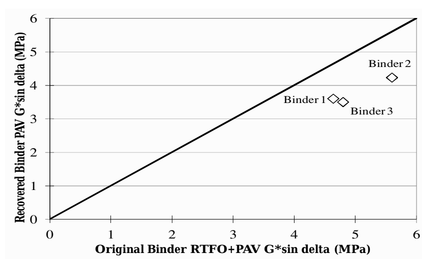
Figure 3. Original and Recovered Binder Continuous PG Data

Differences between original binder and recovered binder properties may be useful in estimating how the WMAs that were not plant produced (i.e., Binders 5 to 12) might have performed and consequently can improve the interpretation of laboratory performance test data for those mixtures. On the low temperature side (Figure 3), the original base binder graded at -23.9°C and the recovered HMA binder graded as -25.1°C, a not unreasonable difference of only 1.2°C. For the WMA Binders 2 and 3, the difference between original and recovered binders was 2.4°C and 0.9°C, respectively. So in general for low PG temperatures, the original binder testing was slightly to somewhat conservative relative to the recovered binder testing. On the high temperature side (Figure 3), the original base binder graded at 67.8°C and the recovered HMA binder graded at 70.2°C, an increase of 2.4°C. For the WMA Binders 2 and 3, the difference between original and recovered binders was practically negligible at 0.5°C and -0.6°C, respectively. So in general for low PG temperatures, the original binder testing was similar to or somewhat conservative relative to the recovered binder testing.

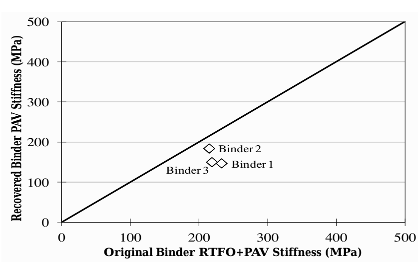
Figure 4 explores this topic further with equality plots of original binder and recovered binder test data at consistent test temperatures from Table 3. For the rutting parameter G*/sinδ (Figure 4*a*), the original binder RTFO residue for the WMAs provided a good estimate of the recovered binder values. Interestingly, values for the recovered HMA were slightly under-predicted by the RTFO residue. The RTFO procedure is intended to approximate the change in binder properties due to batch plant mixing at about 150°C (AASHTO, 2012). For the fatigue parameter G*sinδ (Figure 4*b*), the original binder RTFO residue over-predicted the recovered binder values. For the Bending Beam Rheometer (BBR) low temperature stiffness parameter (Figure 4*c*), the original binder RTFO+Pressure Aging Vessel (PAV) residue tended to over-predict the recovered binder values. For the BBR m-value parameter, the original binder RTFO+PAV residue provided a good estimate of the recovered binder properties. This is encouraging, since the m-value specification requirement controls the low PG temperature for most binders (Iliuta et al., 2004). These data suggest that the rutting parameter and controlling low temperature thermal cracking parameter of binder recovered from plant-produced material are reasonably approximated by tests of RTFO residue. However, this conclusion is limited since only materials produced with one base binder by one specific plant were tested.



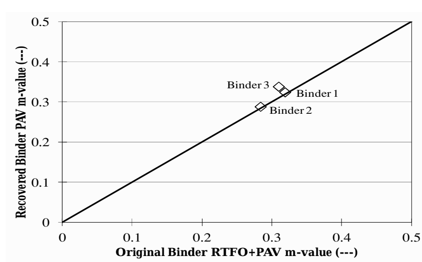
a) DSR G/sinδ tested at 70°C*



*b) DSR G*sinδ tested at 25°C*



c) BBR stiffness tested at -12°C

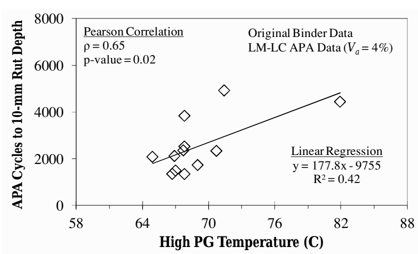


d) BBR m-value tested at -12°C

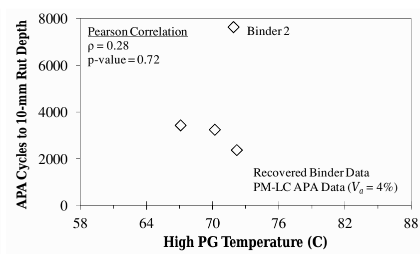
Figure 4. Original and Recovered Binder Raw Test Data Comparison

Relationship of Binder Data and APA Rutting Performance

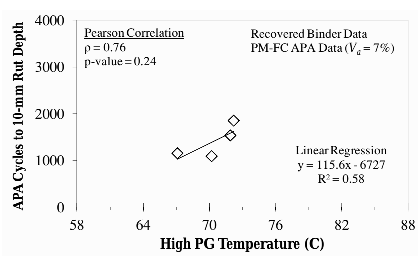
Figure 5 investigates the relationship of high PG temperature binder data to APA rutting performance. Data for the base binder was substituted for original binder testing of foamed asphalt Binders 4 and 12. There was a moderately strong, statistically significant, positive correlation between original binder data and laboratory mixed-laboratory compacted (LM-LC) APA rutting (Figure 5*a*). For recovered binder and plant mixed-laboratory compacted (PM-LC) APA rutting, the correlation strength was poor for specimens compacted to 4% voids (Figure 5*b*), but moderately strong for 7% voids specimens (Figure 5*c*). For recovered binder and plant mixed-field compacted (PM-FC) APA rutting, there was also a moderate correlation. On the whole, these data emphasize the importance of mixture performance testing in combination with binder testing to develop a complete picture of the performance of WMA.



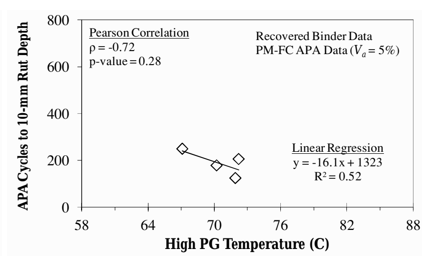
a) LM-LC APA data (4% voids)



b) PM-LC APA data (4% voids)



c) PM-LC APA data (7% voids)



d) PM-FC APA data (5% voids)

Figure 5. Relationship of Binder Data to APA Rutting Performance

SUMMARY AND CONCLUSIONS

The overall conclusion of this paper is that WMA is a viable alternative to HMA to improve the sustainability of airfield pavements. Summary observations are:

- Low PG temperature binder data for some of the WMA additives indicate that performance could potentially be reduced relative to the base binder, additional investigation of WMA mixtures is needed to confirm these results.

- High PG temperature binder data do not suggest that rutting performance will be detrimentally affected by use WMA additives.
- For this project, the rutting parameter (G*/sinδ) and controlling low temperature thermal cracking parameter (BBR m-value) of binder recovered from plant-produced material were reasonably approximated by tests on original binder RTFO residue.
- There was a moderate correlation of binder high PG temperature data to APA rutting performance for some of the data.

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Development of Performance-Based Specifications for Roadside Maintenance

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Abstract

Performance-based specifications (PBS) are emerging as an alternative to method specifications for roadway maintenance. Under PBS, the highway agency specifies measurable performance standards that the maintenance contractor is required to meet throughout the contract period. PBS for roadside maintenance are still evolving. This paper describes the development and field trials of PBS for roadside maintenance, including performance standards, a level of service (LOS) method for assessing compliance with these standards, and pay adjustment formulas. Twelve roadside asset types and maintenance activities are considered in these PBS, including safety elements (attenuators, guard rails and chain link fences), drainage elements (ditches and front slopes, culverts and cross-drain pipes and drain inlets), cleanliness elements (removal of litter, debris and graffiti), and vegetation (roadside grass, landscaped areas, trees and shrubs and vines). The developed PBS were tested on five highway corridors in Texas.

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Introduction

Performance-based specifications (PBS) are increasingly being used for roadway maintenance as an alternative to method specifications. Under PBS, the highway agency specifies measurable performance standards that the maintenance contractor is required to meet throughout the contract period. Performance standards are short descriptive statements of the desired physical condition of the roadway assets. Performance targets represent the desired overall level of service (LOS) of the roadway corridor or network being maintained. Typically, performance-based maintenance contracts extend over 3–10 years, divided into an initial term and subsequent renewals (Pakkala 2005).

PBS for roadside maintenance are still relatively new and are not addressed adequately in the literature. Specifically, there is a need for systematic processes for (a) defining performance requirements (i.e., what performance standards, timeliness, and targets should be used), (b) measuring performance (i.e., what condition assessment methods should be used for evaluating compliance with the performance requirements), and (c) developing optimum pay adjustment formulas that motivate the contractor to maintain the roadway assets at the target performance level specified by the highway agency. The objective of this paper is to address these issues by developing and testing PBS for roadside maintenance, including performance standards, a LOS method for assessing compliance with these standards, and pay adjustment formulas.

An overview of relevant literature is first presented and then the developed PBS are laid out. The results of testing the PBS on five highway corridors in Texas are discussed. Finally, the study findings are presented.

Literature Review

In PBS, public agencies act as the monitor and enforcer of the maintenance contract and apply certain performance assessment methods to ensure that the contractor meets the required performance. The performance of roadway assets and maintenance activities is measured through performance standards and targets. Stankevich et al. (2005) suggested that performance standards should be SMART (Specific, Measurable, Achievable, Realistic, and Timely to schedule). AASHTO published a guide that provides performance standards for highway assets and maintenance activities (AASHTO 2006). Individual departments of transportation (DOTs) have also developed their own maintenance performance standards. Examples of these DOTs includ Virginia DOT (VDOT), Texas DOT (TxDOT), Florida DOT (FDOT), North Carolina DOT (NCDOT), and the District of Columbia DOT (DCDOT) (Hyman 2009). Howard et al. (1997) suggested that in order for PBS to be effective, there must be a reliable and objective way for measuring compliance with the performance standards. Many highway agencies use the LOS concept for this purpose. Determining a LOS for roadway maintenance includes the inspection of randomly selected sample units (typically 0.1 or 0.2 mi long roadway sections). For each sample unit, each asset type (e.g., culverts, drain inlets, etc.) is inspected against the specified performance standards to assign a numerical score or a pass/fail rating. The LOS concept allows for the use of weights to represent the agency's priorities with respect to maintaining different types of roadway assets.

Hyman (2009) cited several methods for a DOT to encourage contractors to perform at the target LOS. These methods include the use of lump sum disincentive, a combination of incentives and disincentives, and A+B+C; where A is the bid price, B is the amount of time to complete the work, and C is a warranty cost.

Development of PBS for Roadside Maintenance

This section of the paper presents three key components of PBS that were developed for roadside assets and maintenance activities. These components are a) performance standards, b) a LOS method for assessing compliance with the performance standards, and c) site-specific pay adjustment formulas.

Performance Standards

An initial set of roadside performance standards was established based on a review of the literature and current practices in various DOTs. The feasibility of these performance standards for actual implementation was assessed through a referendum-style online survey of the 25 districts of the Texas Department of Transportation (TxDOT). Responses were received from 17 districts, representing a 68 percent response rate. Out of the 55 standards that were included in the survey, 42 standards were supported by a clear majority of the respondents (more than 70 percent of the respondents agreed with these standards). Eight standards were supported by 50–70 percent of the respondents. Only 2 standards were supported by less than 50 percent of the respondents (between 40 to 49 percent of the respondents agreed with these standards). The standards were revised based on feedback from the respondents and the field trials (discussed in subsequent sections of this paper). The final performance standards are shown in Figure 1. These performance standards are applicable to the following groups of roadside asset types and maintenance activities:

- Vegetation-related: Mowing and Roadside Grass; Landscaped Areas; Trees, Shrubs and Vines.
- Safety-related: Attenuators; Guard Rails; Chain Link Fence.
- Drainage-related: Ditches and Front Slopes; Culvert and Cross-Drain Pipes; Drain Inlets.
- Cleanness-related: Removal of Litter and Debris; Removal of Graffiti.

Inspector's Name: **Inspection Date:**

District: **Highway:** **Milepoint:** **Sample Unit No.:** **Urban/Rural:**

Roadside Element	No.	Performance Standard	Grade (Pass, Fail, NA)
Mowing and Roadside Grass	1	Any use of herbicide requires advance approval of the Engineer.	
	2	Paved areas (shoulders, medians, islands, slope, and edge of pavement) shall be free of grass	
	3	Unpaved areas (shoulders, slopes, and ditch lines) shall be free of bare or weedy areas	
	4	Roadside vegetation in the mowing area shall be at least 85% free of noxious weeds (undesired vegetation)	
	5	In rural areas, roadside grass height shall be maintained below 24 inches and shall not be cut to below 7 inches.	
	6	In urban areas, roadside grass height shall be maintained below 18 inches and shall not be cut to below 7 inches.	
Landscaped Areas	7	Any use of herbicide requires advance approval of the Engineer.	
	8	Landscaped areas shall be maintained to be 90 percent free of weeds and dead or dying plants.	
	9	Grass height in landscaped areas shall be maintained at a maximum height of 12 inches.	
Trees, shrubs and Vines	10	No trees or other vegetation shall obscure the message of a roadway sign.	
	11	No leaning trees presenting a hazard shall remain on the roadside.	
	12	Vertical clearance over sidewalks and bike paths shall be maintained at 10 feet or more.	
	13	Vertical clearance over roadways and shoulders shall be maintained at 18 feet or more.	
	14	Clear horizontal distance behind guardrail shall be at least 5 ft for trees	
	15	No dead trees shall remain on the roadside.	
Ditches and Front Slopes	16	Ditches and front slopes shall be maintained free of eroded areas, washouts, or sediment buildup that adversely affects water flow.	
	17	Erosion shall not endanger stability of the front slope, creating an unsafe recovery area.	
	18	Front slopes shall not have washouts or ruts greater than 3 inches deep and 2 feet wide.	
	19	No part of the ditch can have sediment or blockage covering more than 10% of the depth and width of the ditch	
	20	Concrete ditches shall not be separated at the joints, misaligned, or undermined.	
	21	Front slopes shall not have holes or mounds greater than 6 inches in depth or height.	
Culvert and Cross-Drain Pipes	22	A minimum of 75% of pipe cross sectional area shall be unobstructed and function as designed. There shall be no evidence of flooding if the pipe is obstructed to any degree	
	23	Grates shall be of correct type and size, unbroken, and in place.	
	24	Installations shall not allow pavement or shoulder failures or settlement from water infiltration.	
	25	Culverts and cross-drain pipes shall not be cracked, have joint failures, or show erosion.	
Drain Inlets	26	Grates shall be of correct size and unbroken. Manhole lids shall be properly fastened.	
	27	Installation shall not present a hazard from exposed steel or deformation.	
	28	Boxes shall show no erosion, settlement, or have sediment accumulation.	
	29	Outlets shall not be damaged and shall function properly.	
	30	Inlet opening areas shall be a minimum of 85% unobstructed.	
	31	Installations shall have no surface damage greater than 0.5 square feet.	
Chain Link Fence	32	Installations shall have no open gates.	
	33	Installations shall have no openings in the fence fabric greater than 1.0 square feet.	
	34	Installations shall have no openings in the fence fabric with a dimension greater than 1.0 feet.	
Guard Rails	35	Installations shall be free of missing posts, offset blocks, panels or connection hardware.	
	36	End sections shall not be damaged.	
	37	Rails shall not be penetrated.	
	38	Panels shall be lapped correctly.	
	39	No more than 10% of guard rail blocks in any continuous section shall be twisted.	
	40	No 25-foot continuous section shall be more than 3 inches above or 1 inch below the specified elevation.	
	41	No more than 10% of wooden posts or blocks in any continuous section shall be rotten or deteriorated.	
Cable Median Barrier	42	Installations shall be free of missing or damaged post, cable, or connections	
	43	Installations shall be free of missing or damaged end sections	
	44	Installations shall be free of loose cable or cable with incorrect weave	
Attenuators	45	Each device shall be maintained to function as designed.	
	46	Installations shall have no visually observable malfunctions (examples – split sand or water containers, compression dent of the device, misalignment, etc.)	
	47	Installations shall have no missing parts.	
Litter and Debris	48	1. No litter or debris that creates a hazard to motorists, bicyclists, or pedestrians is allowed.	
	49	2. No 0.1 mile roadway section shall have more than 50 pieces of fist-size or larger litter or debris on either side of the centerline of the highway.	
	50	Litter volume shall not exceed 3.0 cubic feet per 0.1 mile roadway section on both sides of the pavement.	
	51	In rural areas, traffic lanes shall be free of dead large animals.	
	52	In urban areas, traffic lanes and right of way shall be free of dead animals.	
Graffiti	53	No graffiti is allowed	
	54	Surfaces and coatings shall not be damaged by graffiti removal.	
	55	Surfaces from which graffiti has been removed shall be restored to an appearance similar to adjoining surfaces.	

Fig. 1. Roadside Performance Standards

LOS Method for Assessing Compliance with the Performance Standards

Figure 2 illustrates the developed LOS assessment method for roadside maintenance. The process begins by dividing the maintenance project into sections and then performing visual field inspections (using the developed performance standards) on a randomly-selected sample of these sections. The LOS of each sample unit is computed and then aggregated to determine the LOS for the entire project. Finally, pay adjustment is made based on the project LOS and the target LOS specified in the contract.

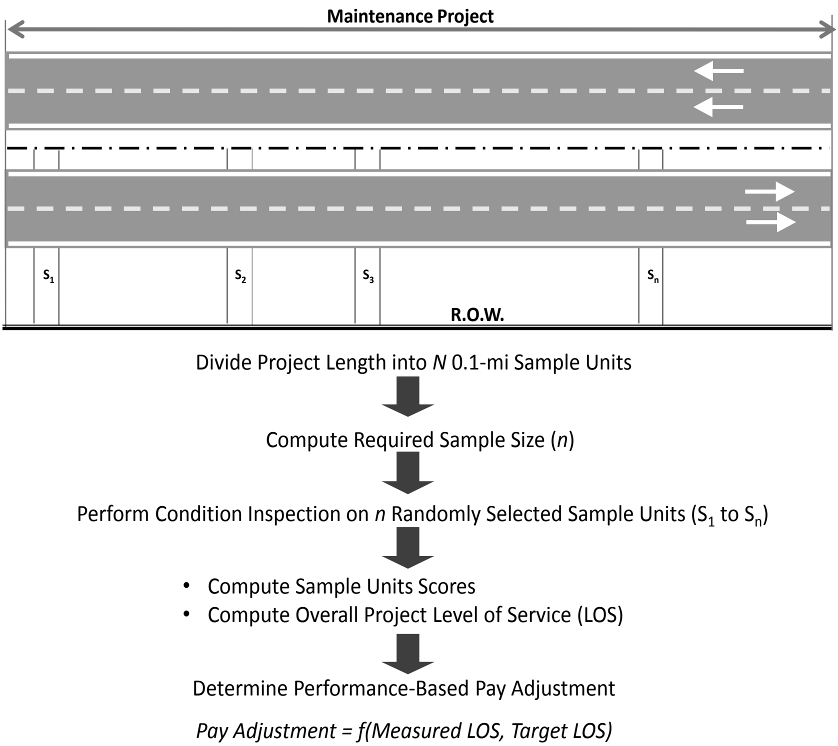

Fig. 2. Illustration of the Developed PBS for Roadside Maintenance

The sampling process and LOS computations consist of the following steps:

1) The highway maintenance project is divided into N sample units (each is 0.1- to 0.2-mi long).
2) n sample units are selected randomly for field inspection. The sample size (n) is computed as follows:

$$n = \frac{s^2 N}{s^2 + \frac{(N-1)e^2}{Z^2}} \qquad (1)$$

where e = Tolerable sampling error (to be specified by the highway agency), which is the maximum acceptable difference between the true average and the sample average; Z = Z-statistic associated with a desired confidence level that the error doesn't exceed e; N = population size (i.e., total number of sample units in the project); and s = estimate of the population's standard deviation. If no historical data exist to estimate s, an s value of 6-11 can be used based on the results of the field trials conducted as part of this study (discussed in later sections of this paper).

3) The randomly selected sample units are inspected and rated on a "Pass/Fail/Not Applicable" basis using the inspection form shown in Figure 1. The form includes a total of 55 performance standards for 12 roadside elements.
4) A 0-100 sample unit score (SUS) is computed as a weighted average score for all elements within the sample unit, as follows:

$$SUS = \frac{\sum_{i=1}^{k} \left(\frac{PS_i}{AS_i} \times PM_i \times 100 \right)}{\sum_{i=1}^{k} PM_i} \qquad (2)$$

where PS is the number of passing performance standards; AS is the number of applicable performance standards; PM is an agency-specified priority multiplier (or weight) for each roadside element; and k is the total number of roadside elements within the sample unit.
5) A roadside average LOS for the maintenance project is computed, as follows

$$LOS = \overline{SUS} = \frac{\sum_{j=1}^{n} SUS_j}{n} \qquad (3)$$

where SUS_j is the sample score for sample unit j and n is the total number of inspected sample units (i.e., sample size).
6) **Optional Step:** Because the LOS is computed based on a random sample, it is recommended that a confidence interval be computed for the LOS. However, to compute confidence interval for LOS (CI_{LOS}), the probability distribution of SUS must be determined. Data gathered from the field trials (discussed later in this paper) showed that the SUS follows a Beta probability distribution. For an independent variable x (SUS in this case), the Beta distribution function is defined by the A factor which defines the lower limit of x (the SUS lower limit is zero), the B factor which defines the upper limit of x (the SUS upper limit is 1.0), and the α and β coefficients which define the shape of the curve. α and β are computed as functions of the average SUS ($\overline{SUS}$) and the variance of SUS (v_{SUS}) as follows:

$$\alpha = \overline{SUS}\left(\frac{\overline{SUS}(1-\overline{SUS})}{v_{SUS}} - 1\right) \quad (4)$$

$$\beta = (1-\overline{SUS})\left(\frac{\overline{SUS}(1-\overline{SUS})}{v_{SUS}} - 1\right) \quad (5)$$

Performance-based Pay Adjustment

Pay adjustment formulas were developed to incentivize the contractor to aim at the agency's specified performance target. The concept here is that maintenance contractors will aim at the quality level (LOS score) that minimizes their total cost. The general shape of these models is as follows:

$$PA = a \times (T - \overline{LOS}) \quad (6)$$

where PA is the pay adjustment, *a* is a model coefficient, T is the target LOS (set by the agency), and $\overline{LOS}$ is the average LOS for the project (computed based on the results of the field inspection). The model coefficient *a* is determined through optimization (or a trial and error procedures) so that the pay adjustment curve ensures that the minimum total cost to the contractor (Total Cost = Maintenance Cost + Pay Adjustment) occurs at the project's target LOS.

Field Trials

The developed performance standards, LOS condition assessment method, and pay adjustment method were tested on five 10-mi highway segments located in five districts of TxDOT (Waco, San Antonio, El Paso, Tyler, and Dallas) (see Table 1). The same team of inspectors (which consisted of one engineer and two engineering technicians) inspected all sites.

Table 1. Characteristics of Field Trial Sites

Site	Location	Urban/Rural	Inspection Cycles
I-35 Northbound	Waco District, TRM* 351 to 361 between the cities of Waco and Hillsboro.	Rural	One (November)
I-20	Tyler District, TRM 556-566 in Smith County.	Rural	Three (April, December, & February)
I-10	San Antonio District, TRM 582-592 in the east side of the city of San Antonio.	Urban & Rural	One (April)
I-35 Eastbound	Dallas District, north side of the Dallas metropolitan area, between Lewisville and Denton.	Urban	One (May)

I-10 Eastbound	El Paso District, east side of the city of El Paso, between TRM 24 and 34.	Urban	One (May)

*TRM: Texas Reference Marker

To assess both the central tendency (i.e., mean values) and variability (i.e., confidence intervals) of the LOS of each field trial, it is necessary to determine the SUS standard deviation and the Beta distribution parameters (α and β) for each site. Since each site was inspected by three inspectors, a pooled standard deviation for these inspectors was computed (see Figure 3). The Beta distribution parameters (α and β) were computed for each site using Equations 4 and 5, along with the pooled standard deviation. Figure 4 shows the frequency distribution of SUS for each site and inspection cycle. It can be seen that the SUS follows a Beta probability distribution (i.e., SUS values are shifted to the right of the SUS scale). This observation is expected since maintenance efforts strive to maximize the SUS score (which has an upper value of 100).

Figure 5 shows the 95 percent confidence interval for the LOS of each field trial, along with the LOS mean values. The El Paso site has the highest average LOS (93) and least variability (as exhibited by the narrowest 95 percent confidence interval of 77.7–99.6). This is perhaps due to the lower number of vegetation and drainage elements present at the El Paso site, compared to the other sites. On the other end, the Dallas site has the lowest average LOS and highest variability. This site has the highest traffic volume among all sites and includes a large number of assets and maintenance activities.

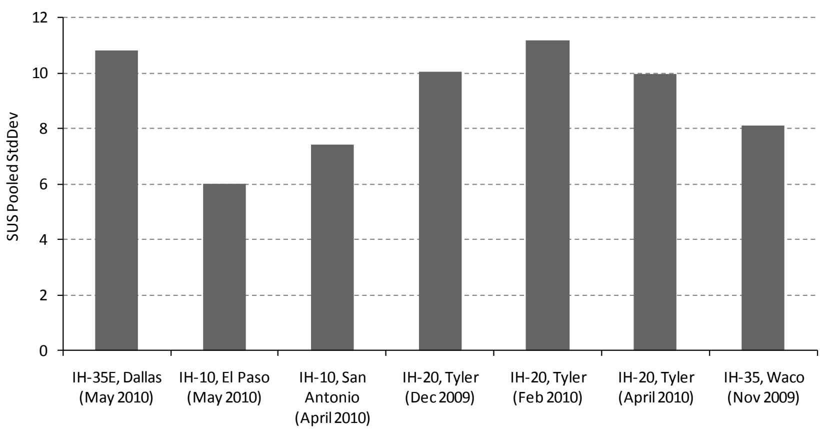

Fig. 3. SUS pooled standard deviation for each field trial

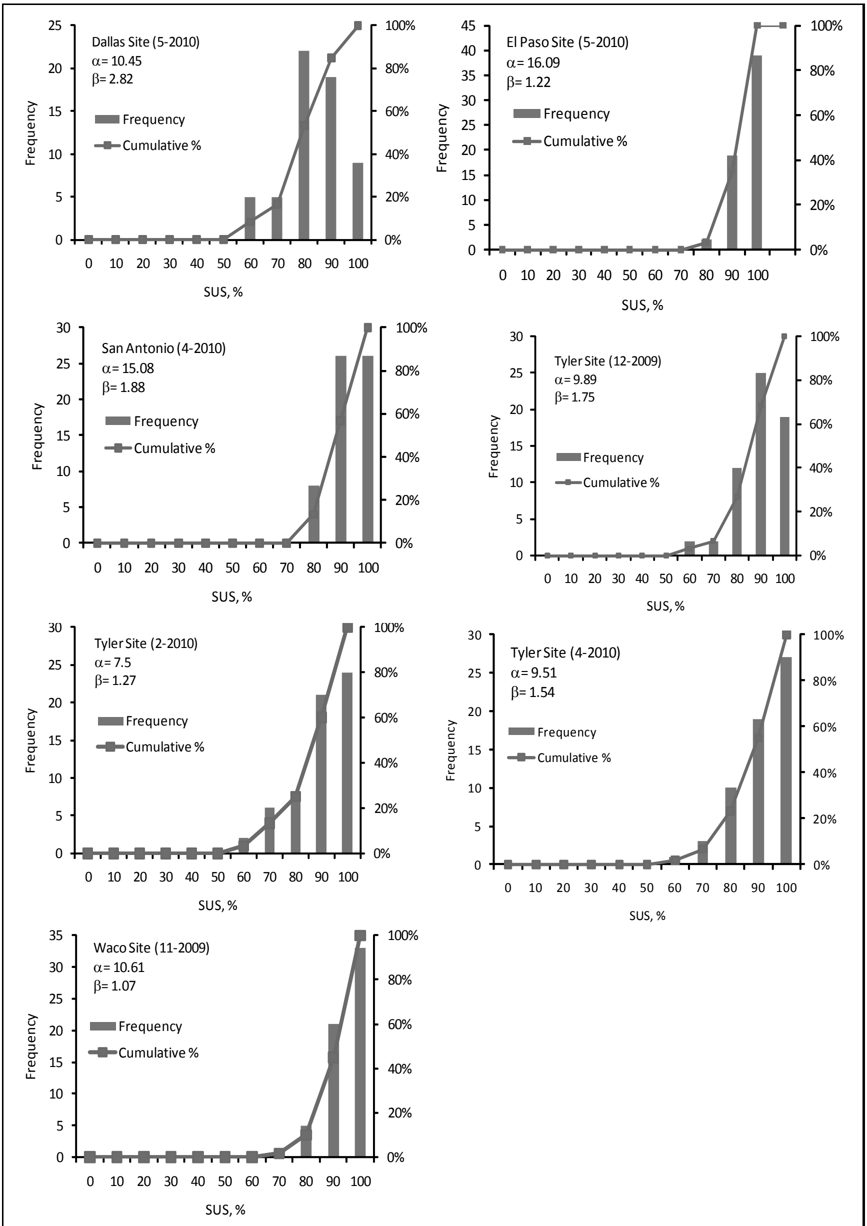

Fig. 4. Frequency Distribution of SUSs for Each Field Trial

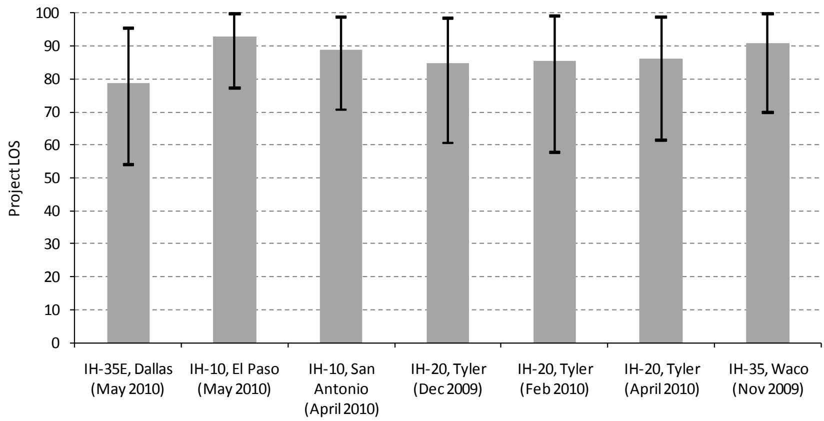

Table 2 shows the pay adjustment (PA) formulas for the five sites. Using these PA equations, a contractor who achieves the target LOS (i.e., project average LOS = Target LOS) receives no pay adjustment; a contractor who exceeds the target LOS (i.e., project average LOS > Target LOS) receives a positive pay adjustment (i.e., pay increase); and a contractor who cannot achieve the target LOS (i.e., project average LOS < Target LOS) receives a negative pay adjustment (i.e., pay decrease).

Table 2. Pay Adjustment Formulas for Field Trials.

Site	Pay Adjustment Equation (Target LOS = 85)	Pay Adjustment Equation (Target LOS = 90)	Pay Adjustment Equation (Target LOS = 95)
IH-35E, Dallas District	PA = 219.6 * (LOS-85)	PA = 220.8 * (LOS-90)	PA = 222.0 * (LOS-95)
IH-10, El Paso District	PA = 180.5 * (LOS-85)	PA = 184.5 * (LOS-90)	PA = 188.5 * (LOS-95)
IH-10, San Antonio District	PA = 123.2 * (LOS-85)	PA = 124 * (LOS-90)	PA = 124.7 * (LOS-95)
IH-20, Tyler District	PA = 85.1 * (LOS-85)	PA = 85.32 * (LOS-90)	PA = 85.57 * (LOS-95)
IH-35, Waco District	PA = 108 * (LOS-85)	PA = 109.3 * (LOS-90)	PA = 110.8 * (LOS-95)

Summary and Conclusions

This paper presents the development and field trials of performance-based specifications for roadside maintenance. These specifications consist of three primary components: specific and measurable performance standards, a level of service (LOS) assessment method for evaluating compliance with these standards, and LOS-based pay adjustment formulas. The field trials consisted of five 10-mi highway corridors located in five districts of TxDOT (Waco, San Antonio, El Paso, Tyler, and Dallas).

Due to the specificity of the performance standards and the relatively high number of performance standards to be evaluated (55 performance standards), a close observation through a walking survey was needed to assess compliance with these standards accurately. Thus, random sampling of relatively short sample units (0.1-mi long) was necessary for the condition survey to be practical. The SUSs were found to follow a Beta probability distribution (i.e., SUS values are shifted to the right side of the SUS scale). This shift is expected since maintenance efforts strive to maximize the SUS score (which has an upper maximum value of 100). Pay adjustment formulas were developed for each site of the field trials. These formulas are designed to motivate the contractor to perform at the performance target specified by the agency.

Acknowledgments

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DEVELOPMENT OF A NATIONAL ASCE STANDARD FOR PERMEABLE INTERLOCKING CONCRETE PAVEMENT

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ABSTRACT

This paper reviews technical development of the emerging ASCE standard for permeable interlocking concrete pavement or PICP. The draft standard notes key design elements which include high strength, impermeable concrete units for a pavement surface that meet ASTM or CSA standards. When installed, the joints between units are filled with permeable aggregate. The units are placed over an open-graded aggregate bedding course which rests on an open-graded aggregate base and subbase for water storage and structural support. While common to all permeable pavements, the document provides a design flow chart for structural and hydrologic design and outlines three commonly used infiltration approaches determined by site and subgrade conditions, as well as designs for sloped subgrades. The draft standard addresses structural design for supporting traffic by modifying conventional flexible pavement design methodology from the American Association of State Highway and Transportation Officials. The draft resolves a key design consideration common to all three permeable pavements; the dichotomy between not compacting the soil subgrade for infiltration and compacting for enhanced structural support especially in saturated conditions. Besides guide construction specifications, construction and maintenance guidelines are provided via checklists. A key tool for assessing surface infiltration and subsequent vacuum cleaning is adoption of an ASTM surface infiltration test for pervious concrete which has been successfully used for porous asphalt and PICP.

Keywords: Permeable pavement standards, permeable interlocking concrete pavement, permeable pavement structural/hydrologic design, permeable pavement construction and maintenance.

INTRODUCTION

The three primary permeable pavement types are pervious concrete (PC), porous asphalt (PA) and permeable interlocking concrete pavement (PICP). These are typically constructed over an open-graded (unstabilized) aggregate base and subbase layers. Since the early 2000s, the National Pollutant Discharge Elimination System incentivized use of permeable pavements as part of permit compliance required under this national legislation. With years of experience and performance research, adoption of design guidelines, construction specifications and maintenance guidelines by state and local stormwater agencies continues. State and local transportation agencies are slower in adoption in part due to lack of experience. Such experience needs to be based on national standards that codify accepted design, construction and maintenance practices. In addition, permeable pavements are generally restricted to parking lots, alleys and low-volume roads. Structural performance data for heavier load applications is needed for unstabilized and stabilized bases/subbase that enables wider use.

PC utilizes the American Concrete Institute for development and distribution of ACI 522 which consists of guidance on material mix design and construction, as well a guide construction specification. In addition, PC has ASTM standards to characterize material properties. Similar ASTM standards exist for PA materials and there is an ASTM guideline under development for PA construction.

For PICP, the ASCE Transportation & Development Institute is creating a comprehensive (and eventual American National Standards Institute) standard for design, construction and maintenance. The highest design loads using unstabilized bases will be 1 million 80 kN equivalent single axle loads. Typical PICP parking lot, alley and street applications are shown in Figures 1, 2 and 3.

Figure 1. Parking lot at Elmhurst College, Illinois

Figure 2. Green Alley in Richmond, Virginia

Figure 3. PICP street in Warrenville, Illinois

When completed, the standard will complement ASCE 58-10 *Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways* (ASCE 2010). This standard covers base designs for conventional interlocking concrete pavement (ICP) up to 10 million ESALs using unstabilized, cement and asphalt-stabilized or asphalt bases. The paving units are typically jointed with sand and placed on sand bedding over an unstabilized dense-graded or stabilized base.

A common error in some state and municipal stormwater guidance documents is in their characterization of ICP defined in ASCE 58-10 as permeable. The research literature (Hade 1988, Madrid 2003) indicates that ICP runoff coefficients typically range between 80% and 95% thereby characterizing the imperviousness similar to that of conventional asphalt and concrete pavements. In contrast, PICP takes in all rainfall and runoff from contributing impervious areas.

DESIGN GOALS

The emerging ASCE design standard for PICP meets the following site design goals.

- National Pollutant Discharge Elimination System (NPDES) permit compliance
- Runoff volume and pollutant control for new development and redevelopment
- Limits on impervious cover (i.e., roofs and pavements) and resulting runoff by being counted as pervious cover.
- Runoff volume storage and/or infiltration to reduce overflows, especially combined sewer overflows.
- Total maximum daily load (TMDL) requirements for receiving waters.
- Managing quality and or quantity storm events, typically expressed as a percentile; e.g. 85th percentile storm depth, or the 95th percentile storm depth as is required for U.S. federal government facilities in Section 438 of Energy Independence and Security Act.

There are other reasons for using PICP besides conformance to state or local regulations. These include:

- PICP as a lower-cost alternative to conventional pavement and drainage system designs
- Stormwater utility fee credits or cost-sharing
- State or local building codes that address pavements such as the International Green Construction Code, ASHRAE Standard 189.1 or CALgreen
- Project owner preference for voluntary conformance rating systems for buildings, sites, roads and transportation infrastructure. Building and site evaluation system examples include Leadership in Energy and Environmental Design (LEED®), the Sustainable Sites Initiative, and GreenGlobes. Road and transportation infrastructure evaluation system examples are the Institute for Sustainable Infrastructure's Envision™, Greenroads, GreenPave or the Federal Highway Administration INVEST or Infrastructure Voluntary Evaluation Sustainability Tool.

- FHWA MAP-21's Technology & Innovation Development program which now includes technology transfer and deployment of permeable, pervious, or porous paving materials, practices.

DESIGN ELEMENTS

Prior to addressing PICP design elements, the designer investigates site-specific items common to all permeable pavement design. Considerations for preliminary design include but are not limited to the following:

- Federal, state, provincial, or municipal stormwater drainage design criteria which may include design storm or storm depths, percentile or return period, intensity, and duration of storms to manage
- Underlying geology and soils maps, horizons, soil types, and estimated depth to the seasonal high ground water table, depth to bedrock or other confining layers
- Identify hydrologic soil groups (i.e., A, B, C, D) as defined in Chapter 7 of the *Engineering Handbook Part 630* published by the U.S. Department of Agriculture Natural Resource Conservation Service
- Soil classification (Unified or AASHTO) and mechanical properties such as strength, particle size distribution, permeability, etc.
- Site history of fill soil, contamination, previous disturbances, or compaction
- Natural drainage systems including intermittent and perennial streams, lakes, rivers, and wetlands
- Surrounding land use, potential sources of pollution etc.
- Existing underground utility lines, e.g., sanitary/storm sewers and structures, water supply, electric, natural gas, cable lines, etc.
- Current and future land uses draining onto the site via overland flow, natural drainage courses, and/or storm sewers
- Applicable NPDES, brown field or other special requirements
- Identification and avoidance of stormwater hotspots

Design elements include the following:

- Traffic loads typically expressed in 80 kN equivalent single axle loads or ESALs
- Soil testing that establishes relationships among soil subgrade compaction, density, and permeability via infiltration tests
- Outflow via underdrains or pipes to handle water not infiltrated within a given time period (typically 48 to 72 hours)
- Slopes adjacent to the permeable pavement that may contribute runoff or sediments
- Sloped PICP subgrades over 3% that typically use berms or barriers to slow

water flow and promote infiltration
- Maintenance-sensitive design features to minimize maintenance (such as slope of adjacent surfaces, supplemental surface drainage features, curbing type and locations, outflows)
- Pollutant loads and treatment designs including targeted pollutants, total maximum daily loads (TMDLs), and airborne sand and dust typical to semi-arid regions
- Geosynthetics such as geotextiles, geogrids and geomembranes
- Rainwater capture and reuse
- Treatment train design where up and down flow practices assist each in moderating water volumes, flows and pollutants.

System Components and Approaches

Since PICP is a fairly new technology, the ASCE standard defines its components and they are illustrated in Figures 4 through 6. Hydrologic design options provide for full, partial or no infiltration. Full infiltration is where all of the rainfall and runoff infiltrate the soil subgrade under the PICP; partial infiltration where some is infiltrated and the remainder exits visit perforated underdrains (often used in low infiltration soils). No infiltration stores water inside the base/subbase using an impermeable liner for eventual release of the stored water.

Concrete Pavers – Paving units assembled in a pattern that creates joints or openings that receive and filled with permeable jointing material. These units comply with ASTM C936 (2012) or CSA A231.2 (2009). For vehicular traffic, pavers have an aspect ratio or length to thickness less than or equal to 3:1 and a minimum thickness of 80 mm (3 1/8 in.). The designer may consider using paving patterns suitable to machine installation for accelerated construction. A 45- or 90-degree herringbone pattern should be used for vehicular pavements. Alternative laying patterns may be considered as long as they are functionally and structurally equivalent.

Permeable jointing material – Permeable crushed stone typically ASTM No. 8, 89 or 9. Selection of aggregate sizes depends on the joint widths created by the assembled concrete pavers. This material is washed angular stone with no fines (<2% passing the 0.075 mm sieve).

Open-graded bedding course – This permeable layer of crushed stone is typically 50 mm (2 in.) thick and provides a level bed for the pavers. It consists of small-sized, angular and washed open-graded aggregate, typically ASTM No. 8 stone or similar sized material.

Open-graded base reservoir – Aggregate layer 100 mm (4 in.) thick and made of crushed angular stone primarily 25 mm down to 13 mm (1 in. down to 1/2 in.). Besides storing water, this layer provides a gradational transition between the bedding and subbase layers. The stone size is typically ASTM No. 57 or similar sized material with a minimum 35% porosity.

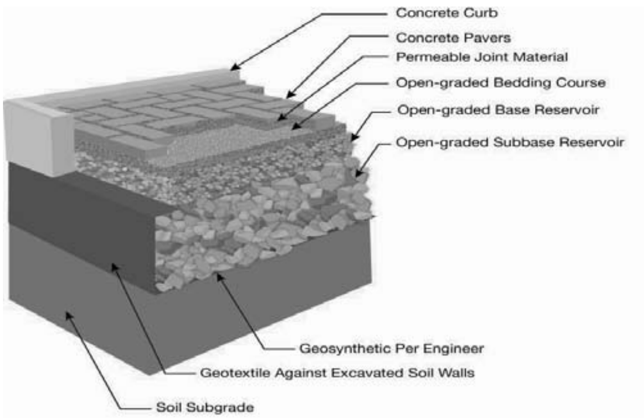

Figure 4. PICP with full infiltration design.

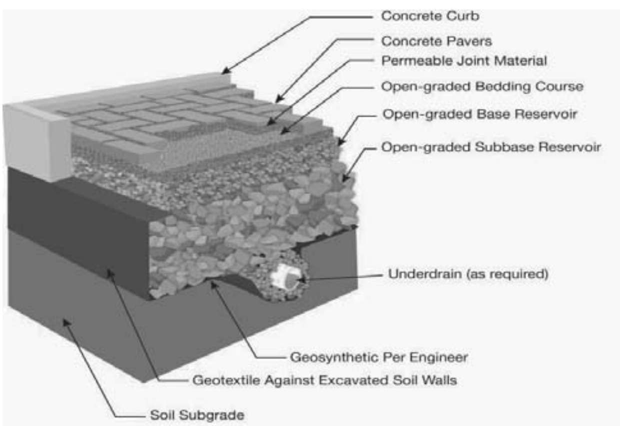

Figure 5.PICP with a partial infiltration design using an underdrain.

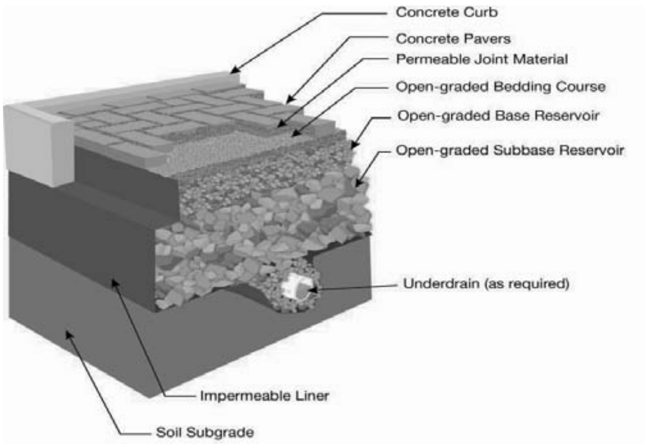

Figure 6. PICP with a no infiltration design using an impermeable liner

Open-graded subbase reservoir – The stone sizes are larger than the base, primarily 75 mm down to 50 mm (3 in. down to 2 in.), typically ASTM No. 2, 3 or 4 angular stone, with a minimum porosity of 32%. Like the base layer, water is stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads. A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer thickness is increased to provide water storage and support.

Underdrain (as required) – In sites where PICP is installed over low-infiltration soils underdrains facilitate water removal from the base and subbase. The underdrains are perforated pipes that “daylight” to a swale or stream, or connect to an outlet structure. Pipe elevation, spacing, diameter and slope will impact outflow volumes and rates from connected PICP. Another design option to which underdrains connect is plastic or concrete vaults or plastic crates. These can store significant amounts of runoff.

Geosynthetic – A geogrid, impermeable liner, geomembrane or geotextile

Geotextile (design option per engineer) – A fabric (woven or non-woven) that separates the bedding/base/subbase from the subgrade and prevent migration of soil into them; selection is based on AASHTO M-288 (AASHTO 2010).

Impermeable liner – A plastic or rubber geomembrane that completely prevents passage of water except through constructed penetrations via pipes.

Subgrade – The layer of soil immediately beneath the aggregate base/ subbase.

STRUCTURAL AND HYDROLOGIC DESIGN METHODS

Structural and hydrologic design processes for determining the subbase thickness are illustrated in Figure 7. First, the designer conducts a structural analysis. Pedestrian use pavement design requires determining the subgrade soil characteristics and then surface and base/subbase thicknesses from established surface, base and subbase properties. In addition to the previous considerations, vehicular use pavement design requires determining traffic loads expressed as lifetime ESALs or Caltrans Traffic Index (TI). Since the aggregate bedding and base layers remain at consistent thicknesses for pedestrian and vehicular designs, the Engineer develops a pavement subbase thickness solution for the subbase layer.

The structural analysis procedure follows the requirements of the American Association of State Highway and Transportation Officials (AASHTO) *Guide for the Design of Pavement Structures* (AASHTO 1993). This design procedure for flexible pavements has been adopted for the ASCE standard because the load distribution and failure modes of PICP are similar to those of other flexible pavement systems (i.e., the main failure mode is increasing rutting due to repetitive shear deformations.

The joint width range for purposes of the structural layer coefficients used in the design procedure typically is 5 mm to 10 mm (3/16 to 3/8 in.). Joints should be completely filled with ASTM No. 8 stone to the bottom of the paver chamfer. If no chamfers are present, the joints should be filled with aggregate to within 6 mm (¼ in.) of the paver surface. ASTM No. 89 or 9 stone may be used to fill paver joints less than 10 mm (3/8 in.) wide.

For design purposes, the assumed AASHTO layer coefficient for the minimum 80 mm (3 1/8 in.) thick paver and 50 mm (2 in.) aggregate bedding layer is 0.30. This layer coefficient considers wider joints and larger aggregates in PICP paver joints compared to the 0.44 layer coefficient for sand-filled paver joints for interlocking concrete pavement as described in ASCE 58-10 *Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways*.

Manufacturers of pavers used in PICP may have additional information and test results that characterize the layer coefficient for their pavers, using specific jointing and bedding materials. They may also have additional information that characterizes benefits of specific paver shapes on structural and hydrologic design, installation and maintenance.

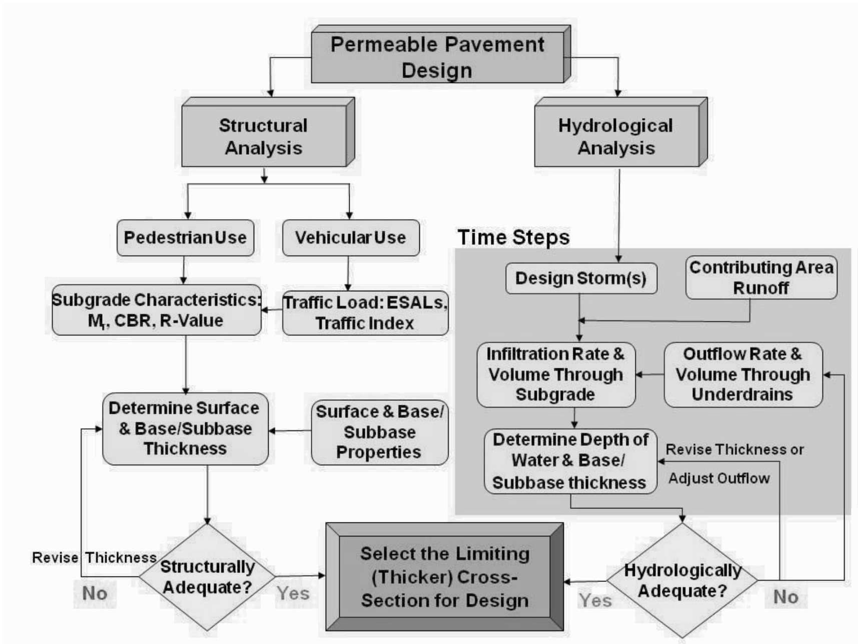

Figure 7. Permeable pavement design flow chart (Smith 2011)

The layer coefficients of the open-graded base and subbase aggregates are assumed to be a portion of that for conventional dense-graded aggregate bases. Since there is a paucity of data characterizing the strength of these materials under traffic loads, the base structural layer coefficient is assumed at 0.09 and the subbase at 0.06. This conservative approach also accounts for base weakness from being completely saturated in high depth rain events. The design reliability is conservatively set at 80% confidence level. The resulting base and subbase thickness are illustrated in Figure 8.

Second, the designer also conducts hydrologic analysis to develop a subbase thickness to store water. Inputs include the:

- Design storm or storms (typically provided by the local municipality)
- Any runoff that becomes inflow from adjacent pavements or roofs
- The soil subgrade infiltration rate and water volume into the subgrade and outflow from underdrains if required

The Engineer calculates the base and subbase thicknesses required to store and infiltrate water, and drain any excess water via underdrains as needed. This analysis involves manual or computer calculated movement of water into the subgrade and outflow over the analysis time, usually 48 to 72 hours (or as specified by the stormwater regulatory agency). This analysis time is divided into time steps or increments to characterize the volume and rate water entering and leaving the pavement structure. The resulting subbase thickness is derived from finding the maximum water storage volume required for the rain event(s) plus any surface inflow while accounting for subgrade infiltration and subbase outflow over the analysis time. The base can also be used for water storage. From the structural and hydrologic analyses, the Engineer selects the thicker pavement subbase section for the project.

Resolving Compaction versus Infiltration

The dichotomy of soil subgrade compaction for structural support and the need for uncompacted soils for infiltration can be resolved by establishing the relationship between soil permeability and in-situ soil density achieved during construction. This is important to establish a relationship between subgrade infiltration capability and the structural capacity necessary to support the design traffic. For example, a CBR determined at a soil compaction level of 95 percent of the standard Proctor maximum dry density will have lower infiltration capacity and higher structural capacity than a CBR determined at a soil compaction level of 90 percent. Therefore, the design must use a lower compaction level or none at all and thicken the subbase to adjust for the reduced support from the soil subgrade. Further, in the event that the field density is less than the design density, it may be necessary to decrease the design CBR, which decreases the structural capacity especially when the soil is saturated, requiring a thicker subbase. While not considered in the standard, stabilized bases are also a design option including PA and PC.

CONSTRUCTION GUIDELINES

PICP construction for vehicular applications follows the steps listed below. The user is directed to industry guide construction specification at www.icpi.org for modification to project conditions. The following lists the general construction steps:

- Attend the pre-construction meeting
- Plan site access and keep PICP materials free from sediment
- Excavate soil or an existing pavement
- Avoid soil compaction unless required in the plans and specifications
- Install geosynthetics, impermeable liners and drain pipes if required in the plans and specifications
- Place and compact the aggregate subbase

- Install curbs or other edge restraints
- Place and compact the aggregate base
- Place and screed the bedding layer
- Install pavers manually or with mechanical installation equipment
- Fill the paver joints and sweep the surface clean
- Compact the pavers
- Fill joints with jointing stone as needed and sweep the surface clean
- Return within 6 months to inspect pavement and refill joints with aggregate

PEDESTRIAN								
	Soaked CBR (R-value)	4 (9)	5 (11)	6 (12.5)	7 (14)	8 (15.5)	9 (17)	10 (18)
	Resilient Modulus, MPa*	43	49	55	61	67	72	77
	Base thickness, mm ASTM No. 57	150	150	150	150	150	150	150

VEHICULAR	Soaked CBR (R-value)	4 (9)	5 (11)	6 (12.5)	7 (14)	8 (15.5)	9 (17)	10 (18)
	Resilient Modulus, MPa*	43	49	55	61	67	72	77
Lifetime ESALs (Traffic Index)								
50,000 (6.3) and Residential Driveways	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	150	150	150	150	150	150	150
100,000 (6.8)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	200	150	150	150	150	150	150
200,000 (7.4)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	325	275	225	175	150	150	150
300,000 (7.8)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	400	350	300	250	225	200	175
400,000 (8.1)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	475	400	350	300	275	250	225
500,000 (8.3)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	525	450	400	350	300	275	250
600,000 (8.5)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	550	475	425	375	350	300	275
700,000 (8.6)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	600	525	450	425	375	350	300
800,000 (8.8)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	625	550	500	450	400	375	325
900,000 (8.9)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	650	575	525	475	425	400	350
1,000,000 (9)	Base thickness, mm ASTM No. 57	100	100	100	100	100	100	100
	Subbase thickness mm ASTM No. 2	675	600	525	475	425	400	375

*M_r in psi = 2,555 x $CBR^{0.44}$; M_r in MPa = 17.61 x $CBR^{0.44}$
Assumptions: 80% confidence level
Commercial vehicles = 10%; Average ESALs per commercial vehicle = 2
ASTM No. 57 stone layer coefficient = 0.09; ASTM No. 2 stone layer coefficient = 0.06
ASTM No. 3 or 4 stone may be substituted for ASTM No. 2 stone subbase layer.
80 mm thick concrete pavers and 50 mm ASTM No. 8 bedding layer coefficient = 0.3
Total PICP cross section depth equals the sum of the subbase, base, 50 mm bedding and paver 80 mm thickness.
Consult with geogrid manufacturers for base/subbase thickness recommendations using geogrids.

Figure 8. Base and subbase thickness design chart for PICP (Smith 2011)

Preconstruction Meeting

Commercial and municipal projects specifications often require a pre-construction meeting. The pre-construction meeting is held to discuss methods of accomplishing all phases of the construction operation, contingency planning, and standards of workmanship. The general contractor typically provides the meeting facility, meeting date and time. Representatives from the following entities should be present:

- Contractor superintendent
- PICP subcontractor foreman
- Concrete paving unit manufacturer's representative
- Testing laboratory(ies) representative(s)
- Engineer or representative

The following items is discussed and determined:

- Test panel (mock-up) location and dimensions
- Methods for keeping all materials free from sediment during storage, placement, and on completed areas
- Methods for checking slopes, surface tolerances, and elevations
- Concrete paving unit delivery method(s), timing, storage location(s) on the site, staging, paving start point(s) and direction(s)
- Anticipated daily paving production and actual record
- Diagrams of paving laying/layer pattern and joining layers as indicated on the drawings
- Monitoring/verifying paver dimensional tolerances in the manufacturing facility and on-site if the concrete paving units are mechanically installed
- Testing intervals for sieve analyses of aggregates and for the concrete paving units
- Method(s) for tagging and numbering concrete unit paving packages delivered to the site.
- Testing laboratory location, test methods, report delivery, contents and timing
- Engineer inspection intervals and procedures for correcting work that does not conform to the project specifications.

Sediment Control

Due care shall be applied to prevent and divert sediment from entering the aggregates and pavement surface during construction. Sediment must be kept completely away from aggregates stored on site as well as the PICP. In some cases, it may be necessary to construct PICP before other soil-disturbing construction is completed. The standard provides planning options for sediment control for inclusion in the project specifications: These are as follows:

(1) Construct the aggregate subbase and base and protect the surface of the base aggregate with geotextile and an additional 50 mm (2 in.) thick layer of the same base aggregate over the geotextile. When construction traffic has ceased and adjacent soils are vegetated or stabilized with erosion control mats, remove geotextile and soiled aggregate (or the asphalt) and install the remainder of the PICP system per the project specifications.

(2) Install the PICP first and allow construction traffic to use the finished PICP surface. When construction traffic has ceased and adjacent soils are stabilized with vegetation or erosion control mats, clean the PICP surface and joints with a vacuum machine.

(3) Protect finished PICP system by covering the surface with a woven geotextile and a minimum 50 mm (2 in.) thick ASTM No. 8 open-graded aggregate layer. This aggregate layer and geotextile are removed upon project completion and when adjacent soils are stabilized with vegetation or erosion control mats. The PICP surface is swept clean.

(4) Establish temporary road or roads for site access that do not allow construction vehicle traffic to ride over and contaminate the PICP base materials and/or surface with mud and sediment. Other trades on the jobsite need to be informed on using temporary road(s) and staying off the PICP. The temporary road is removed upon completion of construction and opening of the PICP surface to traffic.

Other practices are noted such as keeping muddy construction equipment away from the PICP, installing silt fences, staged excavation, truck tire washing stations, and temporary drainage swales that divert runoff away from the area.

Construction Checklist

The standard provides a construction list for agency, owner and contractor use:

Pre-construction meeting

- Walk through site with builder/contractor/subcontractor to review erosion and sediment control plan/stormwater pollution prevention plan or SWPPP)
- Determine when PICP is built in project construction sequence; before or after building construction, and measures for PICP protection and surface cleaning
- Aggregate material locations identified (hard surface or on geotextile)

Sediment management

- Access routes for delivery and construction vehicles identified
- Vehicle tire/track washing station (if specified in Erosion & Sediment plan/SWPPP location/ maintenance

Excavation

- Utilities located and marked by local service
- Excavated area marked with paint and/or stakes
- Excavation size and location conforms to plan

Sediment management

- Excavation hole as sediment trap: cleaned immediately before subbase stone placement and runoff sources with sediment diverted away from the PICP, or
- All runoff diverted away from excavated area
- Temporary soil stockpiles should be protected from run-on, run-off from adjacent areas and from erosion by wind
- Ensure linear sediment barriers (if used) are properly installed, free of accumulated litter, and built up sediment less than 1/3 the height of the barrier
- No runoff enters PICP until soils stabilized in area draining to PICP

Foundation walls

- At least 3 m (10 ft) from foundation walls with no waterproofing or drainage

Water supply

- At least 30 m (100 ft) from municipal water supply wells

Soil subgrade

- Rocks and roots removed, voids refilled with permeable soil
- Soil compacted to specifications (if required) and field tested with density measurements per specifications
- No groundwater seepage or standing water, if so, dewatering or dewatering permit may be required

Geosynthetic (if specified)

- Meets specifications
- Placement and down slope overlap (minimum 0.6 m (2 ft)) conform to specifications and drawings
- Sides of excavation covered with geotextile prior to placing aggregate base/subbase
- No tears or holes
- No wrinkles, pulled taught and staked

Impermeable Liner (if specified)

- Meets specifications
- Placement, field welding, and seals at pipe penetrations done per specifications

Drain pipes/observations wells

- Size, perforations, locations, slope, and outfalls meet specifications and drawings
- Verify elevation of overflow pipes

Subbase, base, bedding and jointing aggregates

- Sieve analysis from quarry conforms to specifications
- Spread (not dumped) with a front-end loader to avoid aggregate segregation
- Storage on hard surface or geotextile to keep sediment-free
- Thickness, placement, compaction and surface tolerances meet specifications and drawings

Edge restraints

- Elevation, placement, and materials meet specifications and drawings

Permeable interlocking concrete pavers

- Meet ASTM/CSA standards (as applicable) per manufacturer's test results
- Elevations, slope, laying pattern, joint widths, and placement/compaction meet drawings and specifications
- No cut paver subject to tire traffic is less than 1/3 of a whole paver
- All pavers within 2 m (6.5 ft) of the laying face fully compacted at the completion of each day
- Surface tolerance of compacted pavers deviate no more than ±10 mm (3/8 in.) under a 3 m (10 ft) long straightedge

Final inspection

- Surface swept clean
- Elevations and slope(s) conform to drawings
- Transitions to impervious paved areas separated with edge restraints
- Surface elevation of pavers 3 to 10 mm (1/8 to 3/8 in.) above adjacent drainage inlets, concrete collars or channels (for non-ADA accessible paths of travel); to ¼ in. or 6 mm (for ADA accessible paths of travel)
- Lippage: no greater than 3 mm (1/8 in.) difference in height between adjacent pavers
- Bond lines for paver courses: ±15 mm (±½ in.) over a 15 m (50 ft) string line
- Stabilization of soil in area draining into permeable pavement (minimum 6 m (20 ft)) wide vegetative strips recommended)
- Drainage swales or storm sewer inlets for emergency overflow. If storm sewer

inlets are used, confirm overflow drainage to them
- Runoff from non-vegetated soil diverted from PICP surface
- Test surface for infiltration rate per specifications using ASTM C1701; minimum 2,500 mm/hr (100 in./hr) recommended

MAINTENANCE GUIDELINES

The standard provides a maintenance checklist for project owners and facility managers. Like all permeable pavements, regular surface cleaning is key to maintaining surface infiltration rates throughout the pavement life.

- 1 to 2 times annually (typically spring/fall): vacuum surface, adjust vacuuming schedule per sediment loading and/or any sand deposits from winter
- Winter: Remove snow with standard plow/snow blowing equipment; monitor ice on surface for reduced salt use than typically used on impervious pavements
- As needed, indicated by water ponding on surface immediately after a storm (paver joints or openings severely loaded with sediment): test surface infiltration rate using ASTM C1701. Vacuum to remove surface sediment and soiled aggregate (typically 13-25 mm (½ to 1 in.) deep), refill joints with clean aggregate, sweep surface clean and test infiltration rate again per C1701 to minimum 50% increase or minimum 250 mm/hr (10 in./hr).

Annual Inspection checklist

- Replenish aggregate in joints if more than 13 mm (1/2 in.) from chamfer bottoms on paver surfaces
- Inspect vegetation around PICP perimeter for cover & soil stability, repair/replant as needed
- Inspect and repair all paver surface deformations exceeding 13 mm (1/2 in.)
- Repair pavers offset by more than 6 mm (1/4 in.) above/below adjacent units or curbs, inlets etc.
- Replace cracked paver units impairing surface structural integrity
- Check drains outfalls for free flow of water and outflow from observation well after a major storm

CONCLUSIONS

Like all ASCE national standards, the emerging ASCE draft standard for PICP described in this paper will pass through committee comments, balloting, and public comments with responses to them. The core information on this pavement technology seeks to present best practices for design, construction and maintenance developed by stakeholders from industry, regulatory, academic research and engineering spheres.

ASCE committee representation reflects these stakeholders' needs as well as developing additional guidelines to increase confidence in civil engineers and their clients. Besides increasing confidence and reducing risks, the intent of this standard is for reference and use by national, provincial, state and local government agencies, as well as by consulting engineers. The standards-making effort will result in higher consistency among users that result in successful projects while allowing for adjustments according to local stormwater management objectives/regulations, materials, construction and maintenance practices. Also, as more is known about PICP performance through practice, this experience can be reinvested into future versions of this standard thereby yielding increased benefits to users in the coming years.

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Rutting and Moisture Damage Wheel Tracking Comparison of Laboratory and Field Compacted Asphalt Concrete

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ABSTRACT

A number of developments have occurred recently to improve asphalt's sustainability. During this time, the asphalt industry has increased the number of mix options arguably more than any other time in history. This ever increasing list of options emphasizes the need for performance testing as opposed to more traditional reliance largely on volumetric properties. A key area related to performance testing is comparing laboratory mixing and compaction to plant mixing and field compaction. Therefore, the primary objective of this paper was to assess differences between laboratory and field compaction for plant mixed asphalt using wheel tracking. A total of 398 specimens were available for this assessment, some of which were field compacted cores from a single lift that was approximately 70 mm thick. Having field compacted cores from a single lift of suitable wheel tracking thickness was a key component of this paper. A secondary objective of this paper was to assess differences between laboratory and plant mixing using wheel tracking; a modest number of specimens were available in this regard. This paper found no meaningful rut depth differences for laboratory and field compacted materials for one wheel tracker, but did find potentially meaningful differences for a second wheel tracker.

INTRODUCTION

In recent years, a number of developments have been introduced to improve asphalt concrete sustainability. Among these have been warm mix technologies to provide environmental, energy, and cost savings over traditional methods. During this time frame the asphalt industry has increased the number of mix design options arguably more than any other time in history. Environmentally friendly options include warm mixed asphalt (WMA), high reclaimed asphalt pavement (RAP) contents, ground tire rubber (GTR) modified binders, and virgin binder replacement via asphalt shingles. Combinations of these items can also be an attractive option.

The ever expanding number of options available to produce asphalt concrete make performance testing more important than ever. Without methods to adequately characterize new materials, their use could be limited, which for the aforementioned options limits sustainability efforts. Producing test specimens with properties representative of the in-place, plant-produced, field-compacted mixture is a key issue with performance testing of asphalt concrete. Aspects of both the full-scale mixing process and the construction compaction method must be approximated in the laboratory to produce representative specimens.

OBJECTIVES AND SCOPE

The primary objective of this paper is to assess differences between laboratory and field compaction for plant mixed asphalt using wheel tracking. A total of 398 specimens were available for this assessment, some of which were field compacted cores from a single lift that was on the order of 70 mm thick and others were laboratory produced with the Superpave Gyratory Compactor (SGC). Having field compacted cores from a single lift of suitable wheel tracking thickness was a key component of this paper. Wheel tracking is a performance test that is gaining popularity, and two of the more popular methods were used in this paper, namely the Asphalt Pavement Analyzer (APA) and the Hamburg Loaded Wheel Tester (HLWT). A secondary objective of this paper was to assess differences between laboratory and plant mixing methods using wheel tracking; 24 addition specimens were available in this regard, bringing the total number of compacted specimens available to 422.

EXPERIMENTAL PROGRAM

The work presented in this paper is part of a larger effort undertaken to evaluate hot mixed and warm compacted asphalt for disaster recovery. Howard et al. (2012a) fully describes the research effort, while aspects pertinent to this paper are described in the following sections. Test methods used are presented first, followed by the materials tested and corresponding test sections where materials were taken.

Test Methods

Bulk specific gravity (G_{mb}) was measured on each core and Superpave Gyratory Compactor (SGC) specimen using AASHTO T166 (i.e., saturated surface dry method). The CoreDry® (i.e., ASTM D7227) was typically used to dry cores prior to testing. All cores were verified to be at constant mass (i.e., no moisture) prior to measuring G_{mb}. Maximum mixture specific gravity (G_{mm}) was performed according to AASHTO T209-10 under vacuum and mechanical agitation (Method A). The average of six G_{mm} determinations on mix sampled pre-haul was used to determine air voids (V_a).

APA testing was performed to 8,000 cycles at 64°C, with a 445 N vertical load, and with an internal hose pressure of 690 kPa. APA rut depth was the value measured at 8,000 cycles, while rut rate was calculated as the mm change in rutting per 1,000 cycles between 2,000 and 8,000 cycles. HLWT testing was performed to 20,000 passes at 50°C, with a 705 N vertical load, and with solid metal wheels contacting the specimen. HLWT rut depth was taken at 20,000 passes, and rut rate was taken from 5,000 to 20,000 passes in the same manner as the APA except passes were used instead of cycles.

Two specimens with similar air voids and otherwise identical properties were placed in one track for APA and HLWT testing. Specimens that were thinner than the target specimen dimensions (63.5 mm for HLWT and 75 mm for APA) were tested with Plaster of Paris under the specimens so they would conform properly to the molds. Specimens that were thicker than the target dimensions were trimmed on the bottom so they would conform to the target dimensions. APA cores should be at least 50 mm tall according to AASHTO T340.

Test Section and Materials Tested

One mix design was utilized throughout (Figure 1), which is a 12.5 mm nominal maximum aggregate size (NMAS) 65 gyration Superpave design. Four binder configurations were used in conjunction with the Figure 1 mix design.

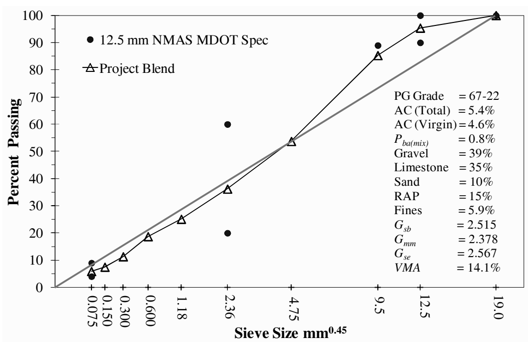

Figure 1. Summary of Asphalt Mixture Properties

Figure 1 was plant-produced, loaded into trucks, then hauled for varying time periods before placement and compaction into thirteen test strips on a parking lot. Test strips were constructed on four days. Each morning, mixture was initially produced that was not used in test strips to allow the plant to reach equilibrium and ensure the proper binder was fully incorporated into the mixture.

Mixtures were hauled for 1.0 to 10.5 hours before placement and compaction. A relatively unique aspect of the field-compacted specimens is that the asphalt was compacted in one lift to 70-mm thick (on average); single lifts of this mixture are traditionally placed less than 70-mm thick. The HLWT and APA performance tests require specimens that are 63-mm and 75-mm thick, respectively. This allows for direct comparison of differences in performance test results for laboratory- and field-compacted specimens.

Howard et al. (2013) investigated the effects of varying haul time and concluded that haul times up to 8.4 hr did not reveal deleterious binder performance effects. All but one of the thirteen test strips was hauled 8.4 hr or less. Therefore, it was decided to remove the strip hauled over 8.4 hr from the data set used in this paper and group all remaining materials by binder configuration and treat specimens of a given binder configuration as replicate data with air void variation.

Table 1 provides the test matrix consisting of 422 compacted specimens. The data set included three asphalt binders that produced plant mixed asphalt with the Figure 1 gradation having four binder configurations (binder 2 was used neat and foamed). Two of these configurations were also laboratory mixed. Compaction was performed with the SGC or using full scale equipment, with cores subsequently taken from the compacted test strips. A large data set was available to compare field to SGC compaction on plant-mixed asphalt, whereas a very modest data set was available to investigate effects of laboratory to plant mixing.

Table 1. Test Matrix

Binder	Mix ID	Test Strips	Mixing	Compaction	T_{mix} (°C)	Number of Specimens APA	HLWT
B1	P	1	PM	FC	174	6	8
B1	P	1	PM	SGC	174	16	16
B2	HMA	4	PM	FC	164	48	48
B2	HMA	4	PM	SGC	164	16	16
B2	Foam	4	PM	FC	153	48	48
B2	Foam	4	PM	SGC	153	16	16
B3	Additive	3	PM	FC	148	36	36
B3	Additive	3	PM	SGC	148	12	12
B2	Lab	None	LM	SGC	160	6	6
B3	Lab	None	LM	SGC	129	6	6

--Binders: B1 = PG 67-22 from Hunt Refining Company, Tuscaloosa, AL
B2 = PG 67-22 from Ergon Asphalt & Emulsions (A&E), Inc., Vicksburg, MS
B3 = PG 67-22 from Ergon A&E, Vicksburg, MS, dosed 0.5% of M1 Evotherm 3G™

--Mix ID's: P = Preliminary test strip
HMA = No foaming or Evotherm 3G™ to serve as control for study
Foam = Binder was foamed with 2% moisture on a binder mass basis
Additive = Binder dosed with Evotherm 3G™
Lab = Specimens were prepared in laboratory

--Mixing: PM = plant mixed, or mixed at full scale production facility
LM = laboratory mixed

--Compaction: FC = field compacted, or compacted with full scale steel wheel rollers
SGC = laboratory compacted using Superpave Gyratory Compactor (SGC)

-- T_{mix}: Mixing temperature

COMPARISON OF FIELD AND GYRATORY COMPACTION

APA Test Results

Figure 2 plots APA rut depths for plant mixed ID P material; a similar rutting rate plot was not shown for brevity. PM-SGC specimens were used to estimate the effect of air voids on rut depth over a wide range of voids; fit of the equation was reasonable with R^2 of 0.73. Rut depths doubled from 2.1 mm at 3% voids to 4.2 mm at approximately 10% voids, and were 5 mm at 12% voids. Rut depths of 5 mm or less up to 12% air voids is a stable mixture. A similar regression equation was fit to the APA rut rate data ($y = 0.012x + 0.12$ with $R^2 = 0.64$). Rut rates also approximately doubled from 0.12 mm/1000 cycles at 3% voids to 0.25 mm/1000 cycles at approximately 10% voids.

FC specimens were not as rut resistant as SGC specimens. Two of the three

FC specimen data points in Figure 2 were tested a week after placement. One of the FC data points was stored in ambient laboratory conditions for approximately 7.5 months while exposed to laboratory air but not to moisture or sunlight. The rut depth of the specimen stored for some time was within 0.3 mm of one of the data points tested a few days after placement. Rut rate data was similar. This test was conducted since specimens were stored several months in some cases prior to rut testing due to the volume of testing performed for this project. These data indicate rut depths and rut rates were representative of those soon after construction.

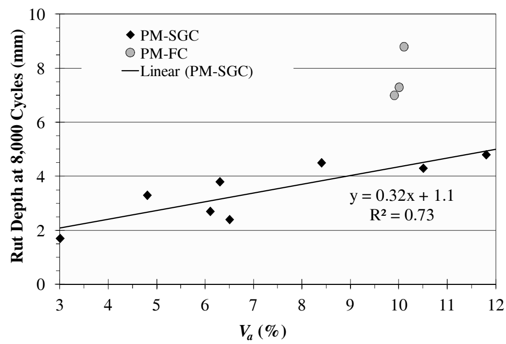

Figure 2. APA Test Results For Mix ID P

Figure 3 plots APA test results for the four field compacted HMA strips described in Table 1 versus V_a. Twelve field cores were tested per strip at six air void levels that encompassed the range of voids in the strip. Two cores from each air void level were tested as a pair in one track of the APA to produce one data point. Similar plots for the Foam and Additive mixes are not shown for brevity.

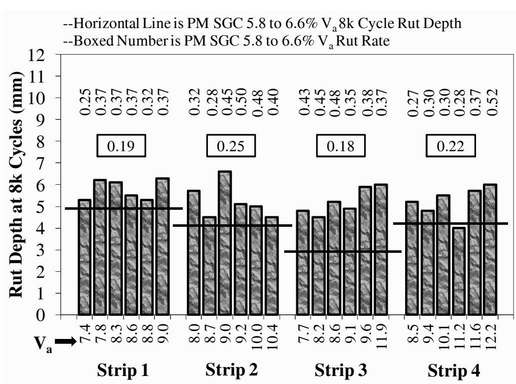

Figure 3. APA Results for HMA Test Strips

Brown et al. (2001) suggested an 8 mm pass/fail rut depth criteria for use with the APA for the equipment configuration used in this study. Generally speaking, this criteria would apply to SGC compacted specimens at 7% air voids. Only one test had values above the 8 mm criteria recommended by Brown et al. (2001) (Additive strip 10 had one value at 8.4 mm). There were no meaningful differences between HMA, Foam, and Additive rut depths in place. FM-FC rut depths did not appear to be greatly affected by air voids.

Note that binder types can change APA rut depths considerably in some cases, but there were not major differences in the high PG grade of the binders tested in this study, nor were where major mixing temperature differences for plant mixed materials. All warm mix technologies were used at hot mix temperatures. Had a wide range of mixing temperatures been used (e.g. 174 ^{o}C to 116 ^{o}C), this issue could have warranted more discussion.

There was no meaningful correlation between average field compacted rut depth or rut rate and laboratory compacted rut depth or rut rate for each test strip. Air voids were higher for field compacted specimens. Therefore, Figure 2 regression line slope data for FM-SGC data relating rut depth to air voids was used to adjust Figure 3 FM-SGC data to the void levels of each FM-FC data point. For example, the average voids and rut depth for strip 1 FM-SGC data were 6.3% and 4.9 mm, respectively and the slope from Figure 2 regression was 0.32 mm per 1% increase in air voids. The lowest air voids of FM-FC cores tested was 7.4% (Figure 3); therefore the calculation to estimate the FM-SGC rut depth at that void level is 0.32*(7.4-6.3) + 4.9 mm = 5.2 mm. This was done for all APA data of strips 1 to 11 and the data were statistically compared to assess the differences due to compaction method (Table 2). The air void adjusted SGC specimens had statistically lower rut rates for all mixtures that also could have some practical meaning. Two of the three rut depth comparisons were statistically different, but not practically different. The mean air void adjusted SGC rut depths were within 1 mm of mean FC compacted specimen rut depths in all cases.

Table 2. Unequal Variance *t*-test Compaction Method Comparison for APA

Category	Mix	Type	*n*	Mean	Std. Dev.	*t*-stat	*t*-crit	Sig. Different?
Rut Depth 8k cycles	HMA	FC	24	5.36	0.67	2.04	±2.01	Yes, FC higher
		SGC	24	4.92	0.64			
	Foam	FC	24	4.88	0.81	-2.37	±2.03	Yes, FC lower
		SGC	24	5.52	1.03			
	Additive	FC	18	5.49	1.30	0.367	±2.05	No
		SGC	18	5.36	0.86			
Rut Rate 2k to 8k cycles	HMA	FC	24	0.37	0.077	7.71	±2.04	Yes, FC higher
		SGC	24	0.24	0.034			
	Foam	FC	24	0.35	0.0072	3.86	±2.03	Yes, FC higher
		SGC	24	0.27	0.0024			
	Additive	FC	18	0.42	0.0887	6.85	±2.09	Yes, FC higher
		SGC	18	0.27	0.0206			

Note: Significance testing performed at the 95% confidence level. SGC data used for statistical analysis was adjusted to match air voids in FC data based on Figure 2.

HLWT Test Results

Figure 4 plots Mix ID P HLWT rut depths for plant mixed material. PM-SGC specimens were used to estimate the effect of air voids on rut depth over a wide range of voids. Rut depths doubled from 2.7 mm at 3% voids to 5.4 mm at approximately 10.5% voids, and were 5.9 mm at 12% voids. HLWT rut depths of 6 mm or less up to 12% air voids after 20,000 passes is a stable mix. A similar regression equation was fit to the HLWT rut rate data between 5,000 to 20,000 passes (y = 0.0088x + 0.0239 with R^2 = 0.74). Rut rates also approximately doubled from 0.05 mm/1000 passes at 3% voids to 0.11 mm/1000 passes at 10% voids.

Field compacted (FC) specimens were not as rut resistant as SGC compacted specimens for Mix ID P. Two of the four FC specimen data points shown in Figure 4 were tested approximately three weeks after placement (rut depths of 10.3 and 12.1 mm). The other two FC data points were collected from specimens stored in ambient laboratory conditions for 7.5 to 9.5 months while exposed to laboratory air but not exposed to moisture or sunlight (rut depths of 7.4 and 7.7 mm). Rut depth was, on average, 3.6 mm less for the specimen stored for some time compared to those tested approximately three weeks after placement. This test was conducted since specimens were stored several months in some cases prior to HLWT testing due to the volume of testing performed for this project. These data indicate that rut depths may have been higher if specimens had been tested immediately; HLWT findings differed from APA findings in this regard as APA rut testing several months later was within the range of values tested soon after construction. With such a limited amount of data on this one particular issue, however, these findings are not conclusive.

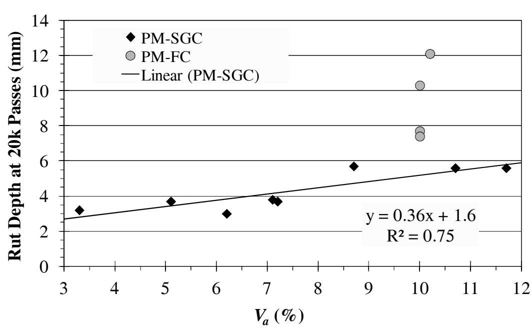

Figure 4. HLWT Test Results For Mix ID P

Figure 5 plots HLWT test results for the four field compacted HMA strips described in Table 1 versus V_a. Twelve field cores were tested per strip at six air void levels that encompassed the strip. Two cores from each air void level were tested as a pair in one track of the HLWT to produce one data point. Similar plots for the Foam and Additive binders are not shown for brevity. Stripping inflection point (SIP) is a term often associated with the HLWT, which is used as an assessment of stripping potential. No specimens tested had a SIP.

Rut depths averaged for each section ranged from 7.9 to 8.9 mm for HMA and 8.4 to 10.2 mm for Foam. For the Additive mixture, five of the eighteen specimen sets (28%) experienced 12.5 mm or more rutting at 20,000 passes or before. High air voids of these specimens are believed to be a contributing factor, but in general HLWT performance of Additive was somewhat below Foam and HMA performance.

Aschenbrener (1995) proposed a rut depth criterion of less than 10 mm after 20,000 passes. Texas DOT (TxDOT) specification criteria are defined as minimum number of passes to reach a 12.5 mm rut depth when the test is performed at 50°C. The criteria are 10,000 and 15,000 passes for PG 64 and PG 70 binders, respectively. These values have been suggested to be too conservative and alternate criteria of 5,000 and 10,000 passes are presented by Rand (2006). Typically these criteria are applied to laboratory compacted specimens. Rut depths measured on FM-SGC specimens were 4.7 to 6.1 mm for HMA (value shown in Figure 5), 4.7 to 6.5 mm for Foam, and 4.1 to 6.3 mm for Additive. FM-SGC results were practically identical between mixture types and easily meet the aforementioned criteria.

Since air voids were higher for field compacted specimens, the same adjustment procedure described for APA data was used to estimate FM-SGC performance at the FM-FC void levels. Table 3 summarizes the data and makes comparisons of FC and SGC compaction. Note the higher variability of FM-FC data. The five specimen sets of Additive with 12.5 mm or more rutting were not included in the analysis. Air void adjusted rut depths of the SGC specimens were significantly lower than for FC cores. Average rut depths between air void adjusted SGC specimens and FC cores were 1.7 to 3.0 mm (3.0 mm value would have been higher if specimens with 12.5 mm or more or rutting had been included).

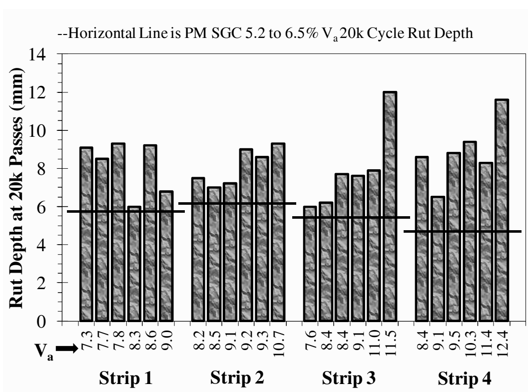

Figure 5. HLWT Test Results for HMA Strips 1 to 4

Table 3. Unequal Variance *t*-test Compaction Method Comparison for HLWT

Category	Mix	Type	*n*	Mean	Std. Dev.	*t*-stat	*t*-crit	Sig. Different?
Rut Depth 20k passes	HMA	FC	24	8.25	1.55	4.96	±2.05	Yes, FC higher
		SGC	24	6.59	0.54			
	Foam	FC	24	9.20	1.47	7.29	±2.02	Yes, FC higher
		SGC	24	6.58	0.96			
	Additive	FC	13	9.42	1.47	5.05	±2.08	Yes, FC higher
		SGC	13	6.40	0.96			

Note: Significance testing performed at the 95% confidence level. SGC data used for statistical analysis was adjusted to match air voids in FC data based on Figure 4.

COMPARISON OF LABORATORY AND PLANT MIXING

Table 4 compares laboratory and plant mixing. Specimens laboratory mixed at 160°C had comparable APA rut depths to the plant mixed specimens (0.4 mm less on average); rut rate data was also comparable. Laboratory mixed specimens at 160°C had lower HLWT rut depths than plant mixed specimens (2.5 mm less on average). When the laboratory mixing temperature was reduced to 129 °C, APA and HLWT rut depths increased 2.8 and 4.0 mm on average, respectively. These data would tend to indicate that there was little difference between laboratory mixing and plant mixing for dry rutting performance tested in the APA. These data would also tend to indicate that there was some difference between laboratory mixing and plant mixing for performance testing in the presence of moisture. Considering the same binder grade, but a different source, was used for laboratory and plant mixing, more detailed statements are not warranted since the data set represented in Table 4 is limited by comparison to the data sets used for Table 2 and Table 3.

Table 4. Comparison of Laboratory and Plant Mixed Specimen Rut Depths

Wheel Tracker	Plant Mixed (174 °C)	Laboratory Mixed (160 °C)	Laboratory Mixed (129 °C)
APA	3.5 to 3.6 mm	2.7 to 3.5 mm	5.5 to 6.3 mm
HLWT	4.2 to 4.4 mm	1.1 to 2.3 mm	5.7 to 5.9 mm

DISCUSSION OF RESULTS

Multiple researchers have investigated the effect of specimen compaction method on mixture performance results. Howard et al. (2012b) evaluated the Linear Asphalt Compactor (LAC) and the SGC using laboratory mixed materials. One component of the investigation was comparison of APA rut depths for LAC and SGC compacted specimens. Rutting resistance of the LAC appeared to be similar to or less than the SGC, which was stated to indicate that the LAC compared more favorably to field compacted specimens according to literature reviewed by the authors.

Peterson et al. (2004) found that plant mixed, SGC compacted specimens generally had lower moduli measured by the Superpave shear tester that than those of field compacted specimens. Alternate SGC compaction parameters were suggested to provide mixture properties closer to those of field compacted mixture. Masad et al. (2009) observed that laboratory SGC compacted and field compacted specimens had comparable HLWT rut depths at similar air void levels. The results of Gibson et al. (2010) suggested that the rutting performance of SGC compacted specimens was sometimes different than that of field compacted mixture, but that the differences were influenced by the stress and confinement levels. Compaction method differences were less pronounced with greater confinement. Based on HLWT results, Glueckert (2012) found that field produced mixture performed better than laboratory produced mixture and that hot mixed asphalt performed better than a wax-based warm mix additive.

Xiao et al. (2010) concluded that APA rut resistance was more strongly related to aggregate type than to moisture in the mixture or hydrated lime content. Xiao et al. (2010) also concluded that Evotherm warm mix additive had similar rut resistance relative to a control. Skok et al. (2002) indicated that at high test temperatures, aggregate properties have a greater effect on APA rut resistance than binder content.

A notable limitation of the current paper is only one aggregate gradation was used. A notable asset of the current paper is considerable replication was available and fairly thick single lift field compacted cores were available. Literature findings related to laboratory versus field compaction indicate differences in some cases (e.g., Peterson et al., 2004; Gibson et al., 2010) and no meaningful differences in other cases (e.g., Masad et al., 2009). The work in this paper found no meaningful APA rut depth differences for SGC and field compacted materials, but did find potentially meaningful differences for HLWT test results in some cases.

SUMMARY

Summary observations are listed below.

- More differences were observed with HLWT testing than with APA testing.
- For plant-mixed SGC specimens, APA and HLWT rut depths followed a linear trend with air voids over a range of approximately 3 to 12%.
- Plant-mixed and laboratory-mixed material exhibited similar APA dry rutting performance for SGC specimens; while differences were noticed for HLWT rut testing in the presence of moisture.
- For APA testing of plant-mixed material, rut rates were 0.08 to 0.15 mm/1000 cycles higher on average for field compacted material.
- For APA testing of plant-mixed material, total rut depths of field-compacted material were on average within 1 mm of SGC compacted material.
- For HLWT testing of plant-mixed material, rut depths of field-compacted material were on average 1.7 to 3.0 mm (+) higher than SGC specimens.

ACKNOWLEDGEMENTS

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Experimental apparatuses for the determination of pavement material thermal properties

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ABSTRACT

Degradation due to temperature fluctuation is the predominant deterioration mechanism affecting many asphalt and cementitious pavement systems. Reduced durability, in turn, limits the sustainability of a materials system: maintenance and replacement are almost always energy and resource intensive. As such, accurate quantification of the thermal properties of any given pavement material is necessary to determine durability and evaluate the effectiveness of novel technologies. Two relatively inexpensive apparatuses have been developed for this purpose. The first, a Guarded Longitudinal Calorimeter (GLC), measures heat flow through a specimen sandwiched between standards of known thermal properties during either heating or cooling; from the measured heat flow data, many useful thermal properties (apparent thermal conductivity, etc.) can be obtained. The second device, a Solar Simulator, measures the temperature at different depths in multiple well-insulated specimens as they are heated or cooled by halogen lamps or cooled air blowers. The theory, construction, and operation of these devices will be detailed, and the results of analyzing pavement materials in each will be discussed.

INTRODUCTION

Maintaining and improving core highways, roads, and bridge decks cost the U.S. more than $100 billion in 2011, an amount that was roughly the same as in previous years [1, 2]. Extreme temperature changes play an important part in these costs as they lead to failure of concrete and asphalt pavements before the end of their expected service life. Very low temperatures cause tensile stresses in the binder, and if the resulting tensile stress exceeds the binder failure stress, cracking occurs [3, 4]. On the other hand, very high temperatures increase the likelihood of deformation related to shear stresses (rutting) [5]. Even if intense temperatures do not cause deterioration directly, cyclic changes in temperature can cause deterioration in pavements due to fatigue.

Over the years, researchers have studied the thermal properties of concrete and asphalt. Different theoretical and experimental research programs have investigated the effects of different parameters such as water-cement ratios, aggregate volume fraction, and humidity on thermal properties of concrete and asphalt [6, 7]. These investigations show that performance, service life, and the long-term quality of a pavement are closely related to properties such as thermal conductivity. However, increasing the service life of pavements and improving their performance necessitates the development of new research approaches to better understand the thermal properties of pavement materials.

Laboratory testing is a promising way to study thermal properties of concrete and asphalt. ASTM standard methods D5470-06 and E1225-09 describe procedures for determining the thermal transmission properties of solids material by means of the guarded-comparative-longitudinal heat flow technique. This paper presents two new pieces of equipments. One is similar to guarded-comparative-longitudinal devices by which the thermal properties of concrete samples can be determined. A cooling plate with adjustable temperature profile is used in order to create temperature gradient and an array of temperature sensors are provided to record temperature at different points. This device provides a simple, practical, and accurate procedure to measure the thermal properties of concrete samples. In the future, these devices can be used to determine the efficiency of new technologies, such as phase change material incorporation, in increasing pavement service life.

The second device is a new design of a machine in order to simulate the cyclic temperature changes in asphalt exposed to the solar and environment condition. The previous laboratories devices include either heating or cooling units, but in the proposed device, different heating and cooling unite are provided to simulate thermal environmental condition. Also, in order to record the temperature at different depths of asphalt specimen, an array of temperature sensors are used. This device can collect sets of data to study the thermal properties of asphalt pavements. The provided information could be comparable with the results of theoretical simulations, such as finite-element simulation, in previous studies [8].

MATERIALS[1]

Guarded Longitudinal Calorimeter (GLC)

The GLC is designed to measure the heat flowing through a sample in a single direction. As it is shown in Fig. 1a, the sample sits in the center of a "sample stack", with meter bars above and below the sample. The meter bars are of known thermal and physical properties, and are of the same cross section as the sample. Early results showed that the GLC did not function well due to poor contact between the sample and meter bars, despite the apparent smoothness of these materials; as such a highly conductive thermal transfer medium must be used (indicated by white arrows). Thermal transfer medium is also placed below the lower meter bar to ensure good contact with the heat source In addition to providing good contact, the transfer medium (usually a putty or clay) provides accommodation for thermocouples; for consistency, although not needed for contact reasons, transfer media is usually placed on top of the upper meter bar in order to secure a fourth thermocouple. The thermocouples are numbered one through four, starting with the thermocouple below the bottom meter bar.

This entire meter bar/sample/meter bar stack is then insulated with common rigid foam insulation and set atop a heat sink or "cold plate" (Fig. 1b). The method of

[1] Certain commercial products are identified here in order to adequately illustrate the experimental methodologies or apparatuses. Such identification is not intended to imply that these products have been evaluated and shown to be the best available for experimental purposes.

insulation is not critical, but in this case insulation into which a hole has been cut has been slid over top of the sample stack. The interior of this hole was sealed with duct tape in order to reduce friction and ease assembly of the device. A small channel must be provided by which the thermocouple wires can exit the insulation. This insulation is intended to reduce lateral thermal transfer to the environment, ensuring only longitudinal heat flow.

Finally, a solid slab of insulation is placed atop the stack-and-donut setup (Fig. 1c). A thermally conductive guard shell (usually aluminum or steel) is placed in contact with the heat sink, surrounding the stack-and-donut, in order to neutralize the temperature gradient through the insulation, further reducing heat losses in the lateral direction. Additional insulation is placed on any other exposed surfaces of the heat sink, simply to make operation of the device more efficient. The wires visible in each image are thermocouples, connected to a nearby data acquisition system.

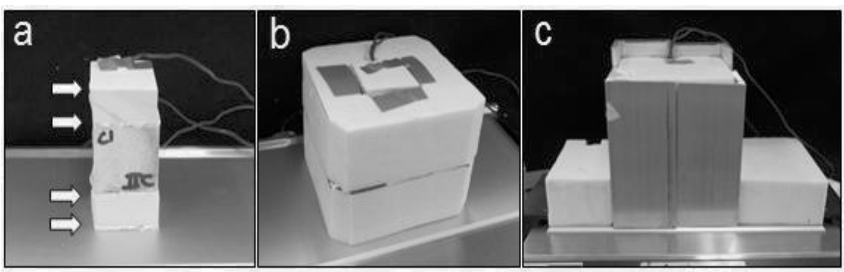

Figure 1. The guarded longitudinal calorimeter.
a) The sample stack; b) the "stack-and-donut", instrumented and insulated; c) the complete GLC.

The above description is appropriate for any calorimeter of the guarded longitudinal type. The physical properties, size, and shape of the materials used can vary, as well as the specific equipment involved, so long as the amount of insulation is sufficient and the sample and meter bars have the same cross-section. Here, the specific materials used were: 2 in.(0.0508 m) mortar cubes, identical to those commonly used to determine compressive strength using ASTM standard C109;1 x 2 x 2 in. (0.0254m) rectangular prisms made of a glass-ceramic material (Pyroceram, Corning Inc.) for the meter bars; the conductive medium was a 1/8thin. (.003 m) thick layer of high performance elastomer (TC3008, Stockwell Elastomerics); the insulation was rigid expanded polystyrene insulation commonly used in roofing applications; the shell guard was assembled from scrap aluminum; and the heat sink was a thermoelectric cold plate (AHP-1200DCP, TECA Corp.). 16 gauge insulated type K thermocouple wires were used, connected to a USB data acquisition system. Dictated by the size of the heat sink, the insulation took the form of a 6" x 6" (0.1524 m) square 'donut', with a 2" x 2" (0.0508 m) square hole in the center.

Solar Simulator

The frame of the Solar Simulator is essentially a wooden chamber; two of the sides are plywood secured with screws and wood glue, while the front and back are transparent polymer sheets, held in place with clamps (Fig. 2). Fig. 2a displays the isometric planning of the Solar Simulator, showing four halogen lamps sitting above four insulation 'jackets' in which cylindrical samples of pavement are placed. The vertical slits in the jackets are to accommodate thermocouples. Fig. 2b shows the interior of the Solar Simulator, including a pyranometer used for calibration and one insulation jacket. One of the plywood sides has a port to which a chilled-air vent can be connected. The top of the chamber contains four round ports that serve to secure in place four halogen lamps (Fig. 2c).

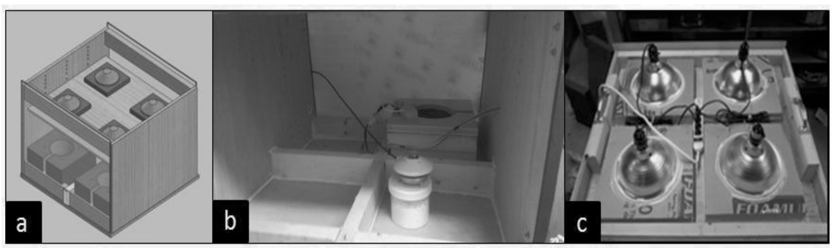

Figure 2. Solar Simulator.
a) Isometric planning view; b) Interior of the Solar Simulator; c) Top of the Solar Simulator.

Beneath the lamps, the base of the cube is formed of insulation 'jackets' sitting atop plywood. Each jacket is a cube with a cylindrical opening; 4" x 8" (101.6 x 203.2 mm) cylindrical asphalt mix samples sit inside the jackets, so that only the top surface is exposed. These asphalt mix samples contain thermocouples, in order to measure the temperature at the asphalt surface, as well as at varying heights throughout the sample. The halogen lamps and chilled-air blower can be connected by computer and used to simulate a variety of real-world temperature profiles.

The main components of the equipment consist of a microcontroller, a servo, a dimmer, and four halogen lamps. An algorithm (programmed with PuTTY software) in the microcontroller controls the dimmer through the servo, to provide time dependent radiation from each of the four halogen lamps, allowing the simultaneous testing of four samples. The angle of rotation of the dimmer was calibrated against radiation (kW/m2) through test data acquired with a pyranometer (CMP3, Kipp and Zonen). Essentially, once the user inputs the radiation as a function of time the dimmer setting vs. radiation calibration curve is utilized to set a dimmer setting vs. time function for the servo to control the dimmer. The microcontroller also collects data from the six thermocouples per sample and four ambient temperature thermocouples, and provides them to the user through the computer, as .csv files, which can be converted to Excel spreadsheets.

DATA ANALYSIS

In the GLC, the thermocouples provide a record of temperature vs. time. When combined with the known properties of the meter bars, this can be used to calculate the average heat flow through the sample using equations from ASTM standard D5470-11, *Standard test method for thermal transmission properties of thermally conductive electrical insulation materials* [9]:

$$Q_{xy} = \frac{A(\lambda_{xy})(T_x - T_y)}{d_{meter}} \quad \text{(Eqn. 1)}$$

In which Q_{xy} is the heat flow between thermocouples x and y (i.e., Q_{12} is heat flow in the lower meter bar and Q_{34} is the heat flow in the upper meter bar, in W); A is the cross-sectional area of the sample; λ_{xy} is the thermal conductivity of the meter bars; T_x and T_y are the temperatures recorded by thermocouples x and y, respectively; and d_{meter} is the thickness of the meter bars (or, technically, the distance between the thermocouples). As the thermal conductivity of the meter bars are known (in this case, λ_{12} equals λ_{34} at 4.18 W/m·K, the known value for pyroceram) Q_{12} and Q_{34} can be calculated; Q_{13}, the heat flow through the sample, is assumed to be the arithmetic average of the heat flow through the two meter bars.

A similar equations described in ASTM standard E1225-09, *Standard test method for thermal conductivity of solids by means of the guarded-comparative-longitudinal heat flow technique* [10]. This same standard provides an equation by which the 'apparent thermal conductivity' (λ_{sample}) of the sample can be calculated:

$$\lambda_{sample} = \frac{(Q_{12} + Q_{34}) d_{sample}}{2A(T_3 - T_2)} \quad \text{(Eqn. 2)}$$

In which d_{sample} is the thickness of the sample, and the other variables are as defined in the Eqn. 1.

The Solar Simulator requires little data analysis; as it provides temperatures at varying depths in cylindrical samples, it is used primarily for comparing temperatures in different formulations of pavement materials.

RESULTS

Guarded Longitudinal Calorimeter

Basic operation of the GLC produces a plot of temperature vs. time as recorded by at least four thermocouples. Depending on the capabilities of the cold plate being used, it may be possible to program specific heating/cooling rates, hold times, etc. The data shown in Fig. 3 were collected for a system in which the cold plate was simply set to reach -20 °C as quickly as possible. The inset image shows the type of discontinuity that would be expected during an exo/endothermic reaction taking place; in this case, the solidification of pore solution at roughly -9 °C.

As the thermal conductivity of the meter bars and the geometry of the sample stack are known, Eqn. 1 can be used to determine heat flow through the meter bars; Eqn. 2 can be used to estimate the average thermal conductivity of the sample. The results of such calculations are shown in Table 1. Three control samples, containing either normal weight sand aggregate (C1), or internal curing via an expanded clay lightweight aggregate (C2) or a naturally occurring pumice lightweight aggregate (C3) were investigated using the GLC. The results were compared to thermal conductivity measurements carried out using a 'hot disk' system, which is commonly used and has been described in detail elsewhere [11, 12]. At least five hot disk measurements were collected and averaged for each sample; several thousand data points were used in the GLC analysis. Also, the uncertainty represents the measured standard deviation.

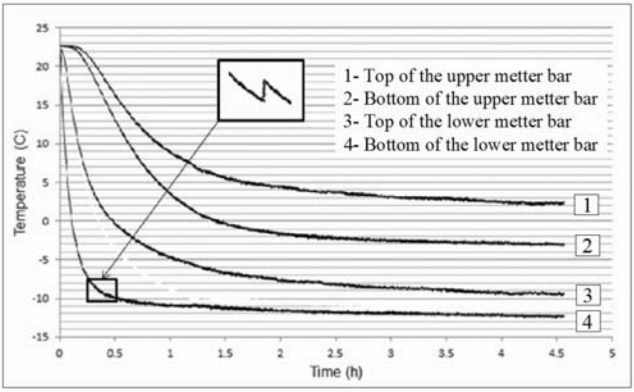

Figure 3. Data collected by the GLC for a system set to reach -20 °C as quickly as possible.

Table 1. Thermal conductivities of three mortar samples, as measured using the GLC and a conventional 'hot disk' apparatus.

Sample	λ_{GLC} (W/mK)	$\lambda_{HOT\ DISK}$ (W/mK)	Difference (%)
C1	4.11 ± 0.39	2.7 ± 0.24	34.4
C2	2.8 ± 0.4	2.1 ± 0.18	25.0
C3	2.74 ± 0.32	2.4 ± 0.03	12.5

The discrepancies in thermal conductivity measured by these two techniques are compounded by the relatively large number of variables. The state of saturation of the sample can greatly alter thermal conductivity; specimen age has a somewhat smaller effect. The values for the GLC were calculated at *every* data point collected after the initial hour, in order to compensate for the rapid temperature decrease in the thermocouple closest to the cold plate; this value was arbitrarily selected, and may not represented the optimal data treatment methodology. Further, the collection of data for 4.5 hours was limited by logistical constraints; longer analysis might have provided 'smoother' data.

Solar Simulator

Figure 4 shows the results of a test on a hot mix asphalt sample. The sample was instrumented at depths of 25 mm and 50 mm below the surface. A quadratic radiation vs. time function was applied for 1 hour. One simulated hot/cold cycle was used. The data show that the equipment was able to simulate the intended radiation and collect the temperature data from the sample.

The following (expected) observations confirmed the proper functioning of the data acquisition system: The temperatures at the two depths increased over time; There is a "lag" in the temperature data compared to the radiation – the peak temperatures do not coincide with the peak radiation; The maximum increase in the temperature at a depth of 25 mm (17 °C) was higher than the maximum increase in the temperature at a depth of 50 mm (14 °C); and the temperatures start decreasing along with a decrease in the radiation.

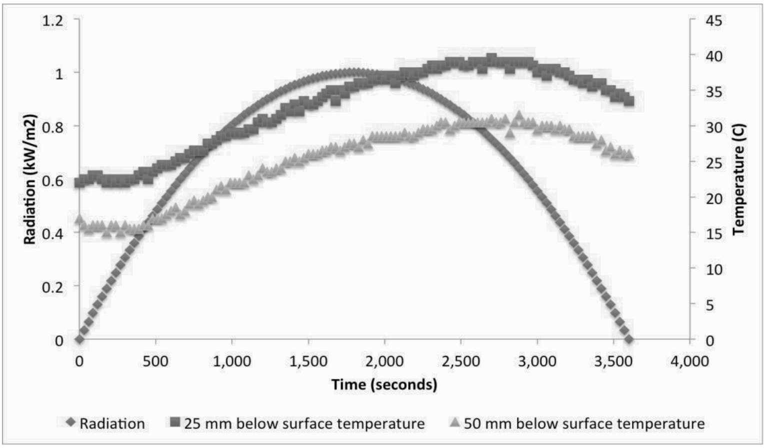

Figure 4. Data collected from the Solar Simulator for a hot mix asphalt sample.

CONCLUSIONS and FUTURE WORK

The guarded longitudinal calorimeter and Solar Simulator are two pieces of equipment that are relatively simple to construct and operate, and provide important data on the thermal properties of infrastructure materials that cannot be found with other techniques. As society refocuses on increasing sustainability, the durability of materials will continue to increase in importance; as thermal deterioration is one of the primary damage mechanisms at work in pavements, control and customization of thermal properties will continue to be a subject of importance to national research efforts.

There are significant opportunities for future work. First, the optimum testing parameters of the GLC need to be determined, such as cooling rate, holding times, holding temperatures, etc. Once determined, this piece of equipment is especially well suited to investigating novel composite materials, such as concrete containing phase change materials (PCM). PCMs are substances that undergo exothermic solidification and endothermic melting reactions; when incorporated in a pavement, they can help to regulate the temperature profile of the system and avoid damage.

Currently, work is being conducted to increase the number of thermocouples that can be accommodated by the system. A total of 24 thermocouples will be utilized to capture the temperature data from four samples and the "ambient" temperature inside the chamber of the solar simulator. Some work will be conducted to identify the best possible method of attaching a thermocouple on the surface of the sample with minimum disturbance. Work is also being done on fabricating four insulation jackets, with appropriately placed holes for inserting thermocouples. The insulation jackets are expected to be 150 mm tall, and shims of appropriate thicknesses will be utilized to make sure that the surface of all of the samples (which may be of different heights) are at the same distance from the lamp. Finally, in the near future work will be conducted to accommodate a fan and an anemometer inside the chamber to allow the simulation of wind and determination of the effect of natural convection on the temperature of the samples.

ACKNOWLEDGEMENTS
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Optimizing the COTE of Concrete by Blending High and Low COTE Aggregates to Meet TxDOT Limit

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The coefficient of thermal expansion (COTE) is an important concrete property that characterizes the dimensional change of concrete subjected to temperature change. In jointed concrete pavements (JCP), expansion joints are used to accommodate length changes due to temperature variations. However, for continuously reinforced concrete pavements (CRCP) with high COTE aggregates, there are no expansion joints to accommodate the length changes. In Texas some districts with high volumes of CRCP such as Houston, Dallas, and Forth Worth experience a high degree of transverse cracking, horizontal cracking, and punchouts due to the environmental loading in high COTE concrete CRCP. Very recently the Texas Department of Transportation (TxDOT) has imposed a limit on COTE as an acceptance criterion for pavement concrete aggregates. Houston and Beaumont do not have low COTE aggregate sources in the vicinity, and to meet the current TxDOT requirement these two districts have to haul aggregates from long distances. This will not only increase the transportation cost but also limit the use of locally available good quality aggregates, which has high COTE. COTE of concrete can be reduced by blending high and low COTE aggregates. This research study used three high COTE aggregate sources from different strategic locations in Texas suggested by TxDOT; they were each blended with low COTE limestone aggregate at different replacement ratios. Results showed that concrete COTE can be reduced by blending low COTE aggregates with high COTE aggregates. The COTE of concrete decreases linearly with an increase in limestone replacement. These findings will help TxDOT use the local high COTE aggregate sources by blending with imported low COTE aggregates. Aggregate producers with high COTE aggregates can also determine the degree of replacement necessary for their aggregates to be accepted in a TxDOT CRCP paving projects.

Introduction

The Texas Department of Transportation (TxDOT) has 16,400 lane miles of concrete pavements. About 75% of the concrete pavements are continuously reinforced concrete pavement (CRCP). Though CRCP is an expensive option, this type of pavements showed superior performance, low repair, and maintenance requirement. Therefore, TxDOT prefers CRCP over other types of pavement in heavy traffic areas such as Houston, Dallas, and Fort Worth to minimize traffic interruption caused by repair and maintenance. Significant distresses have been observed in CRCP of Texas when certain types of aggregate were used. TxDOT has been recognizing the incompatibility of coefficient of thermal expansion of cement paste and aggregate as one of the major reasons of these problems for years. Current researches also support their claim (Choi et al. 2011; Kim and Won 2004).

Coefficient of thermal expansion can be defined as the strain developed due to a unit change in temperature. As a result concrete pavements change its length (contraction and expansion) due to the daily temperature cycles. Temperature through the depth of concrete is not uniform due to the thermal gradient. During the day the top surface temperature of concrete pavement is higher than the bottom surface and at night the thermal gradient is reversed. This thermal gradient results in differential changes of length in the top and bottom surfaces. These differential changes of length cause curling. This effect is further amplified by the variation in moisture content over the thickness of the concrete slab. Generally the top surface of concrete pavement is in dry state, whereas the bottom surface is saturated. The COTE of concrete is influenced by the moisture content of concrete (Mindess et al. 2002; Simon and Dallaire 2002). Simon and Dallaire (2002) observed that maximum concrete COTE values were obtained at 60 to70% relative humidity, which is about 20 to25% higher than the COTE at 100% relative humidity. Tensile stresses develop in pavement concrete due to the daily expansion and contraction cycles, and the frictional resistance between the pavement slab and base interface. If the developed tensile stress is larger than the tensile strength of concrete, the pavement cracks. CRCP has reinforcement to control the crack width. If excessive cracking occurs, these crack eventually cause faulting, punchout, and delamination. Though COTE is such an important parameter of pavement concrete, it was not considered as a design input until it was first considered as a design parameter by the Mechanistic-empirical pavement design guide (MEPDG) developed through NCHRP 1-37A (NCHRP and ARA 2004).

Aggregate occupies about 70 to 80% of the concrete volume and has major influence on the COTE of concrete (Mindess et al. 2002; Jahangirnejad et al. 2009). Various researches observed COTE values ranging from 3 to 8 microstrain/^{o}F (Naik et al. 2011; NCHRP and ARA, Inc. 2004). Concrete pavement with higher COTE shows a higher level of distress (Huang 2003; Mallela et al. 2005). General approach to overcome this problem was by designing pavement with higher thickness and reinforcement. TxDOT also adopted this technique by introducing thicker CRCP with two layers of reinforcement in 1989. This is probably an easy solution of the problem but may not be the most economical. As good quality aggregate sources are being depleted due to the increased use, high COTE aggregates are introduced to Texas pavements. This problem is most severe to those districts where no low COTE aggregate is locally available, such as Houston and Beaumont district. As a part of the quality control of pavement concrete, very recently TxDOT has started to impose COTE limit on concrete as an acceptance criteria for aggregates, although no published COTE limit is available yet. However, according to some aggregate manufacturers and TxDOT personnel, 5.5 microstrain/^{o}F is the maximum COTE limit for concrete was specified for CRCP construction projects. It is not known yet how many aggregate manufacturers will be affected by this new COTE limit. According to Jahangirnejad (2009), the Federal Highway Administration (FHWA) has tested over 1800 aggregate sources as a part of the long-term pavement performance program since 1996, and about 70% of the aggregate has COTE values between 5.5 to 6.5 microstrain/^{o}F.

Aggregates that have COTE values greater than the TxDOT limit are no longer accepted in TxDOT CRCP projects. TxDOT is the single largest consumer of aggregates in Texas, and many of these high COTE aggregate quarries were developed to meet TxDOT aggregate demand. Even some districts with high CRCP pavements such as Houston does not have low COTE aggregate sources in the vicinity. Low COTE aggregates need to be transported from long distances for CRCP projects, these additional transportation costs will increase the project cost. Also, use of locally available good quality, but high COTE, aggregates will be limited for pavement applications. This situation also affects the sustainable use of locally available good quality material. This problem is seeking a solution for the sustainable use of high COTE, but good quality aggregate sources.

Blending low COTE aggregate with high COTE aggregate has long been thought to be a potential method of reducing concrete COTE. However, little effort has been given to verify this hypothesis. First this study will focus on the COTE of different strategic aggregate sources for TxDOT and finally evaluate the effect of aggregate blending on the COTE of concrete.

Experimental Procedures

Materials

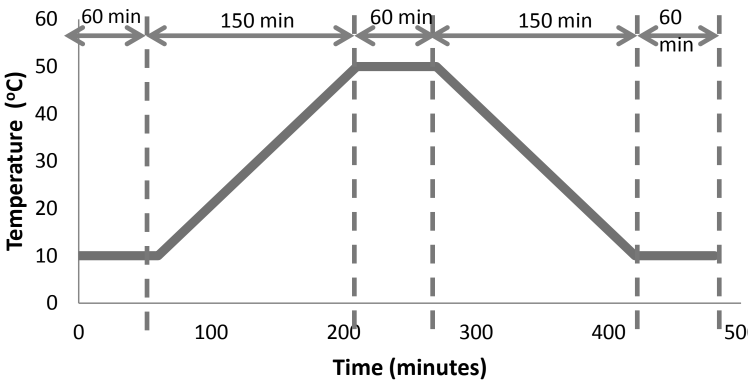
Aggregates were selected strategically from five TxDOT districts: Atlanta, Houston, Amarillo, Paris, and Wichita Falls. These districts were selected based on the availability of acceptable aggregate sources and the potential of concrete pavement construction. Two sources of aggregate from each district were selected. Table 1 shows the selected aggregate sources. Texas and Oklahoma have four sources each, and the other two sources are from Arkansas. Four of the coarse aggregates are siliceous river gravel (RG), two of them are a natural blend of siliceous and limestone gravel (RGLS), and one source each supplies granite (GR), rhyolite (RH), sand stone (SS), and dolomite (DL). A limestone (LS) source near Dallas and Fort Worth (DFW) was selected as the low COTE aggregate source. Known mineralogy of the aggregates was obtained from the TxDOT Concrete Rated Source Quality Catalog (CRSQC) data sheet. RH and SS were not on the list, and were identified by petrographic analysis. A Type I cement and TxDOT recommended river sand source was used for concrete mixtures.

Test Procedures

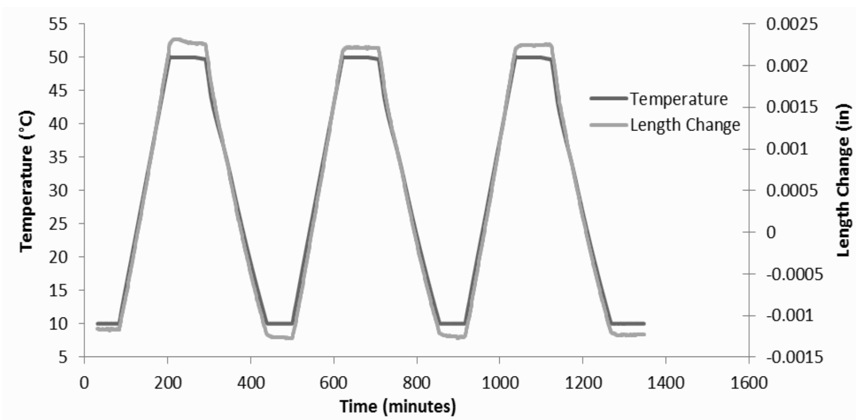
Absorption and oven dry specific gravity (SG_{OD}) of Coarse and fine aggregates were determined according to TxDOT test method Tex-403-A (1999). Concrete proportioning was done according to Tex-428-A (2011). This method suggests a specific concrete proportioning and coarse aggregate gradation to produce comparable COTE concrete by minimizing the influence of other factors such as: volume of aggregate, volume of paste, aggregate gradation, and water-to-cement ratio (w/c). The mixture design for all ten concrete mixtures confirmed to Tex-428-A (2011). Before mixing, coarse aggregates were regraded according to Tex-428-A (2011). The 4-in. x 8-in. (200-mm x 400- mm) cylinders were made according to ASTM C192 (2007). Compressive strength and modulus of elasticity (E) were measured according to Tex-418-A (2008) and ASTM C469 (2010), respectively. The COTE of concrete cylinders made with the selected aggregates was determined in accordance to Tex-428-A (2011). Each concrete cylinder was subjected to multiple cycles of heating and cooling for the COTE test as suggested by Tex-428-A(2011). Figure 1 shows one typical cycle of heating and cooling and a representative length change response of a concrete cylinder.

Table 1: List of selected coarse aggregate sources

Aggregate ID	Districts	Quarry location
RG1	Houston	Briggs, TX
RG2	Houston	Eagle Lake, Tx
RG3	Atlanta	Lockesburg, AR
RG4	Atlanta	Little River, AR
RGLS1	Amarillo	Vega Vally, TX
RGLS2	Amarillo	Kritser Fain, TX
GR	Wichita Falls	Snyder, OK
RH	Wichita Falls	Davis, OK
SS	Paris	Sawyer, OK
DL	Paris	Stringtown, OK
LS	DFW	PerchHill, Tx



(a) Typical one cycle of heating and cooling.



(b) Typical response of a concrete cylinder subjected to three heating and cooling cycles.

Figure 1: Heating and cooling cycles and response of a cylinder.

Results and Discussions

Physical Properties of Aggregates and Concrete

Oven dry specific gravity, percent absorption, compressive strength, and modulus of elasticity of coarse and fine aggregates are shown in Table 2. SG_{OD} of all the aggregates were in the range of 2.47 to 2.65. Igneous rocks (GR and RH) had the highest SG_{OD} and SS had the lowest. The lower SG_{OD} of SS may be due to the higher porosity of the aggregate. Higher porosity of SS is also supported by high absorption.

Sand stone had the highest absorption followed by LS. The rest of the coarse aggregates had absorptions close to 1.0. Sand used for concrete mixture had SG_{OD} and absorption of 2.58 and 0.6, respectively.

Table 2: Specific gravity and absorption of coarse and fine aggregate

Aggregate ID	SG_{OD}	Absorption (%)	Compressive Strength (psi) 7-day	Compressive Strength (psi) 28-day	28-day E (Million psi)
RG1	2.56	0.9	4418	5487	5.85
RG2	2.56	0.7	4415	5866	5.87
RG3	2.55	1	4441	6103	5.83
RG4	2.54	1.1	4254	5488	5.66
RGLS1	2.59	1.2	5056	6222	5.4
RGLS2	2.61	0.9	5165	5933	5.11
GR	2.61	0.7	5314	6719	4.48
RH	2.65	0.9	5090	6421	4.3
SS	2.47	2.2	5548	6831	5.52
DL	2.54	1.2	4467	5726	6.2
LS	2.58	2.04	x	x	x
Sand	2.58	0.6	x	x	x

Seven- and 28-day compressive strength and 28-day modulus of elasticity of concrete were determined for each aggregate source. No compressive strength and modulus of elasticity for LS were determined, as this coarse aggregate was intended to use only for blending purposes. Since concrete strengths for mixture designs in the average strength range are primarily controlled by the w/c and all 10 mixes used the same w/c, all specimens fell into the 4,000 to 5,000 psi range at 7 days and 5,500 to 7,000 psi range at 28 days. All the concrete mixtures satisfied the class P concrete strength requirements according to item 360 of TxDOT document Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. The modulus of elasticity varied from 5.2 to 3.5 million psi. DL had the highest E followed by RG and RGLS. Sand stone showed the lowest E, probably because of the porous structure of the aggregate. Modulus of elasticity of concrete is influenced by the E of aggregate. Because the same w/c and fine aggregate were used for all the concrete mixtures, the mortars should have very similar properties.

Coefficient of Thermal Expansion of Concrete

Figure 2 presents the COTE of concrete made from the aggregate sources used in this study. COTE values varied from 3.2 to 5.8 microstrain/^{o}F (5.8 to 10.4 microstrain/^{o}C).

Obtained COTE values are consistent with the values found in the literature (Chung and Shin 2011; Naik et al. 2011; Jahangirnejad et al. 2009; Mallela et al. 2005; M. Won 2005). RG1 had the highest COTE, and LS had the lowest. Limestone showed the lowest COTE among all the aggregate types. River gravel sources had higher COTE than the natural blend of river gravel and limestone. This is an indication of the possibility to reduce the COTE of concrete by blending lower COTE aggregates with higher COTE aggregates.

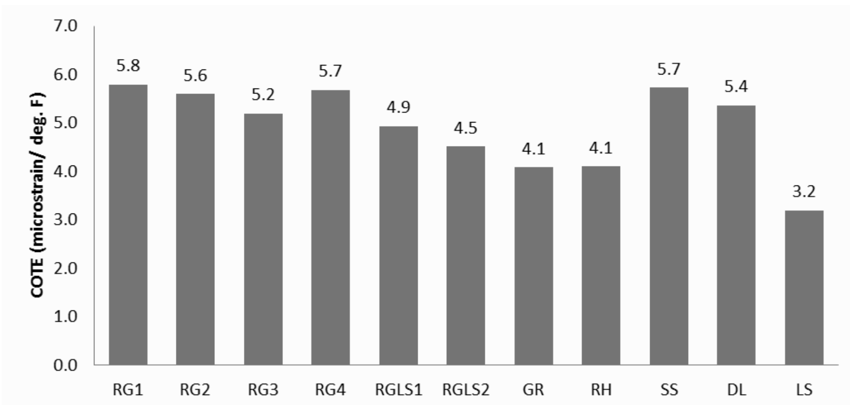


Figure 2: Coefficient of Thermal Expansion (COTE) for concrete specimens older than 28 days.

Effect of Aggregate Blending on Concrete COTE

Three different aggregate sources were chosen based on the COTE and type. Aggregate sources RG1, GR, and DL were blended with limestone at replacement level of 20, 50 and 80% by volume. Figure 3 shows the effect of blending on the change of concrete COTE. According to Figure 3 the relationship between concrete COTE and percent replacement was linear. Also the relationship is in good agreement, because the coefficient of determination (R^2) values for all the three blends are close to 1.0. Though limestone was used for all three cases, any low COTE aggregate could be used in blending to reduce concrete COTE. Rate of change of COTE (slope of line) is also proportional to the difference of the COTE of two aggregate sources used in the blend. Therefore, the degree of replacement has to be selected based on the target COTE and the difference of COTE between the two blended aggregates.

All the concrete mixture used in this study used same mixture proportioning. The linear relationship between COTE of concrete and percent replacement is only applicable for concrete with the same mixture proportions. As a result, while selecting a replacement level to obtain a target COTE for a particular concrete mixture, the COTE of base aggregate and replacement aggregate has to be determined using the same mixture proportioning as the target concrete. Achievable target COTE of concrete cannot be higher or lower than the COTE of aggregates used in the blend.

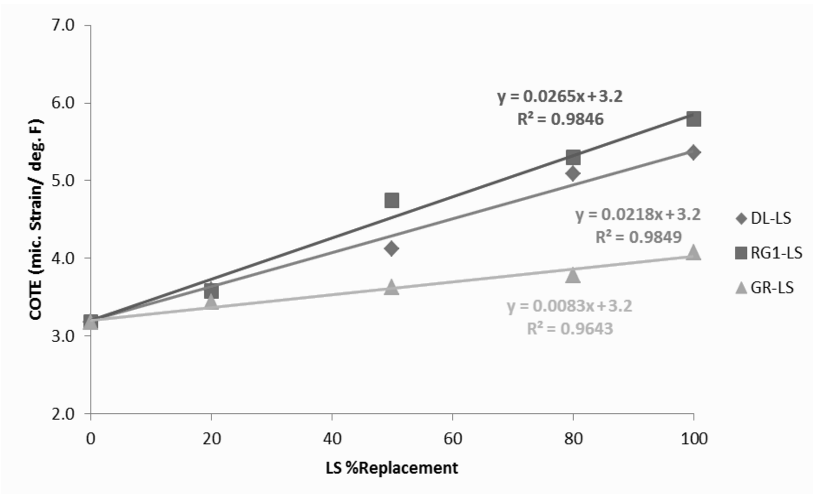


Figure 3: Relationship of change in concrete COTE with limestone %replacement.

Conclusions

Coefficient of thermal expansion is an important property of pavement concrete due to its association to the pavement distresses caused by the environmental loading. TxDOT has been recognizing COTE as one of the potential causes of pavement distress for long time. To avoid these types of pavement distress, TxDOT increased the thickness and reinforcement of CRCP pavement. In addition to those design modifications, some districts also limited the COTE of aggregates for the CRCP concrete. Recent statewide COTE limit in Texas prevents use of high COTE aggregates in CRCP projects. In addition to that some districts those do not have aggregate sources with acceptable COTE, but have high volume CRCP, have to haul acceptable aggregates form longer distances. This is limiting the use of locally available good quality aggregates and also increasing the project cost due to additional transportation cost. This study documented a potential way to reduce the COTE of concrete by blending low COTE aggregates with high COTE aggregates. This method is also promoting the sustainable use of locally available good quality aggregates. This study was done focusing the need of Texas, but the findings are implementable nationwide. Important findings of this study are listed below:

- Obtained COTE values were between 3.2 to 5.8 microstrain/^{o}F (5.8 to 10.4 microstrain/^{o}C). These values are in good agreement with the COTE values obtained in previous studies.
- Aggregate type has significant influence on the COTE of concrete. The lowest COTE was obtained for limestone, and the highest for river gravel which is also in a good agreement with previous studies.
- The COTE of concrete was reduced by blending low COTE aggregates with high COTE aggregates. Change of concrete COTE of blended aggregate is linearly related to the percent replacement. The degree of replacement necessary to achieve a target COTE depends on the difference between the COTE of two blended aggregates.

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Treatment of Highway Runoff using the Permeable Friction Course (PFC)

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ABSTRACT

Concern about the environmental impacts of highway runoff has led many regulatory agencies to require its treatment prior to discharge. An emerging technology for treating highway runoff is the Permeable Friction Course (PFC). PFC consists of a layer of porous asphalt approximately 50 mm thick placed as an overlay on top of an existing conventional surface. The objective of this paper is to demonstrate the effectiveness of PFC on highways with curb and gutter systems. Data from two sites on an urban Texas highway are presented. Observed concentrations of pollutants were much lower in the runoff from the PFC than from the conventional asphalt. The reduction in total suspended solids concentration was about 92%. A comparison with the discharge quality observed from media filters is also included that indicates equal or better pollutant removal on PFC highways. A comparison of water quality from various pavement mixes and shoulder types demonstrates that PFC can be effective under many different conditions.

INTRODUCTION

Permeable friction courses have been installed on highways to improve safety and reduce noise. The water quality benefits are more recently becoming understood and appreciated. Many of the initial investigations on the water quality of runoff from porous pavements were conducted in Western Europe. Stotz and Krauth (1994) analyzed runoff from a 40-mm thick porous asphalt section in Germany over the course of a year. Yearly pollutant loadings from impervious highway runoff in a previous study were used for constituent comparison. A reduction in the filterable solid loads of 50% was found.

In France, (Ranchet 1995) investigated the impact of a porous overlay on runoff quality over a period of two years. The research was conducted at both an urban site and a divided freeway. At the urban site, runoff from both a PFC section and an impervious stone-matrix section were sampled and tested for contaminants. An 87 % reduction in lead was seen at the urban site. At the freeway site, samples were taken and compared from both a conventional pavement section and a PFC overlay. A 62% and 67% reduction in total copper and total zinc respectively was found. Total suspended solids (TSS) was less affected, with a reduction of only 7%. The reduction values in this study are lower than many later studies; this may be due to the orientation of the freeway as the wind is likely to transfer pollutants from the impervious lanes onto the pervious asphalt pavement at the location.

Berbee et al. (1999) also compared runoff water quality from a 50 mm thick overlay and a conventional pavement surfaces in the Netherlands. The highways were similar, although more traffic was present on the porous overlay section. Runoff was collected in a gutter over 1-week periods and then analyzed for pollutant concentrations. The results showed significantly higher reductions in pollutant concentrations than the study conducted by Ranchett (1995). TSS concentrations were 91% lower, total Kjeldahl nitrogen (TKN) 84% lower, and heavy metals ranged from 67% to 92% lower than in runoff from the conventional asphalt pavement.

Another French highway was studied by (Pagotto et al. 2000) before and after the placement of a 30 mm thick porous overlay. This study examined both total and dissolved metals. A decrease in concentration for all the constituents of concern was observed. TSS was reduced by 81%, total metals were reduced between 33% and 78% and dissolved metals were reduced between 16 to 61%. Pagotta et al. (2000) assumed that the removed solids were physically filtered out and contained in the pore space of the pavements. The dissolved metal species were assumed to have adsorbed onto the pavement.

In recent years, US agencies have started to appreciate the potential that porous overlays offer as a water quality best management practice (BMP). Eck et al. (2012) published data from a study of three locations in Texas and four locations in North Carolina. The combined data spanned 10 years and showed similar TSS concentrations across the board. Eck concluded from the study that the stormwater benefits of PFC last for at least a design life of 10 years. The seven sites investigated had vegetated shoulders running along the pavement.

Most studies conducted on urban PFC occurred on highways with vegetated shoulders. While no research was found concerning PFC on curbed section, past studies suggest that pollutants can build up on the roadside and effect water quality in the presence of curbed sections. Stotz (1987) conducted research on three German highways, two with an impermeable system of curbs and sewers and one that included a catchment area drained through grass-covered ditches. Stotz concluded that drainage methods were more important than pavement type in determining the quality and quantity of highway runoff.

Other researchers came to similar conclusions when investigating stormwater runoff from traditional pavements. Sartor and Boyd (1972) found that the highest concentration of solids is in the gutter since the curb forms a barrier to any particles moving transversely. Likewise Burch et al.(1985) suggested that without curbs, wind and turbulence was likely to remove much of the fine materials from the road. One goal of this research is to determine if curbs and gutters negatively affect pollutant removal by PFC.

This paper presents data from two urban highway sites in Texas paved with PFC in 2010. Samples were taken over the course of two years and tested for a variety of common stormwater constituents. The water quality data was compared to previously collected data at a nearby conventional pavement site on the same highway. This research adds to the current understanding of PFC in two ways. The effect of pavement binder composition on water quality is investigated by comparing the water quality at two sites with different asphalt mixes. In addition the effect on pollutant reduction of a curb and gutter which collects contaminants is evaluated by comparison with the reduction values published by Eck et al. (2012).

MATERIALS AND METHODS

Experimental Set-Up and Operation. An analysis of storm water runoff from conventional asphalt at the 35th street overpass along the Mopac freeway was completed by Barrett et al. (1998) at The University of Texas at Austin for TxDOT. The two PFC sites selected for this study are located a few blocks north of the previous conventional asphalt study; between 35th and 45th Streets in Austin, Texas. Mopac is a highway with a curb and gutter section that was paved with a 1.5” thick PFC overlay in 2010. Two different asphalt binder mixtures were used on the north and southbound lanes. This gives us the option to compare the water quality results from mixtures with different compositions and hydraulic conductivities. A satellite image of the sites is presented in Figure 1.

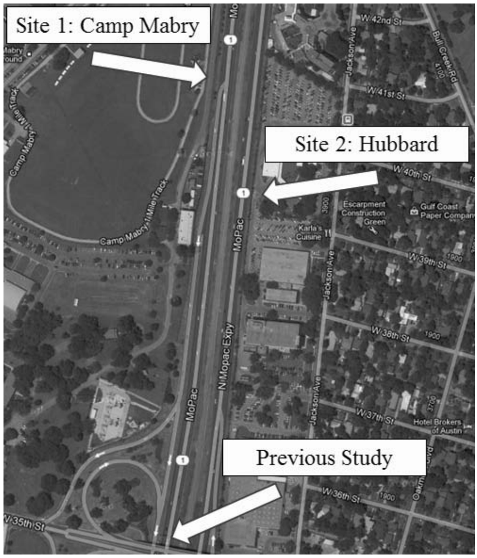

Figure 1. Satellite Image of sites on Mopac (Google Maps, 2013)

The sites are located off of exit lanes and the equipment is kept inside the fence lines of government facilities providing safe storage and accessibility. Monitoring equipment was installed and sampling began in November 2010 for both PFC sites. Automatic Samplers were used and flow weighted samples were taken for a total of 32 storms. In between storms, clean sampling containers were placed in each sampler, the equipment was reset, and debris was removed from the rain gauge. The day before an expected storm, an air blower was used to clear the gutter in the immediate vicinity of the equipment to prevent flow obstruction, and downstream to prevent ponding. The tubing and strainer were checked and re-secured in the correct location if necessary. During storms, the sites were observed if possible and maintenance was performed to fix any problems.

After a storm event, lids were placed on the collected samples and the containers were exchanged. The samples were then taken to the Lower Colorado River Authority (LCRA) lab in Austin for analysis. If the lab was closed, the samples were stored at CRWR in a 4°C room and delivered as soon as the lab was open. Samples were analyzed using EPA methods for Total Suspended Solids (TSS), Total Kjeldahl Nitrogen (TKN), NO_2/NO_3, and total and dissolved forms of phosphorus, copper, lead, and zinc.

Statistical Analysis. The water quality data from both the Camp Mabry and Camp Hubbard sites were compared to the previous studies data retrieved from Barrett et al. (1998) along Mopac. A Mann-Whitney test was conducted since the two groups are independent. The Mann-Whitney test was also selected over the two sample t-tests assuming unequal variance because it is nonparametric and avoided assumptions regarding the distribution. A confidence interval of 95% was used for this research, requiring a p-value less than 0.05 to indicate statistical significance. Observations below the reporting limit were replaced with the detection limit for all statistical procedures. This provides a conservative estimate of the differences between medians and minimizes the chances of detecting a significance that does not exist (Type 1 Error).

One focus of this study was to compare the water quality impacts of the two mix designs used at the sampling sites. Camp Mabry uses a Performance Graded Binder (PG-76), and Camp Hubbard uses an Asphalt-Rubber Binder (A-R). A statistical comparison was also conducted between these two groups to determine if there was any significance between the water quality at the two sites. The Wilcoxon signed rank test was selected for this analysis since the samples were paired. This test is also nonparametric and used a confidence interval of 95%.

The effect of a curb and gutter on PFC efficiency was evaluated by comparing the reductions of contaminants between this study and the previous Texas PFC study published by Eck et al. (2012). Reductions for individual contaminants were calculated for each of the five test sites based on the median concentration for the PFC and the corresponding conventional control. Median was selected over mean because it is a more robust parameter that minimizes the importance of extreme values.

RESULTS AND DISCUSSION

The individual concentrations of all 12 constituents for each storm along the PFC test segment of Mopac were compiled for both sites and statistical parameters were analyzed. The water quality results from this study were then compared with the previous conventional pavement values from the conventional asphalt stormwater study along Mopac (Barrett et al. 1998). The data from Camp Mabry was also compared to the data at Camp Hubbard to analyze the effect of the different binder compositions on water quality. Lastly, a comparison of the reduction values from this study and the previous PFC study completed by Eck et al. (2012) is presented to determine the effect of a curb and gutter on pollutant reduction. A discussion of the overall performance based on this study is also included.

Mopac Monitoring Results. Stormwater monitoring along Mopac occurred between 1/09/2011 and 10/11/2012. Over the course of the study, 30 storms were sampled and analyzed at Camp Mabry and 31 at Camp Hubbard. The mean, median, standard deviation and range for concentrations of each constituent monitored at Camp Mabry can be seen in Table 1. The TSS data has a mean of 34 with a standard deviation of 47.2. The large range of TSS data is due to a period of sampling in 2011 where maintenance on the vegetated shoulder nearby may have caused increased debris.

Table 1: Summary Statistics of the Concentrations at Camp Mabry

Constituent	Mean	Median	Standard Deviation	Range	Units
TSS	34.1	11.95	47.2	3.4-162	mg/L
TKN	1.496	0.9935	1.946	0.228-10.9	mg/L
NO_3^-/NO_2^-	0.350	0.267	0.283	0.02-1.45	mg/L
P_{total}	0.168	0.089	0.310	0.02-1.7	mg/L
$P_{dissolved}$	0.07	0.0235	0.58	0.02-0.812	µg/L
Cu_{total}	18.8	12.7	16.5	4.08-84.2	µg/L
$Cu_{dissolved}$	13.1	9.4	9.1	4.7-40.8	µg/L
Pb_{total}	3.16	1.63	3.92	1-19.1	µg/L
$Pb_{dissolved}$	1.13	1	0.58	1-4.1	µg/L
Zn_{total}	53	37.4	54	15.8-276	µg/L
$Zn_{dissolved}$	29	19.95	35	12-183	µg/L

The same statistics were calculated for each constituent at camp Hubbard and are presented in Table 2. The range of TSS at this site was also increased during the period of maintenance, however since the maintenance was on the south bound side of the freeway, less debris ended up near Camp Hubbard.

The data was also compared to the conventional pavement data and reductions for each constituent were calculated based on the median concentration. The median was selected over the mean because the distribution of each constituent was skewed as a result of outliers. The results of this comparison for both sites can be seen in Table 3. The median concentrations for the conventional pavement site are also presented.

A Mann-Whitney test was performed to determine if the difference in the medians of each sites water quality data compared to the conventional data could be seen as statistically significant. The p-values calculated for each constituent at both sites were all 0.0001 or lower and all well below 0.05, indicating significance within a 95% confidence interval. The TSS value which is often used as a surrogate for all constituents of concern in highway runoff was found to be reduced by 92% at both sites. TSS is a constituent of particular concern because TCEQ requires new land developments to remove 80% or more of TSS before discharging (Texas Administrative Code. 2005). This value easily exceeds the reduction requirement, supporting the recent decision to add PFC as an accepted Best Management Practice (BMP).

Table 2: Summary Statistics of the Concentrations at Camp Hubbard

Constituent	Mean	Median	Standard Deviation	Range	Units
TSS	20.8	12	18.8	4.0-76.5	mg/L
TKN	1.336	0.937	1.188	0.305-6.32	mg/L
NO_3^-/NO_2^-	0.385	0.301	0.268	0.044-1.44	mg/L
P_{total}	0.114	0.064	0.114	0.02-0.457	mg/L
$P_{dissolved}$	0.05	0.02	0.31	0.02-0.3	µg/L
Cu_{total}	19.3	13.1	18.5	3.83-100	µg/L
$Cu_{dissolved}$	13.6	9.4	13.4	3.2-70.1	µg/L
Pb_{total}	3.30	2.4	2.56	1-9.57	µg/L
$Pb_{dissolved}$	1.06	1	0.31	1-2.7	µg/L
Zn_{total}	124	85.8	123	34.3-665	µg/L
$Zn_{dissolved}$	85	51.3	107	20.4-566	µg/L

Table 3: Concentrations and Reductions at Both Sites

	Median Concentration			Percent Reduction	
Constituent	Conventional	Camp Mabry	Camp Hubbard	Camp Mabry	Camp Hubbard
TSS (mg/L)	152.0	12.0	12.0	92	92
NO_3^+/NO_2^- (mg/L)	0.7	0.3	0.3	61	56
Total P (mg/L)	0.5	0.1	0.1	81	86
Total Copper (µg/L)	50.0	12.7	13.1	75	74
Total Lead (µg/L)	130.0	1.6	2.4	99	98
Total Zinc (µg/L)	285.0	37.4	85.8	87	70

Binder Comparison. One focus of this study was to compare the water quality impacts of the two mix designs used at the sampling sites. Camp Mabry uses a Performance Graded Binder (PG-76), and Camp Hubbard uses an Asphalt-Rubber Binder (A-R). The pavement with A-R Binder had a hydraulic conductivity of 0.76 in/s compared to the PG-76 Binder with higher hydraulic conductivity of 2.14 in/s.

A statistical test was performed for all the constituents to see if there was any significance between the two sites. The Wilcoxon signed rank test was selected over the Mann-Whitney test because paired occurrences were present. Storms that were analyzed at only one site due to complications with one of the samplers were removed from the comparison. The p-values are shown in Table 4. Once again significance was indicated by p-values less than 0.05.

Table 4: Binder Comparison Statistics

Constituent	Median Concentration		P-Value
	Camp Mabry	Camp Hubbard	
TSS (mg/L)	11.95	12	0.4247
NO3+/NO2- (mg/L)	0.2665	0.301	0.209
Total P (mg/L)	0.089	0.064	0.281
Total Copper (µg/L)	12.7	13.1	0.484
Total Lead (µg/L)	1.63	2.4	0.0869
Total Zinc (µg/L)	37.4	85.8	<0.0001
Dissolved P (mg/L)	0	0	0.3632
Dissolved Copper (µg/L)	9.4	9.4	0.352
Dissolved Lead (µg/L)	1.0	1.0	0.492
Dissolved Zinc (µg/L)	20.0	51.3	<0.0001

Out of the 10 constituents, only total and dissolved zinc showed a significant difference in concentration. Not only are the median concentrations higher at Camp Hubbard, but Figure 2 shows that the same is true for each individual storm event. One explanation for the higher zinc concentrations observed at Camp Hubbard is related to the asphalt binder used. The A-R Binder used on the Camp Hubbard lanes contains recycled tires. Tires contain about 20 different types of metals. Zinc is present in particularly high amounts, since zinc oxide is used in the vulcanization process. Tire-tread material has a zinc content of about 1% by weight (ISS, 2008).

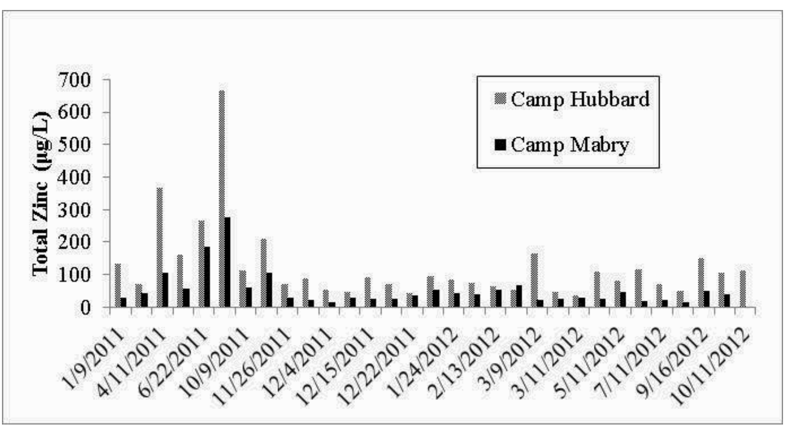

Figure 2. Total Zinc for Individual Storm Events

Curb Type Comparison. While other water quality studies of PFC have been conducted in the past, they were typically completed on roadway segments with vegetated strips along the shoulder. This study investigated a section of Mopac with a curb and gutter system which addresses the concern that curbs contributes to accumulation of debris affecting water quality. The reduction values from this study are presented in Table 5 along with the values obtained from a similar study published by Eck et al. (2012). Eck's research was conducted along highways 360 and 620 in Austin Texas. Both these highways have vegetated shoulders instead of curbs and gutter systems. The values in the table are averages from the three sites studied by Eck et al. (2012) and the two sites from this study.

Table 5: Reduction Values for Two Curb Types

Constituent	**Average Reduction**	
	Vegetated Shoulder	Curb and Gutter
TSS (mg/L)	93	92
NO_3/NO_2 (mg/L)	-28	59
Total P (mg/L)	71	84
Total Copper (µg/L)	62	74
Total Lead (µg/L)	92	98
Total Zinc (µg/L)	87	78

The reduction values for NO_3/NO_2, total phosphorus, total copper, and total lead are higher for the curb and gutter system. The TSS reduction is just slightly lower than the reduction from the previous study. Total zinc is the only constituent that shows any real decrease in efficiency and this could be due to the asphalt rubber binder used at Camp Hubbard. Total zinc at Camp Mabry was reduced by 87%, the exact amount reduced on average at the vegetated shoulder sites. While these studies were conducted for different storms and traffic loads, the results suggest that a curb and gutter system does not hinder the ability of PFC to improve water quality.

Overall Performance. The data gathered from the monitoring of Mopac agrees with former studies conducted in the US and across Europe. Insight on the effect of binder composition and curb configuration is also provided by the study. The water quality results are shown to be consistent and can be compared with the performance of other highway stormwater treatment practices.

Sand filters are the current standard treatment method for reducing TSS and other pollutants from runoff in Austin, Texas. The performance of 5 Austin sand filters was evaluated for TSS, Total N, and many heavy metals by Barrett (2003). A comparison of the PFC along Mopac to the removal capabilities of the Austin sand filters is presented in Table 6.

Table 6: Comparison of PFC to Austin Sand Filter

Constituent	Sand Filter	PFC
TSS (mg/L)	89	92
NO3+/NO2- (mg/L)	17	59
Total P (mg/L)	59	84
Total Copper (µg/L)	72	74
Total Lead (µg/L)	86	98
Total Zinc (µg/L)	76	78

Sand filters are effective at treating runoff but require extra land and extended time. PFC is able to reach and exceed levels of treatment for the constituents monitored in this study but incorporates the treatment into the roadway surface without additional right of way or construction. Maintenance is also limited only to resurfacing that would already occur on traditional roadways.

CONCLUSIONS

Over a period of two years, 32 storms have been monitored at Camp Mabry and Camp Hubbard. The results show a reduction in the concentration of TSS, NO3+/NO2- , total phosphorus, zinc, lead and copper. The median TSS removal observed on Mopac was 92%, easily exceeding the expectations as a Best Management Practice (BMP) for highway treatment of stormwater runoff in the Austin area. Two different binders were used in the mixes at the test site along Mopac. The performance graded binder had a higher hydraulic conductivity allowing water to move more easily into and through it, while the asphalt-rubber binder produced more sheet flow. The only statistically significant difference in water quality between the binders is that the runoff from the asphalt-rubber binder contained higher concentrations of total and dissolved zinc. This is likely from the zinc composition of the material itself.

Most previous studies on the effects of water quality with PFC installation investigated highways with vegetated shoulders. This study was conducted at sites with a curb and gutter between the roadway and vegetation. The presence of a curb and gutter did not hinder overall pollutant removal when compared to previous studies. However, debris accumulation is more likely when curbs are in place, which can cause pollutant buildup if the roadway is not properly maintained. Despite the safety and water quality benefits of PFC, many agencies throughout the US are cautious about installing PFC on highways. Test sections, such as the strip along Mopac, are being used to address these concerns and further understand the benefits.

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Removal of Dissolved Heavy Metals in Highway Runoff

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Abstract

The focus of this project is the assessment of the potential for sorption to reduce the concentration of dissolved heavy metals in runoff. One difficulty in evaluating adsorption in multi-component systems is to capture the impacts of background organic matter and other complexing ions on adsorption behavior. A compromise between using natural and synthetic storm water in this evaluation was therefore made by recognizing the importance of capturing the organic matter from natural storm water, but adding the flexibility of using laboratory chemicals to provide the inorganic constituents. To alleviate concerns associated with storing large volumes and aging of organic solutions, 1000 gallons of storm water was collected and then concentrated by a factor of 150 using reverse osmosis. It was then freeze-dried. The freeze-dried organic matter was reconstituted as needed at concentrations that mimic the initial total organic concentration of the stormwater when it was collected. A series of column experiments were then run using iron oxide, manganese oxide, Portland cement concrete and crab shell waste as sorbents. Factors that were evaluated included organic matter concentration, competition between metal ion species (copper and zinc), pH and ionic strength. The results of the column experiments indicate that iron oxide provides substantially better removal of dissolved metals than manganese. Portland cement concrete and crab shell waste were both found to be effective at controlling pH, which is the largest factor in determining dissolved metal removals. These experiments indicate that use of iron oxide augmented with either concrete or crab shell is potentially a cost effective way to remove dissolved metals in highway runoff.

Introduction

This paper describes the laboratory testing of various materials to determine their capacity for reducing the dissolved metals concentration in storm water. The first objective of this work was to develop a standard protocol for evaluating effectiveness of various processes for treating highway runoff. A literature review suggested that adsorption is the most promising technology for removal of metal ions from highway runoff, and the most appropriate adsorption media identified were oxide minerals, calcite based minerals and/or chitin based media (a waste material). Since the most promising application of these media may be a combination of media that includes oxide minerals for maximum adsorptive capacity combined with a calcite containing media such as limestone based Portland cement concrete (PCC) for pH control, various combinations of these media were tested.

A significant amount of research progress has been made with respect to collecting equilibrium adsorption data for metal ions on oxide minerals in well-defined solution matrices. These data provided a substantial head start for this project as they define a baseline of adsorption properties in well-defined systems. However, the major challenge that remained was to determine how well the results obtained from these well-defined systems are able to predict adsorption in the multi-component systems defined by highway runoff.

The difficulty associated with predicting adsorption in multi-component systems is to capture the impacts of background organic matter and other complexing ions on adsorption behavior. Very few studies have evaluated the ability of surface complexation models to predict adsorption in systems that contain natural organic matter from highway runoff. Consequently, the series of experiments described included some with and without organic matter and at various pH and ionic strengths.

Material and Methods

One of the goals of this project was to identify a means of conducting experiments with organic matter from actual highway runoff events while overcoming concerns of variability in water quality from different stormwater events and changes in stormwater composition during the course of the experimental system. To overcome these challenges, this research utilized an organic matter isolation approach developed by Pressman et al. (2010) in which organic matter is pretreated to remove suspended solids and cations, and then concentrated in a reverse osmosis system. This section describes this approach to concentrate organic matter.

Concentration processes employing reverse osmosis require significant pretreatment to prevent fouling of the reverse osmosis membrane. As a result, prior to concentration, pretreatment must remove suspended solids and excess ions from the water. In some cases, if the material is to be freeze-dried and the concentrate contains sulfate, sulfate precipitation may be required as well (Serkiz 1990; Maurice 2002; Pressman 2010).

The pretreatment process consists of filtration followed by ion exchange. A schematic of the process is shown in Figure 1. This can be accomplished using in-line water filters. Due to the variation in particle size in stormwater, a step-wise filtration process is justified. Previous research has shown that triple filtration accomplished using a series of three progressively smaller in-line filters is sufficient to remove suspended solids, maintain flow, and reduce system pressure (Serkiz et al. 1990; Maurice et al., 2002). The resulting water after passing through the 0.45

micron filter should be free of all suspended solids (TSS) and consist only of dissolved solids (TDS). It is important to note that the TDS includes both organic and inorganic compounds. Inorganic compounds adsorbed onto suspended solids may have been lost in this process, but the loss of organic anions is likely minimal.

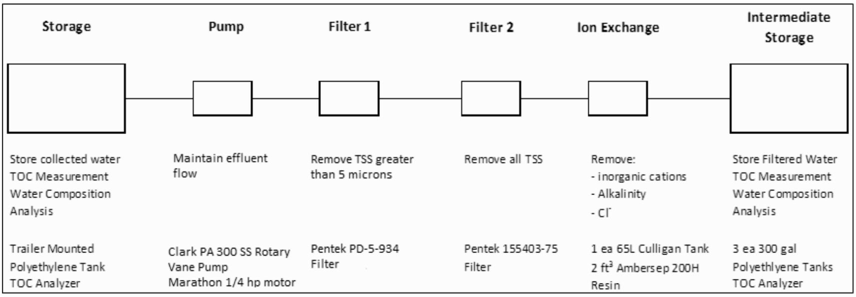


Figure 1. Schematic diagram of the organic matter pretreatment process using filtration and ion exchange. Specific brands of equipment are provided as examples.

Following the removal of suspended solids (TSS) from the water sample via filtration, the water sample is passed through an ion exchange resin to remove inorganic cations and isolate the organic anions. Since the objective is to isolate the organic anions in the water sample a hydrogen ion (H+) form macroporous resin is used to remove inorganic cations.

Selecting the appropriate ion exchange resin is critical to the successful removal of inorganic cations and, therefore, to the successful concentration of dissolved organic matter (DOM) through reverse osmosis. Many types of resin are available on the market. For this application, it is generally agreed that macroporous resins are more effective and pose less of a threat to the integrity of the organic matrix than gel type resins (Serkiz 1990; Speth 2008; Pressman 2010). One of the key design parameters for successful ion exchange is empty bed contact time (EBCT), which is calculated by dividing the resin container volume by the flow rate. EBCTs between 5 and 30 minutes are typical for ion exchange processes.

Concentration of the dissolved organic matter is accomplished using reverse osmosis operated in a recycle mode as shown schematically in Figure 2. This membrane process is typically used to remove ions from water and provide ion free water for consumption or use. The concentrate stream containing the ions is then disposed. However, in this case, the goal is to utilize the concentrate flow. As the feed water passes through the reverse osmosis membrane, the organic constituents are retained in the concentrate flow and constituent free water flows in the permeate stream. Thus, the permeate stream is wasted in our system and the concentrate flow is recycled back to the feed and the system run in recycle mode until the desired concentration factor is achieved. During this process, the concentration of organic matter in the recycled feed water steadily increases as the constituent mass is retained and the “clean” water is wasted as permeate.

In the practical sense, several design and operation parameters can be manipulated to maximize permeate flow and constituent rejection to achieve optimal results depending on the operation. The primary parameters that are easily modified to meet the system requirements are the number, size, type, and alignment of membranes and the influent, permeate, and concentrate flow rates.

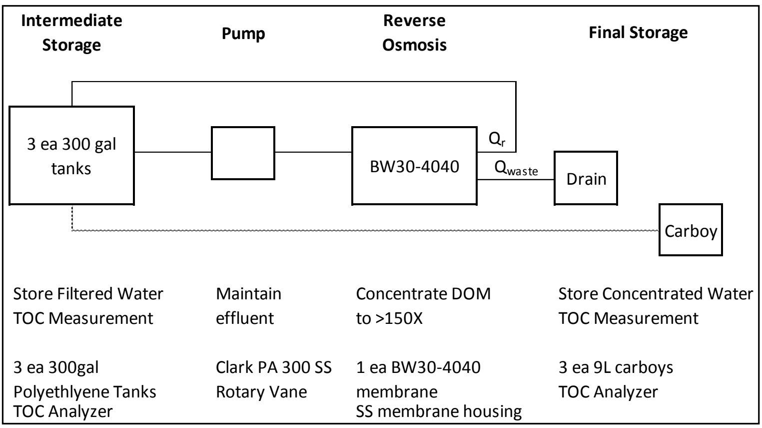


Figure 2. Schematic view of the concentration process using one Filmtech BW30-4040 membranes.

The type and size of the reverse osmosis membrane control the rejection properties and membrane surface area of the system. For this application, a brackish water membrane provides the tightness and pressure rating required to concentrate the DOM. The reverse osmosis system is capable of achieving concentration factors for the organic matter of approximately 150X. This material may be used in this form, further purified through electro-dialysis, or freeze-dried and stored for future use.

The organic matter represents only one component of the highway runoff composition. The inorganic composition of the water to be used in experimental evaluation must also be selected to match conditions anticipated in the field. The stormwater recipe created to match the composition and ionic strength of literature values is detailed in Table 1 below.

A previous review of the literature identified a variety of media that offered promise for substantial dissolved metals removal in highway runoff. These include:

1. Iron and manganese oxides have demonstrated the highest potential for adsorbing the range of metals observed in highway runoff. Therefore, commercially available forms of these oxide metals were evaluated as well as mixtures containing both types of media.

2. Concrete materials and calcite offer the possibility of providing adsorptive capacity as well as pH buffering. Both of these materials were assessed for their potential for adsorption of metal ions. While calcite represents a well characterized and less variable material, concrete provides the opportunity to recycle waste materials.
3. Crab shell has also been shown to have potential for removal of metal ions from storm water due to the presence of chitin and calcium carbonate. Thus, these sorbents should be evaluated for their potential to synergistically promote adsorption of metal ions.

Table 1. Synthetic stormwater composition

Lab Salts	g/mol	{Conc} mg/L	Measured Mass (mg) / 40L Batch Solution
$MgSO_4 \cdot 7H_2O$	246	55	2,200
KCl	74.5	25	1,000
KNO_3	101	90	3,600
$NaNO_3$	85	90	3,600
$CaCl_2$	111	200	8,000
$CuSO_4 \cdot 5H_2O$	249.5	0.196 (0.050 Cu)	From Concentrate
$ZnSO_4 \cdot 7H_2O$	287.6	0.440 (0.100 Zn)	From Concentrate

Two iron oxides and two manganese oxides were obtained commercially and the two waste products, crab shell and concrete, were obtained locally. The basis for selecting the oxide minerals included previous use as an adsorbent for metal and oxyanion sorption, commercial availability, and availability in particle diameters suitable for the experimental column and field conditions. The mineralogy of the iron and manganese oxides were similar; however, they were purchased through two different sources. The two sources of goethite based oxide mineral were obtained from Bulk Reef Supply and AdEdge Inc. The manganese oxide minerals were MTM (Northern Media Company) which contains a granular core with a coating of manganese dioxide and a similar product provided by Pureflow PM-200 manganese dioxide.

The Portland cement concrete used in the experiments was obtained from a recycling facility in the Austin area and the crab shell was purchased from DirtWorks (www.dirtworks.net), where it is sold as a soil amendment/fertilizer. The crab shell waste was chosen because crab shell is known to contain calcite and chitin. Calcite can be used to increase the pH of the stormwater and chitin exhibits adsorptive properties for metal ions.

All filtration media used were sieved to particle diameters between 0.25mm to 0.40mm (Sieve sizes 60 and 40) which meets the criteria that the diameter of the particles be at least 30 particle diameters smaller than the column internal diameter. Media diameter can be controlled either by crushing the media to the appropriate size or sieving the material to the appropriate diameter.

The essential components of the column experiments include an influent storage tank, a pump or system configuration that provides constant flow, a means of maintaining constant pH and water chemistry of the influent, and influent and effluent sampling ports for analysis of flow rate, pH, metal ion concentrations, and TOC as required (Figure 3). It is often desirable to run columns in parallel so as to allow evaluation of different media using the same influent water composition. The experimental columns used in this research were constructed from Teflon components.

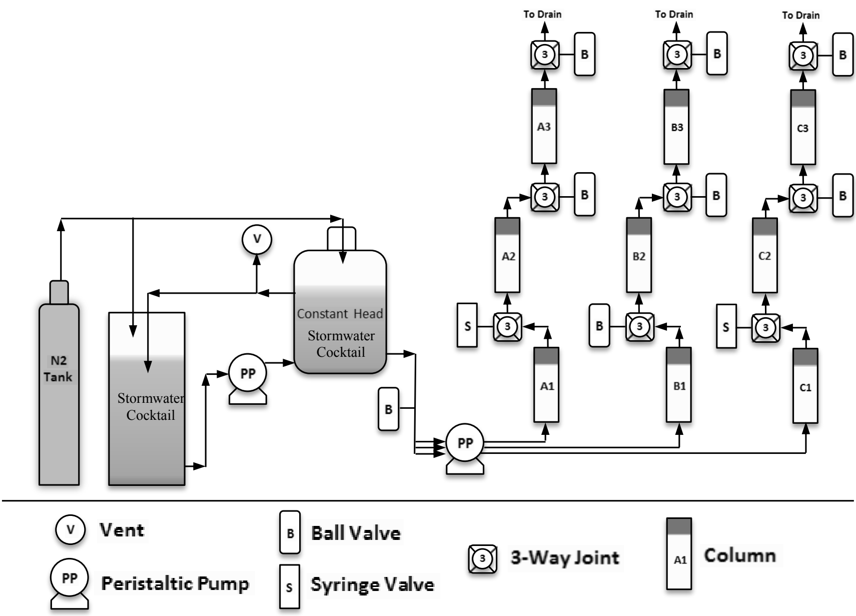


Figure 3. Experimental column setup (not to scale)

Results

Selected results from column experiments conducted in this research are presented to highlight several different key issues including the ability to distinguish performance of different media for different metal ions, sensitivity of removal to changes in pH, the role of organic matter, the role of ionic strength, and the potential benefits of dual media systems.

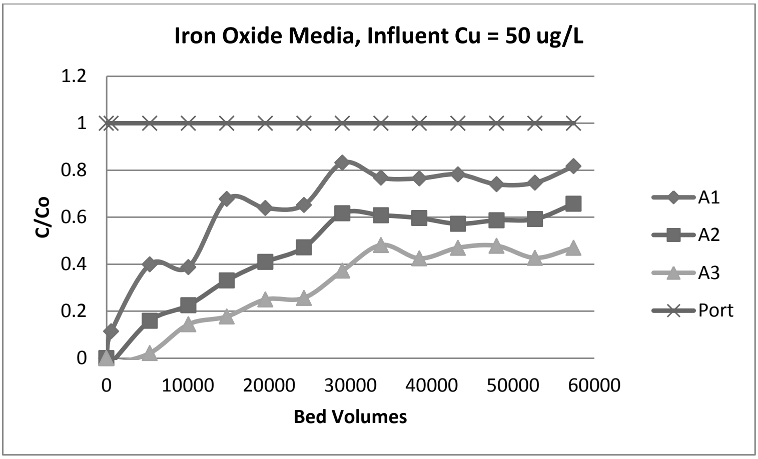
The capacity of each type of media to adsorb copper or zinc was determined by measuring the difference in influent and effluent concentrations over the course of each run (until breakthrough or a plateau was observed). By the principle of mass balance, the metal not accounted for in the effluent stream was attributed to adsorption by the media.

The coefficients of adsorption, K_D, were calculated by dividing the mass capacity of each bed by the concentration of solution in equilibrium with the media. In cases where the column achieved breakthrough, this calculation was straightforward since the equilibrium concentration was simply the influent concentration to the column. However, in cases where a plateau was observed at lower-than-influent concentrations the equilibrium concentration of the solution was assumed to be the average between the true influent concentration and the effluent concentration of the observed plateau. This assumption stems from the hypothesis that the observed plateaus are a result of precipitation processes occurring within the column, hence lowering the apparent effluent concentration while potentially maintaining higher metal concentrations within the column itself.

Figure 4 and Figure 5 show the results for sorption of copper and zinc using granular ferric oxide obtained from Bulk Reef Supply in column train A and MTM granular manganese dioxide from Northern Media Company in column train B. Two significant points are evident in comparing the effluent breakthrough profiles and the pH data collected from these columns. The iron oxide media performs significantly better than the manganese dioxide media. Complete breakthrough of copper occurs in the manganese dioxide columns at approximately 20,000 bed volumes. In contrast, copper breakthrough profiles plateau at 80 percent, 60 percent and 40 percent in the three sequential columns, A1-A3. This behavior suggests that adsorption is not the only removal mechanism in the iron columns and suggests that copper precipitation is occurring within the bed. In contrast, zinc adsorption reaches complete breakthrough for both media. Since copper is significantly less soluble than Zn, the dramatic differences in the results are not surprising.

In a separate experiment, reconstituted organic matter was added to the synthetic stormwater solution containing salts and adjusted to a pH of approximately 6. Results from these experiments for the iron oxide media are shown in Figure 6 for the 3 columns, A1-A3. For all three columns in series the initial breakthrough in columns with and without organic matter appears similar; however, the plateau obtained as breakthrough occurs in each case is at a higher value of C/Co indicating lower Cu removals. In fact, in the presence of organic matter almost complete breakthrough is achieved for column A1, the first column in the treatment train. The reduced removal of copper could be due to the presence of organic matter complexation with the copper which reduces the extent of copper precipitation.

The strong effect of pH on column performance suggests that a media that both increases and stabilizes column pH would yield improved performance in the field. Two different media were tested in this research to assess whether performance could be improved by adding pH stabilizing media to the front of the treatment system. Experiments were conducted by adding either crushed crab shell or concrete to the first two columns in the treatment train (columns C1 and C2). The addition of the crab shell particles initially had a dramatic impact on increasing pH and removal of zinc. In fact, the crab shell itself appears to outperform the manganese dioxide. The addition of crab shell waste had less impact on copper removal in the column experiments. Regardless, it appears that the presence of a pH stabilizing material is beneficial in the design of a passive treatment system for metal ion removal.



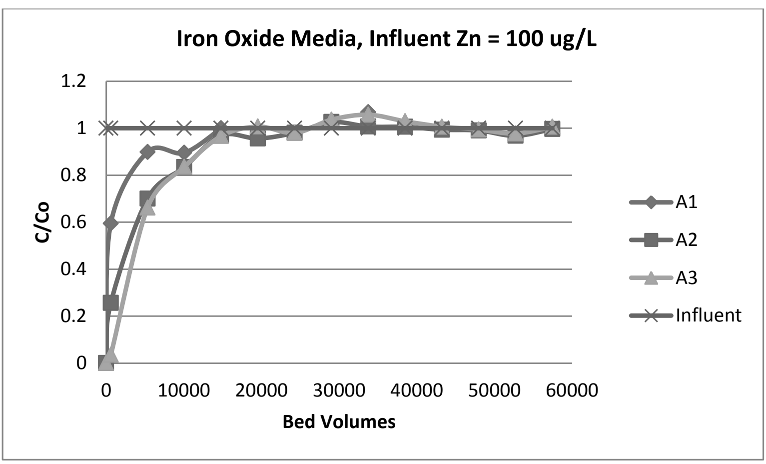
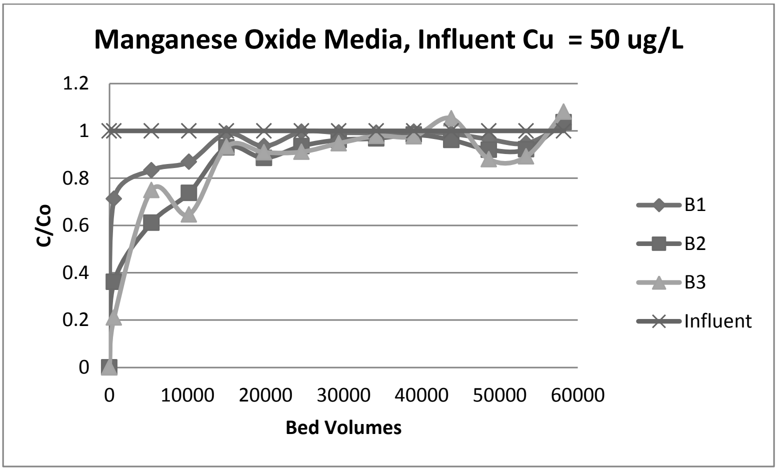


Figure 4. FBR breakthrough profiles for Cu(top) and Zn (bottom) from a synthetic stormwater solution onto granular iron hydroxide (columns A1-A3 in series).



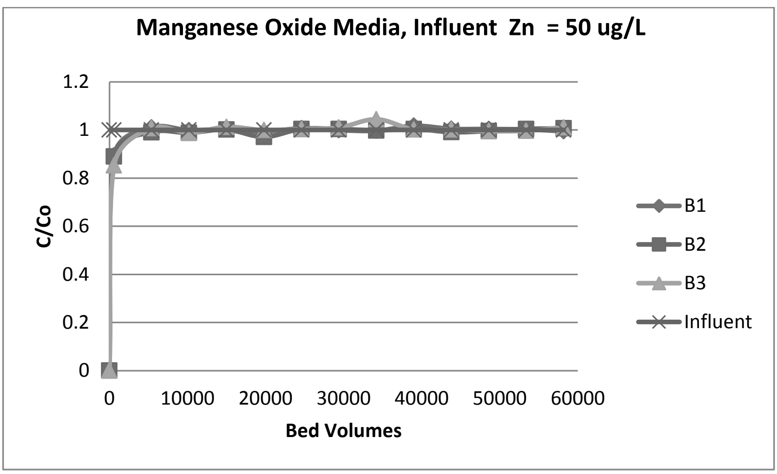


Figure 5. FBR breakthrough profiles for Cu(top) and Zn (bottom) from a synthetic stormwater solution onto granular manganese oxide (columns B1-B3 in series).

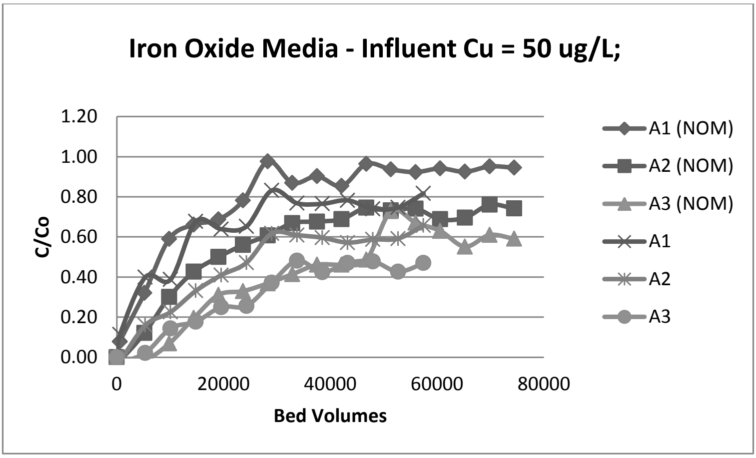


Figure 6. Comparison of FBR breakthrough profiles for Cu from synthetic stormwater solution with and without reconstituted highway organic matter (NOM).

Experiments conducted at higher pH (between 6.8 and 7.0) demonstrate the potential of the iron oxide media for achieving the effluent criteria of 3.0 μg/L copper for a sustained period of time. The columns were operated in this pH range for 130,000 bed volumes. However, after approximately 40,000 bed volumes the influent pH began dropping due to the loss of the nitrogen blanket used to maintain the storage tank CO_2 free. While removal of Cu from the column packed with manganese dioxide also shows dramatic improvement at the higher pH, the results are still not as promising as the iron oxide media. In fact, the waste crab material outperforms this particular manganese dioxide in part because the average pH in the column is higher within the crab shell/GFO columns.

Performance of the media for zinc removal also improves at pH 7. Log K_D values for zinc removal from the GFO column series and the waste crab/GFO column series were similar at pH 7 whereas at lower pH, zinc removal was significantly better in the columns packed with crab/GFO or crab/MnO_2. Thus, the presence of the crab shell contributes significantly to zinc removal in this system.

Application of Results for Field Scale Design

Most highway runoff waters are characterized by relatively low alkalinity and pH between 6.5 and 8.0. The results of the experimental testing suggest that iron oxide media is capable of achieving copper effluent concentrations of 3 μg/L or less for extended periods of time in the column reactors. The results also indicate that the use of a mixed oxide system containing concrete or crab shell can achieve similar, if not better, results for copper without raising the pH of the effluent. The mixed media system with iron oxide also provided better removal of zinc. The data from experiments conducted using the protocol described above can be used to guide the design of field-scale treatment systems by assisting in selecting appropriate media and by estimating the capacity of the media. In addition, modeling approaches can be used to assist in scaling from the bench scale system to the field.

In this research, iron oxide was identified as the most promising media. The adsorption capacity of the iron oxides tested in this work was evaluated using column data. The impact of organic matter may reduce the capacity of the system, but as shown in this research the impact may be minimal if pH is controlled near circumneutral values. Finally, the results also suggest that adsorption to the oxide media is rapid and at flow rates typical of a highway runoff filtration system adsorption kinetics should not limit the adsorption process.

The K_D values obtained at pH 7 can be used to provide an estimate of the capacity of the full scale system for copper removal from highway runoff of similar composition and to assess the economic feasibility of the material. K_D represents the mass of contaminant removed per mass of adsorbent. Therefore, for a given amount of copper to be removed from the stormwater, the required mass of media can be calculated. This process is described below for copper removal by the GFO iron oxide media used in this research.

At pH 7, the estimated log K_D for this system is conservatively assumed to be 5. In addition, the assumption of 30 in/yr of rainfall over a one acre drainage area yields a volume of stormwater runoff of approximately 3,000 m^3 per year. For an influent copper concentration in the stormwater runoff of 10 μg/L and desired effluent concentration of 3 μg/L, the required mass of copper adsorbed per year is approximately 22 g. Using the linear isotherm equation:

$$q_e = K_D C_e$$

and a value of 3 μg/L for C_e and a K_D of 10^5 L/kg, yields a required adsorption capacity of 300 mg removed/kg of GFO. Dividing the mg of copper adsorbed per year by 300 mg removed/kg of GFO yields a GFO demand of 72 kg/yr (150 lbs/yr) or 1,600 lbs over a ten year design period. The reported bulk density of GFO and E33 are 0.45 g/cm^3, which means that 720 kg of media 1.5 m^3 of volume. Assuming a design depth of 45 cm indicates that 1.5 m^3 of media are required for the ten year design period. The cost for oxide media ranges from \$4 to \$10/lb. Thus, the media costs for the ten year design period ranges between \$6,400 to \$16,000/acre.

Conclusions

This study investigated the removal of dissolved heavy metals in highway runoff in a laboratory study using synthetic stormwater and a variety of adsorbent materials. One novel aspect of the study was the use of natural organic matter extracted from highway runoff in the synthetic stormwater cocktail. The organic matter was extracted by collecting 1000 gallons of storm water, which was concentrated by a factor of 150 using reverse osmosis. It was then freeze-dried. The freeze-dried organic matter was reconstituted as needed at concentrations that mimic the initial total organic concentration of the stormwater when it was collected.

A series of column experiments were then run using iron oxide, manganese oxide, Portland cement concrete and crab shell waste as sorbents. Factors that were evaluated included organic matter concentration, competition between metal ion species (copper and zinc), pH and ionic strength. It was found that the organic matter content of stormwater has a substantial impact on dissolved metals removal. Higher concentrations of organic matter complexed with the dissolved metals reducing their removal by adsorption. The results of the column experiments also indicate that iron oxide provides substantially better removal of dissolved metals than manganese. Portland cement concrete and crab shell waste were both found to be effective at controlling pH, which is the largest factor in determining dissolved metal removals. These experiments indicate that use of iron oxide augmented with either concrete or crab shell is potentially a cost effective way to remove dissolved metals in highway runoff.

Acknowledgements

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Catchment Scale Hydrologic and Water Quality Impacts of Residential Stormwater Street Retrofits in Wilmington, North Carolina

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ABSTRACT

Low Impact Development (LID) is a design approach that utilizes Stormwater Control Measures (SCMs) to maintain and restore the natural hydrologic regime of an urban watershed through infiltration, runoff treatment at the source, and minimization of impervious surfaces. This paired watershed study evaluated the impacts of LID SCMs on hydrology and water quality at a catchment-scale. In February 2012, a pair of bioretention cell (BRC) bumpouts, two permeable pavement parking stalls and a tree filter device were installed to treat residential street runoff in Wilmington, North Carolina. In the LID-Retrofit catchment, SCMs treated 52% of the directly connected impervious area (DCIA) and 69% of the total drainage area for potential mitigation of peak discharge and runoff volume. For water quality improvement, 94% of the DCIA and 91% of the total drainage area was retrofitted. Underlying soils in the study area were Baymeade Urban and Leon Urban sands. Mean peak discharge significantly decreased 28% post-retrofit and lag times in the catchment remained unchanged, while mean runoff depth significantly decreased 52%. When compared to the control catchment, runoff depths in the LID-Retrofit catchment were significantly less for storms with low hourly storm intensities (<2.7 mm/hr), but significantly greater for storms with high intensities (>7.4 mm/hr). Runoff thresholds in the LID-Retrofit and control catchments were 5.2 mm and 3.5 mm, respectively. The LID runoff coefficient significantly decreased by 47% from 0.22 to 0.13, and is substantially less than other runoff coefficients reported for traditional residential development. Post-retrofit, concentrations of TKN, TP, TSS, Cu, Pb and Zn significantly decreased by 62%, 38%, 82%, 55%, 89% and 76%, respectively. Concentrations of $NO_{2,3}$-N and TAN did not change. Mass exports of TKN, TAN, O-PO_4^{-3}, TP, TSS, Cu, Pb and Zn significantly decreased by 78%, 61%, 55%, 73%, 91%, 53%, 88% and 77%, respectively. $NO_{2,3}$-N load decreased by 46%, although this was not significant. Most improvements in water quality were due to dramatic decreases of particulate and particulate-bound pollutant loads. This was attributed to first flush retention of runoff by the BRC and permeable pavement that treated 52% of the DCIA and treatment by the tree filter unit that serviced 42% of the DCIA. This study has shown that a limited

number of LID SCMs installed within a medium density residential street right-of-way over sandy soils can mitigate some hydrologic and water quality impacts of existing development.

INTRODUCTION

Impervious land cover associated with urbanization has led to increases in stormwater runoff volumes and pollutants entering surface waters (Jennings and Jarnagin, 2002). In forested watersheds of the Southeastern United States, 95% of rainfall evapotranspires or infiltrates the soil to become groundwater, with just 5% of rainfall being converted to surface runoff (Swift et al., 1987). As a watershed is developed, soil compaction and impervious surfaces including rooftops, roadways and parking lots can cause 55% (or more) of annual precipitation to become surface runoff (Tourbier and Westmacott, 1981). Increased runoff volumes and frequency of erosive peak discharges leads to stream bank instability, which is detrimental to macroinvertebrate communities and stream ecosystems (Pratt et al., 1981; Walsh et al., 2001).

Low Impact Development (LID) is an integrated design approach intended to mimic pre-development hydrology and water quality (Dietz, 2007). LID intends to preserve the natural characteristics and ecological integrity of a watershed, and when this is not possible, to reduce impacts to vegetation, topography, soils and aquatic communities. This is achieved by discretely locating and minimizing impervious surfaces and utilizing stormwater control measures (SCMs) to capture and treat runoff at the source (Coffman, 2000).

LID SCMs provide infiltration, filtration, adsorption, storage and/or groundwater recharge. Examples include: bioretention cells (BRCs), level spreaders, tree filter boxes, grassed bioswales, green roofs and permeable pavements. Peer-reviewed literature of LID practices has shown promise in preserving or restoring pre-development hydrology and water quality at new and existing urban development (Dietz, 2007). However, limited peer-reviewed literature is available on the hydrologic and water quality impacts of LID SCMs at a watershed or catchment-scale. Bedan and Clausen (2009) studied an LID residential neighborhood in Waterford, Conn., known as the Jordan Cove Project, where shared driveways, BRCs, grassed swales and permeable pavements were utilized. Impervious cover in the watershed increased from 0% to 21% following construction. However, no change in mean peak discharge was observed at the watershed outlet, and mean runoff depth was significantly reduced by 42%. The authors concluded this to be a direct result of distributing LID SCMs throughout the watershed designed to capture and treat runoff associated with the first 25.4 mm of rainfall.

Bedan and Clausen (2009) reported pollutant mass exports of TKN, TAN, Pb, Zn and pathogens decreased post-construction although mass exports of TP and TSS increased. The increase in TP load was attributed to fertilizer application by homeowners, which is common in residential watersheds (Gray and Becker, 2002). Periodic erosion of the grassed swales was cited as the cause for increases in TSS exports. Per US EPA (1983), medium and high-density watersheds have an average TN export of 9.6 kg/ha/yr and TP exports between 1.48 – 2.45 kg/ha/yr. Bedan and

Clausen (2009) found TN and TP exports of 2 kg/ha/yr and 0.4 kg/ha/yr respectively, which is substantially less than the US EPA average and is similar to nutrient exports from forested watersheds (Frink, 1991).

Line et al. (2012) characterized runoff, nutrient and sediment exports from three commercial watersheds in North Carolina: (1) a site with no SCMs, (2) a site with a wet detention basin and (3) an LID site with undersized permeable pavement, BRC and stormwater wetland installations. The LID site provided a greater mass load reduction for TKN, TAN, TP, TSS and substantially greater runoff volume reduction (34%) than the wet detention site. Mass exports for three of the five pollutants (TKN, TAN, TSS) were significantly reduced at the LID site while the wet detention site only significantly reduced mass exports for one of the five pollutants (TAN). The authors noted the LID SCMs were not sized and constructed according to current regulatory standards in North Carolina, and suggested that the runoff and pollutant mass reductions may have been even greater with properly sized and constructed LID SCMs.

Applying LID SCMs to existing urban development as retrofits may require systems to be undersized. As discussed above, Line et al. (2012) showed that undersized SCMs effectively reduced runoff volumes and pollutant loads at a commercial watershed outlet when compared to a commercial site with no stormwater treatment in place. Brown and Hunt (2011) reported two undersized BRCs of different media depths (0.6 m and 0.9 m) substantially reduced TN, TP, and TSS pollutant loads and runoff volume, with the 0.9 m media-depth cell outperforming the 0.6 m cell. In another North Carolina study of a 50% undersized BRC, TN and TSS loads were reduced by 27% and 49%, respectively (Luell et al., 2011).

PURPOSE OF STUDY

BRCs, permeable pavement and tree filters are well suited as retrofits to capture and treat residential street surface runoff. BRC bumpouts installed in the roadway provide treatment and storage of runoff while increasing pedestrian and bicyclist safety. Permeable pavements may be used to replace sections of existing asphalt and concrete pavement, or where speed and vehicular braking force is a concern, permeable pavements may be placed in parking lanes adjacent to the driving lanes. Tree filters require minimal space for installation, but may provide effective particulate treatment for impervious areas with loading ratios up to 300:1. This study evaluated the impacts of stormwater retrofits installed with the residential street right-of-way on hydrology and water quality at a catchment-scale.

MATERIALS AND METHODS

Site Description

The project site was located in the Burnt Mill Creek watershed of Wilmington, North Carolina. Wilmington is located in the southern coastal plain between the Cape Fear River and the Atlantic Ocean in Southeastern North Carolina, USA. Two residential street catchments, a control and retrofit (LID-Retrofit), were selected for use in a paired watershed study. The control and LID-Retrofit drainage areas were

0.35 ha and 0.53 ha, respectively. The straight-line distance between the catchments was 0.5 km.

Both catchments were considered to be medium-density residential areas with street surfaces, sidewalks, driveways, rooftops and open space; they were drained using conventional curb and gutter drainage systems. Control and LID-Retrofit housing densities were 25.7 home/ha and 28.3 homes/ha, respectively. Impervious cover was the same in each catchment at 60%. However, the directly connected impervious area (DCIA) (street surface) in the LID catchment was 24%, which was substantially greater than 16% observed in the control catchment (Table 1). The catchment outlets were existing stormwater catch basins. The control outlet was located at the northwest corner of the intersection of 8th Street and Orange Street, and the LID outlet is located at the southwest corner of 12th Street and Dock Street.

Table 1: Summary of catchment areas and imperviousness

Parameter	Catchment	
	LID-Retrofit	Control
Drainage Area (m^2)	5,300	3,480
% Impervious Fraction	60%	60%
Street Surface (DCIA)	24%	16%
Rooftop	26%	35%
Sidewalk	10%	9%
Open Space	40%	40%
Maximum Slope	0.5%	0.7%
Outlet Location	N34.235293,W77.934061	N34.233696, W7.939200

The New Hanover County soil survey indicated underlying soils in the control and LID-Retrofit catchments were Baymeade Urban and Leon Urban, respectively. Particle size distribution analysis (PSA) using the hydrometer method (Gee and Bauder, 1986) showed the USDA texture classification for the underlying soils was sand (Gee and Or, 2002). Infiltration rates in sandy urban soils range from 50 mm/hr to 460 mm/hr and are greatly impacted by compaction (Pitt et al., 2008). Maximum longitudinal slopes in the control and LID-Retrofit catchments were similar at 0.7% and 0.5%, respectively.

LID SCM Retrofits

LID SCMs constructed in February 2012 included a BRC bumpout, four permeable pavement parking spaces installed in two separate sections and one tree filter box installed along Dock Street and 12th Street (Figure 1). Post-retrofit, total impervious area decreased from 60% to 58% and DCIA decreased from 24% to 12%. BRC bumpouts were constructed just west of the intersection of Jasmine Street and Dock Street to treat runoff from Dock Street. The BRCs extend 1.8 m into the existing roadway to create 3.5 m driving lanes (east and west bound) for the added benefit of traffic calming and pedestrian safety. Four permeable pavement parking stalls, 7 m x 2.4 m apiece, were installed in two separate sections on 12^{th} Street between Dock Street and Orange Street to treat runoff from 12^{th} Street. Permeable pavement loading ratios (DCIA/SCM surface area) of 7.8 and 6.6 were atypically high, and the impacts of loading ratios this large have not been reported in the literature. Flow diverters (16 mm tall) were installed along the curb and gutter at 3.6 m intervals to force runoff onto the permeable pavement. The BRC and permeable pavement combined to treat 52% of the street surface and 69% of the total catchment area for potential runoff quantity reductions (Figure 2).

Figure 1: Clockwise from top: BRC bumpouts along Dock Street, permeable pavement parking stalls on 12^{th} Street, and atree filter device at intersection of 12^{th} Street and Dock Street.

A Filterra® tree filter device was installed on Dock Street at the southwest corner of the intersection with 12^{th} Street to treat runoff from Jasmine Street and Dock Street (Figure 1). The tree filter treated any overflow from the BRC bumpouts. The devices functioned as rapid flow-through filters such that ponding on the surface of the media did not occur. Lenth et al. (2010) measured infiltration rates of ten Filterra® devices with varying maintenance periods (recent – 2 years) and found infiltration rates from 2200 mm/hr to 5200 mm/hr with up to 110 mm of sediment accumulation at the surface. Volume reduction is negligible because the concrete lining does not allow exfiltration to occur.

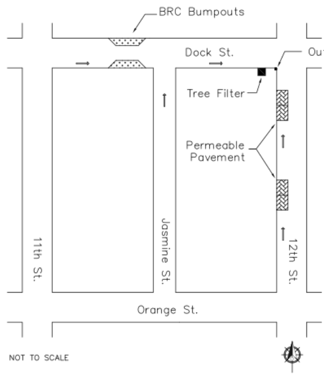

Figure 2: Layout of LID SCMs with arrows indicating direction of flow (not to scale)

Monitoring Design

The paired watershed study design was used to evaluate the hydrologic impacts of the LID SCM retrofits (Clausen and Spooner, 1993; Grabow et al., 1998). This approach requires two watersheds: control and treatment (LID-Retrofit) and two monitoring periods: calibration and treatment. During the calibration period, management practices in the catchments remained the same (no SCMs). Then, SCMs were installed in the LID-Retrofit catchment and treatment monitoring began post-construction. The paired watershed approach is underpinned by a quantifiable and predictable (linear) relationship between the catchments. A relationship is developed during the calibration period, and is considered valid until the SCM treatment is applied to the LID-Retrofit catchment, at which time a new relationship between the catchments is developed during the second period of monitoring (Clausen and Spooner, 1993).

Monitoring equipment was installed at the catchment outlets in May 2011. Manual and HOBO™ Tipping Bucket rain gauges were installed on a wooden post free of trees and overhead obstructions at the LID-Retrofit station. Hydrologic data were recorded by installing V-notch weirs and/or weir boxes inside the existing catch basins. Forty-five degree and 60° V-notch weirs were installed at the control and LID-Retrofit stations, respectively. ISCO 730™ bubbler flow modules were used to monitor discharge and total runoff volume by measuring stage above the weir at two minute intervals.

Sampling Protocol

ISCO 6712™ portable samplers were programmed to produce 200 mL flow proportional aliquots. A minimum of 10 aliquots (2 L) was needed for a full set of water quality analyses to be conducted. The samplers were programmed to collect samples from rainfall events ranging from 6 mm to 380 mm. Runoff samples were obtained 10 cm behind the weir in an area of well-mixed flow.

Water quality samples were collected within 24 hours of a rainfall event. Total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrate-nitrite-nitrogen ($NO_{2,3}$-N), total phosphorous (TP), and ortho-phosphate (O-PO_4^{-3}) samples were analyzed by the North Carolina Center for Applied Aquatic Ecology at NCSU in Raleigh, NC. Total nitrogen (TN) concentrations were calculated by summing TKN and $NO_{2,3}$-N; organic nitrogen (ON) concentrations were determined by subtracting TAN from TKN for each sampled storm event. Total polycyclic aromatic hydrocarbons (∑PAHs), copper (Cu), lead (Pb) and zinc (Zn) samples were analyzed by the NCDENR Environmental Chemistry Lab in Raleigh, NC. Both labs were located approximately 210 km (130 mi) from the study site. Laboratory analytical methods followed Standard Methods and US EPA Methods (US EPA, 1993; APHA et al., 1995).

Statistical Analysis

SAS Version 9.3™ was used for all statistical analyses (SAS Institute, 2012). Data sets from the calibration and treatment periods were log transformed and tested separately using analysis of variance (ANOVA) for a significant linear relationship with metrics from the LID-Retrofit and control catchments as covariates (control = x, LID-Retrofit = y). The residuals of regression were inspected graphically for normality and constant variance. Skew coefficients and the Shapiro-Wilk goodness-of-fit test were also used to assess residual normality. Analysis of covariance (ANCOVA) was used to detect significant impacts on the slopes and intercepts of concentration and mass load regressions for each water quality constituent. No significant differences in slopes were observed, thus the reduced ANCOVA model with constant slopes was used for all water quality analyses. A significant difference in intercepts of calibration and treatment regression lines implied the LID SCM treatment had a significant impact on that water quality parameter. Least squared means (LSM) analysis was used to quantify significant changes in pollutant concentrations and loads from calibration to treatment monitoring.

RESULTS AND DISCUSSION

Precipitation

Normal annual rainfall at Wilmington International Airport is 1,448 mm (State Climate Office of North Carolina, 2012). The calibration and treatment monitoring periods occurred from 10 May 2011 to 31 October 2011 and 8 June 2012 to 13 February 2013, respectively. Total rainfall recorded during the calibration and treatment periods was 514 mm and 957 mm, respectively. Storms less than 2.5 mm were not included in the data set. A six-hour antecedent dry period was used to separate discrete rainfall events.

Similar rainfall characteristics were observed in both monitoring periods. Mean storm depth during the calibration period was 21.3 mm compared to 19.3 mm recorded during treatment monitoring, while median rainfall depth was 10.7 mm and 9.9 mm, respectively. The difference in mean rainfall depth was primarily caused by

143 mm of rainfall from Hurricane Irene that occurred on August 26, 2011. Nine storm events were sampled for water quality during the calibration period, with six samples during the summer and three in the fall. During the treatment period, 16 storm events were sampled and were well distributed across the seasons.

Hydrologic Results

Mean peak discharge in the LID-Retrofit catchment decreased from 15.0 L/s pre-retrofit to 12.4 L/s post-retrofit. The LID SCMs had a significant impact on flow rates evidenced by the difference in intercepts of the calibration and treatment regression lines in the reduced ANCOVA model. Peak discharge in the LID-Retrofit catchment significantly decreased 28% (α=0.10) during post-retrofit monitoring by LSM comparison.

Mean runoff depth in the LID-Retrofit catchment significantly decreased by 52% during the post-retrofit period. The slopes and intercepts of the calibration and treatment regression lines were significantly different. Decreases in runoff depth were not consistent across all values, unlike observations reported by Bedan and Clausen (2009). In the full ANCOVA model for runoff depth, the greater slope of the treatment regression line and magnitude of the difference at lower values of runoff depth indicates greater decreases at smaller runoff depths and little to no change at large runoff (and rainfall) depths.

Runoff threshold is the rainfall depth at which runoff is generated and was determined by the x-intercept of the regression line from a rainfall depth vs. runoff depth plot. All paired data points from post-construction monitoring were used in the analysis. LID-Retrofit and control runoff thresholds were 5.2 mm and 3.5 mm, respectively. The greater runoff threshold in the LID-Retrofit catchment was due to the BRC and permeable pavement installations that provided infiltration and depressional storage. These thresholds were very similar to those observed by Hood et al. (2007) in Connecticut, where runoff thresholds from residential LID-Retrofit and traditional watersheds were 6.0 mm and 3.0 mm, respectively.

Runoff coefficient is determined by dividing runoff depth by rainfall depth for a single storm. Line and White (2007) and Leopold (1991) have shown that runoff coefficients increase with impervious cover and urbanization in a watershed. Mean runoff coefficients in the LID-Retrofit and control catchments during calibration monitoring were 0.22 and 0.14, respectively. The larger mean runoff coefficient observed pre-retrofit in the LID-Retrofit catchment is due to the greater DCIA fraction. Line et al. (2002) reported a runoff coefficient of 0.57 for a residential drainage area with 25% DCIA in the Piedmont region of North Carolina, which is substantially greater than runoff coefficients reported in this study. The difference is due to higher slopes (2%-10%) and sandy loam soils in the watershed monitored by Line et al. (2002). As noted previously, soils in the study area were very sandy, and the topography was flat (0.5% - 0.7% slopes).

Nutrients – Nitrogen

For the most part, median pollutant concentrations were less than the computed means due to several events with spikes in pollutant concentrations at both monitoring stations. During treatment monitoring, TKN concentrations from the LID-

Retrofit catchment significantly decreased by 62%. The median TKN concentration was 0.45 mg/L, which is more than three times less than median TKN concentration of 1.48 mg/L reported by Line et al. (2002) for traditional residential development in North Carolina. The median control TKN concentration was 1.14 mg/L. Dissolved nitrogen pollutant concentrations of TAN and $NO_{2,3}$-N remained unchanged after the SCMs were installed (Table 2). The decrease in TKN concentration was likely due to particulate ON capture (leaf litter and woody debris) by the SCMs. Median $NO_{2,3}$-N concentrations at the control and LID outlets were 0.14 mg/L and 0.07 mg/L, respectively, which are less than $NO_{2,3}$-N concentrations observed at other residential sites and well below a previously suggested irreducible concentration (0.7 mg/L) defined by Schueler and Holland (2000). $NO_{2,3}$-N in runoff tends to originate from commercial fertilizer use (Bannerman et al., 1993). In both drainage areas monitored, there was minimal ornamental landscaping and lawn area, and fertilizer use was not documented.

Overall, annual nitrogen mass export rates from the catchments in this study were less than those reported for residential development in North Carolina and the U.S. (Bedan and Clausen, 2009; Hood et al. 2007; Line and White, 2007). This is primarily due to the sandy soils in the study area, which is reflected by the low runoff coefficients of the control and LID watersheds. At the LID-Retrofit outlet, mass exports of TKN and TAN significantly decreased by 78% and 61%, respectively. $NO_{2,3}$-N mass export rate decreased by 47%, although this was not significant. Post-retrofit, annual TKN load was five times less than the untreated control drainage area (0.5 kg/ha/yr compared to 2.6 kg/ha/yr). Decreases in TAN and $NO_{2,3}$-N loads were due to reductions in runoff volume after construction of the LID SCMs, as evidenced by the decrease in LID runoff coefficient from 0.22 to 0.13.

Nutrients – Phosphorus

Post-retrofit, O-PO_4^{-3} concentrations in the LID catchment were 54% less than those observed in the control catchment (Table 2). However, mean O-PO_4^{-3} concentrations in both drainage areas were skewed by several events with spikes in O-PO_4^{-3} concentrations. Median O-PO_4^{-3} concentrations (0.10 mg/L) in the LID catchment remained unchanged compared to those observed at the control station (0.11 mg/L) and pre-retrofit conditions (0.10 mg/L). Dissolved O-PO_4^{-3} originates from fertilizers and lawns in residential watersheds, and can also be leached from soils that have reached their phosphorus sorption capacity (Waschbusch et al., 1999). TP concentration significantly decreased by 38% (α=0.10). The modest decrease in TP concentration was mainly due to sediment retention by the SCMs.

Mass export of O-PO_4^{-3} and TP at the LID-Retrofit outlet significantly decreased by 55% and 73%, respectively (Table 3-9). Annual LID TP load was three times less than TP load from the control catchment (0.2 kg/ha/yr compared to 0.6 kg/ha/yr). LID TP mass export was the same as the TP load reported by Bedan and Clausen (2009) for a residential LID watershed and 11.5 times less than a residential watershed with no SCMs studied by Line et al. (2002). The majority of TP load reduction from the LID-Retrofit catchment was due to substantial reductions in runoff volume, some treatment of runoff was observed, evidenced by the 38% decrease in TP concentration.

Total Suspended Solids

Mean TSS concentration decreased from 50 mg/L pre-retrofit to 11 mg/L post-retrofit and was significantly less than TSS concentration (53 mg/L) observed at the control station (Table 2). LID-Retrofit TSS concentration was nearly the same as those observed by Line et al. (2012) and Bedan and Clausen (2009) from commercial and residential LID sites, respectively. However, mass export rates of TSS from both catchments in this study were less than half of TSS loads observed by Line et al. (2002), presumably due to the flat topography and sandy soils of drainage areas in this study that generated low runoff coefficients. Post-retrofit, TSS load at the LID-Retrofit outlet significantly decreased by 91%. The dramatic decrease in TSS load is due to runoff treatment and volume reduction. At the LID-Retrofit outlet, annual TSS load was 12 kg/ha/yr, which was similar to TSS loads observed by Bedan and Clausen (2009) where a low runoff coefficient of 0.07 was also reported.

Metals – Cu, Pb and Zn

In residential watersheds, Cu, Pb and Zn in runoff have been linked to vehicular brake wear, aged exterior paint, and tire wear, respectively (Bannerman et al., 1993; Davis et al., 2001). Cu concentrations in the LID-Retrofit catchment significantly decreased by 55% (p=0.0051) (Table 2). LID-Retrofit concentrations of Pb and Zn were significantly less than those observed in the control catchment by 89% and 76%, respectively. Post-retrofit, Cu, Pb and Zn concentrations in the LID-Retrofit catchment were similar to those reported by Bedan and Clausen (2009) from a residential LID watershed. Mass exports of Cu, Pb and Zn at the LID-Retrofit outlet significantly decreased by 53%, 88%, and 77%, respectively. Large reductions of heavy metals loads were due to decreases in concentration and runoff volume leaving the LID-Retrofit catchment.

Table 2: Summary of nutrient, sediment, and metals concentrations at the catchment outlets (units of mg/L for nutrients and sediment, μg/L for metals)

Station	Duration (yr)	n[a]	TKN	TAN	$NO_{2,3}$-N	TSS	$O\text{-}PO_4^{-3}$	TP	Cu	Pb	Zn
Control	1.14	25									
Mean			1.92	0.2	0.25	53	0.23	0.44	16	37	84
Median			1.14	0.06	0.14	42	0.1	0.22	13	35	70
LID-Calibration	0.47	9									
Mean			1.52	0.07	0.3	50	0.21	0.29	14	22	85
Median			1.35	0.04	0.26	54	0.11	0.21	14	14	65
LID-Treatment	0.67	16									
Mean			0.66	0.04	0.18	11	0.12	0.21	6	4	21
Median			0.45	0.03	0.07	7	0.1	0.17	5	2	18
LSM Difference[b]			-62%*	0%[NS]	0%[NS]	-82%[T]*	-54%[S]*	-38%[NS]	-62%*	-89%[T]*	-76%[T]*

*significant

[NS]not significant

[t] paired t-test used for statistical comparison of paired post-retrofit data from LID-Retrofit and control catchments

[S]Sign test used for statistical comparison of paired post-retrofit data from LID-Retrofit and control catchments

[a]number of events sampled

[b]Negative sign "-" indicates reduction

SUMMARY AND CONCLUSIONS

In this study, 52% of DCIA and 69% of total impervious area in a residential catchment was retrofitted with a BRC, permeable pavement, and a tree filter box. Results have shown that LID SCMs installed as retrofits within the residential street right-of-way can mitigate some of the hydrologic and water quality impacts of existing residential development at a catchment-scale. The following conclusions were drawn from this study:

- Post-retrofit, mean peak discharge at the LID-Retrofit outlet significantly decreased by 28%, but no impact was observed on lag times. The decrease in mean flowrates may have been greater if hydrologic treatment had been applied to the entire DCIA, rather than just 52%. Lag times likely remained unchanged because the infiltration-based LID SCMs did not introduce a large amount a new storage (detention) to the existing drainage area.
- Runoff depth in the LID-Retrofit catchment decreased significantly by 52%, which is comparable to other studies of individual BRC and permeable pavement systems and watershed-scale studies of LID SCMs (Bedan and Clausen, 2009; Line et al., 2012). Runoff coefficient in the LID catchment significantly decreased by 47%. Post-retrofit, the LID runoff coefficient was 0.13, which is substantially less than other values reported for traditional residential developments and similar to the runoff coefficient (0.07) reported for a larger residential LID watershed (Line et al., 2002; Hood et al., 2007).
- At the LID site post-retrofit, concentrations of TKN, TSS, Cu, Pb and Zn significantly decreased by 62%, 82%, 55%, 89% and 76%, respectively at α=0.05. TP concentration significantly decreased by 38%. Concentrations of $NO_{2,3}$-N and TAN did not change. TKN concentration reductions were due to particulate ON capture. Mean LID-Retrofit outlet concentrations of O-PO_4^{-3} were 55% less than those observed in the control drainage area, but median O-PO_4^{-3} concentrations not were different between the drainage areas or pre-retrofit conditions. Decreases in TP concentration were likely due to TSS retention by the SCMs.
- Mass exports of TKN, TAN, O-PO_4^{-3}, TP, TSS, Cu, Pb and Zn significantly decreased by 78%, 61%, 55%, 73%, 91%, 53%, 88% and 77%, respectively. $NO_{2,3}$-N load decreased by 46% (although not significantly). Dramatic reductions of particulate and particulate-bound pollutant loads implied water quality treatment and runoff volume reduction. This was attributed to first flush retention of runoff by the BRC and permeable pavement that treated 52% of the DCIA and treatment by the tree filter unit that serviced 42% of the DCIA.

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Optimizing Stormwater Green Infrastructure in the Municipal Roadway Environment: Lessons from Southern California

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Introduction

Municipalities in Southern California are facing an increasing amount of complexity in Municipal Separate Storm Sewer Systems (MS4) permits. Two of the more trying requirements for roadway projects that have been incorporated into permits in the region are hydromodification management (HM) and low impact development (LID). These are being implemented as specific measurable requirements in permits and create significant challenges for municipalities. This paper analyzes the challenges that these requirements present for linear roadway projects and details the application of a storm water model and technical feasibility analysis to identify cost effective solutions.

HM and LID requirements include quantitative targets intended to require new and improvement roadway projects to include elements that retain the beneficial hydrologic functions of the natural environment. Hydromodification is defined as the alteration of natural flow characteristics and sediment transport in streams and channels. The HM requirements are intended to reduce the impact of urban development on receiving water bodies by incorporating design elements and best management practices (BMPs) to mimic the hydrologic conditions present before development. LID can be defined as design elements that incorporate existing natural features or implement natural functions into the development to lessen the impact of development on the environment. For stormwater discharge permits, LID elements focus on the capacity of the natural environment to retain, infiltrate, and treat stormwater.

Stormwater Requirements & Implementation Plan (California)

Within the State of California, there are nine Regional Water Quality Control Boards (Regional Boards) charged with protecting water quality and allocating surface water rights. Four of the Regional Boards are located in Southern California and draft MS4 permits in these regions. The Regional Board boundaries are based on hydrologic basins that do not necessarily align with political boundaries and LID and HM requirements vary under the Regional Boards. As a result, municipalities in Southern California may have more than one MS4 permit and each may have different LID and HM requirements.

While many regions are working toward measurable goals, some regions do not have measurable requirements. For the regions that do have measurable goals, some of the differences may include maximum storm design volumes to be treated, types of devices, and alternatives for areas where these are not feasible.

LID and HM requirements themselves often overlap, and LID devices can be part of the solution to address HM. The following sections describe some of the permit requirements in Southern California.

Low Impact Development (LID)

Several municipal permits in Southern California include LID requirements that require that development and significant redevelopment projects integrate LID principles and implement BMPs to mitigate the impacts of development on downstream waterbodies.

The San Diego Region MS4 permit for South Orange County requires the implementation of LID best management practices (BMPs) for paved surfaces that are 5,000 square feet or greater used for transportation to “minimize directly connected impervious areas, limit loss of existing infiltration capacity, and protect areas that provide important water quality benefits”. The permit requires that runoff from impervious areas into pervious areas may not exceed the capacity of the available pervious areas to infiltrate or treat the runoff. To evaluate this, geologic and soil conditions, slope, and other pertinent factors must be considered.

Specifically, the San Diego Region MS4 permit for South Orange County requires that LID BMPs bioretain the 85^{th} percentile storm through infiltration and biofiltration. Where this is not feasible, the permit requires that permittees implement conventional treatment control BMPs and participate in the LID waiver program or offsite mitigation program. The Santa Ana Regional Water Quality Control Board MS4 permits for Riverside and San Bernardino Counties require project proponents to infiltrate, harvest and use, evapostranspire, and/or bio-treat the 85^{th} percentile storm event.

The Santa Ana Regional Water Quality Control Board MS4 permits for North Orange County and Riverside County recommend that project proponents utilize the Low Impact Development Manual for Southern California to implement LID techniques. Project proponents are required by the permit to consider preventative and conservation techniques before mitigation. LID site design principles should be implemented for priority development projects to the maximum extent practicable to get the post-project site hydrograph to match pre-project conditions as closely as possible.

Hydromodification Management (HM)

Many permit regulations in Southern California place limitations on potential increases of runoff discharge rates and durations and often require that naturally occurring hydrology and sediment supply conditions be maintained by green street projects. The requirements are triggered by project specifics and receiving channel conditions, notably by the susceptibility to hydromodification of the receiving streams.

The San Diego Region permit for South Orange County requires that estimated post-project runoff discharge rates and durations do not exceed those for pre-development by more than 10 percent for flows ranging from 10-percent of the 2-year peak discharge up to the 10-year peak discharge. Pre-development is defined as that of the naturally occurring condition. In addition, projects must mitigate for the loss of sediment supply due to development, if any.

The Santa Ana Regional Water Quality Control Board MS4 permits for North Orange County and Riverside County require that a project must either meet conditions to ensure that downstream water bodies are not impacted by hydrologic conditions of concern (HCOC) or implement measures to protect downstream waterbodies. If there is the potential for the project to impact downstream erosion, sedimentation, or stream habitat, the project proponent must address HCOCs by mimicking the pre-development hydrograph with the post-development hydrograph by limiting it to a 110% of the pre-development 2-year peak flow.

The permits for Riverside County and San Bernardino County also allow for a crediting system to be established for alternatives to hydromodification requirements and include hydromodification monitoring requirements to evaluate the effectiveness of controls implemented in the permit area.

Green Infrastructure Guidelines

There are numerous resources available for municipalities and project proponents that outline requirements and provide assistance for the identification of available LID and HM implementation options. The US Environmental Protection Agency (USEPA) offers general guidelines on how to implement a green street approach to manage stormwater and local agencies often provide their own guidelines and design standards.

In *Managing Wet Weather with Green Infrastructure: Municipal Handbook, Green Streets* the USEPA defines Green Streets and provides options, challenges, and case studies for green streets. The functional goals of green streets are listed as:

- Provide source control of stormwater,
- Limit transport and pollutant conveyance to the collection system,
- Restore predevelopment hydrology to the extent possible, and
- Provide environmentally enhanced roads.

The Orange County Model Water Quality Management Plan (WQMP) adopted in 2011 requires that for street, road, highway or freeway projects with 5,000 square feet or more of paved surface the project incorporate the USEPA guidance manual.

The *Technical Guidance Document* prepared by the County of Orange in 2011 includes site design measures that should be applied to the maximum extent practicable:

- Minimize street width to the appropriate width for maintaining traffic flow and public safety,
- Add tree canopy by planting or preserving trees and shrubs,
- Use porous pavement or pavers for low traffic roadways, on-street parking, shoulders or sidewalks, and
- Integrate traffic calming measures in the form of bioretention curb extensions.

Technical guidance prepared by the Counties of San Bernardino, San Diego, and Riverside include similar recommendations on design measures.

In many cases there are barriers to overcome for implementation of these design measures created by local codes and other requirements. For example, municipalities require minimum street widths for safety and traffic flow. With limited right of way, the minimum street widths may not allow adequate space for implementation of LID measures. The MS4 permits for the County of San Bernardino and County of Riverside include requirements to identify such barriers to LID implementation and remove them where possible. It is important to define and understand the local barriers to LID implementation when identifying options for a project. LID barriers that were identified by the permit include:

- Use of permeable surface roadway designs,
- Integration of natural drainage systems,
- Reducing curb requirements,
- Designing narrower streets, and
- Integrating vegetated landscape as integral elements of streets.

Similar barriers are quite common and implementing changes to municipal requirements that remove barriers to LID implementation may be a time consuming process.

Site Considerations

The technical guidance document for Orange County includes considerations that should be made when assessing sites for implementation of storm water controls. These include potential limitations that are unique to transportation projects, including:

- Ownership of land adjacent to right of ways, which translates into the lack of sufficient right-of-way,

- Location of existing utilities,
- Grade differential between road surface and storm drain systems,
- Longitudinal slope,
- Potential access opportunities, and
- Existing local, state, and federal design and code specifications.

Approach to Meet Permit Requirements

There are four critical steps to meet the LID and HM permit requirements in a cost effective manner for a new or re-development project. The first step is developing an understanding of the specific requirements for the region of interest. As discussed previously, these may change from one county or region to the next. The second step is to analyze site conditions and develop a thorough understanding of the feasibility of LID devices and other BMPs to meet the requirements. The third step is to choose the appropriate water quality treatment devices. The fourth step is to estimate the required size of the water quality features that will be required to meet the LID and HM requirements, in addition to any other water quality requirements for the site. A brief description of the LID and HM requirements was provided in Chapter 1 of this report. Steps 2 through 4 are discussed in this chapter.

Description of Technical Feasibility Analysis for Roadway Projects

The MS4 permits require that the feasibility assessment for implementing source control LIDs and structural BMPs into roadway projects be completed based only on project-specific considerations. Municipalities in Orange County and Riverside County have developed technical guidance documents that establish a framework for evaluating the technical feasibility of incorporating LID and HM BMPs into the design of a transportation project. The fundamentals of a technical framework lie within the identification of the project type, technical constraints, and, if necessary, the comparison of engineering costs to the benefits of implementing LID principles and hydrologic controls to the maximum extent practicable. These elements should be integrated in a technical feasibility analysis that demonstrates the capacity, if any, to incorporate these controls. The designer acknowledges that the engineering costs associated with the implementation of LID principles and BMPs are typically driven by the state of the built-up environment and other soils and geotechnical constraints. The methodology presented here focuses essentially on roadway projects but could also be applied to Class I bikeway or sidewalk projects. This paper does not investigate the specificities associated with such capital improvement projects.

The opportunity to implement source control and/or structural BMPs is highly dependent on the type of roadway project. The methodology differs for each of three classified categories:

- **Emergency and maintenance projects** are typically exempt from LID and HM requirements as they maintain the original line and grade, hydraulic capacity, and the original purpose of the facility. Emergency roadway project are typically completed outside of the planning process to eliminate threatening hazards from the right-of-way. Maintenance projects consist of routine shaping and repair of the road surface, cleaning and maintenance of drainage structures, and vegetation control alongside roadways.

- **New roadway projects** are supported by federal, state, or local multimodal transportation plans that ensure the economic development of identified urbanized areas provided that funding is available. During the planning process of a new roadway project, the designer gathers information about the physical character of the area and the values of the surrounding community. New roadway projects are linear projects in a confined right-of-way but may, however, dispose of sufficient flexibility for the designer to incorporate LID and HM hydrologic controls.

  The project proponent should conduct a feasibility study, in which regulatory requirements, site-specific characteristics, and infrastructure and project-specific characteristics are evaluated independently. Factors that should be considered include:

  - Regulatory requirements, such as the identification of Total Maximum Daily Loads (TMDLs) and Clean Water Act Section 303(d) impaired waterbodies downstream of the project site, the identification of Environmentally Sensitive Areas within the vicinity of the site, and the identification of mitigation alternatives as adopted during the California Environmental Quality Act (CEQA) process;
  - Site-specific characteristics include the drainage characteristics, the soil and geologic conditions, the seasonal level of groundwater, the presence of contaminated plumes, and if the site is major contributor of bed sediment to the receiving stream;
  - Infrastructure and project-specific characteristics that identify the programmatic or funding restrictions, potential right-of-way constraints, existing features, utility constraints, if power and irrigation water are available, and the traffic load; and
  - Other site-specific constraints that are identified by the developer.

  For new roadway projects, the comparison of engineering costs associated with the implementation of LID and HM hydrologic controls to the overall project benefits and costs is not proscriptive. Only programmatic, geotechnical, and other technical constraints allow a project to move forward without incorporating LID features. Programmatic constraints may include, but are not limited to, the compliance with the Americans with Disabilities Act (ADA) or the available funding for specific features of a project only. In such an occurrence, the municipality could investigate the option of offsite mitigation, which consists of mitigating an equivalent volume, intensity, and duration of runoff using LID and HM BMPs elsewhere in the same watershed.

- **Roadway improvement projects** typically consist of either increasing the road capacity to reduce an existing or a projected congestion (capacity improvement) or minimizing the risks associated with trucks, railroad crossing, environmental concerns, air quality, pedestrian and bicycle facilities, access to human services, storm water management, and others (non-capacity improvement). These roadway improvements include changes to the road alignment, subgrade widening, and significant upgrades to the existing infrastructures. Opportunities to incorporate LID and HM controls within the existing built environment are technically challenging.

  The project proponent should conduct a technical feasibility study that includes the elements identified in the methodology for new roadway projects. In addition, the developer may evaluate the engineering costs engendered by the modifications of the built environment that are necessary to incorporate LID principles and hydrologic structural controls. These engineering costs may be compared to the overall costs and water quality and public safety benefits of the improvement project. The municipality must demonstrate on a qualitative and cost-effectiveness basis that mitigation to the maximum extent practical has been achieved. These recommendations are in line with the guidelines presented in the EPA Green Street Guidance Document.

Choosing the Appropriate Mitigation Devices

Identified constraints, including the identification of pollutants of concern, will drive the selection of the appropriate structural BMPs. These include physical and geological constraints as described above and the pollutants and treatment requirements. The physical and geological constraints include:

- Soil types,
- Layout of the areas where BMPs will be located, and
- Slopes.

In addition, the type of LID/ BMP device chosen should be made with careful consideration of the pollutants of concern for the region. Numerous studies have been performed on the effectiveness of BMPs for various pollutants. Data on LID devices is not as readily available; however, load reductions can be estimated according to volumes of water infiltrated and the associated pollutant concentrations.

Optimization of Mitigation Systems

The County of Orange with assistance from Clear Creek Solutions developed the South Orange Hydrology Model (SOHM) to enable users to analyze the potential impacts of development and re-development projects on hydromodification and to evaluate the effectiveness of BMPs to mitigate these impacts. The SOHM uses the Hydrologic Simulation Program-Fortran (HSPF) as its computational engine. The tool generates flow duration curves for pre-project and post-project conditions. The tool allows the user to size BMPs to match discharge from the project to the natural condition of the site. The model performs a continuous simulation of site runoff to generate the flow duration curves. Similar hydrologic models have also been developed in San Diego County and Riverside County.

Municipal Roadway Cases

To illustrate the design of roadway projects to meet LID and HM requirements, two innovative case studies are presented. The first case study evaluated is the integration of green infrastructure into a project for a new roadway. The second case study is for integration of green infrastructure into a roadway improvement project. For both studies, BMPs were optimized using the SOHM water quality model.

Integrating Green Infrastructure into a New Roadway

The first case study considers the integration of green street elements into a 4,700-foot section of a new roadway project in Orange County, California. The project consists of a 6-lane divided roadway of paved and unpaved sections and will ultimately be developed as highway in later project phases. The project will connect two major nodes of the local transportation corridor agency, and is designated as a major arterial highway. Because of the interim condition of the project, only the north side of the highway will be paved during this interim phase. The technical feasibility approach was applied to the project to integrate green infrastructure into a roadway and bridge. The total project area covers 50.8 acres and would create 6.8 acres of impervious surface in the interim condition. The site is currently open space with mild to steep slopes and used for agricultural purposes, including cattle grazing, crops, and landscape nurseries. The site has an underlying mix of group C and D soils. There are no existing storm drain facilities or utilities that need to be accounted for when locating or sizing BMPs. The project area is located in the San Diego Region and receiving reaches are identified as susceptible to hydromodification, as defined by the South Orange County MS4 permit for that region.

The SOHM model was used to estimate sizes for four bioretention BMPs with underdrains to treat runoff from the project area prior to discharge to the receiving creek. The bioretention systems were sized to meet LID design capture volume and HM treatment requirements for the ultimate condition of the project.

Challenges

There are numerous potential challenges to implementation of green infrastructure into new roadways. These include geotechnical and structural concerns, physical constraints, slope, infiltration feasibility, and municipal codes. For the new roadway project, the challenges that were identified include:

- Regulatory requirements including HM because of the susceptibility of receiving waters,
- Topology of the project coverage (mild to steep slopes) and the requirement to integrate natural drainage systems,
- The entitlement process limits the project to a set right-of-way,
- Geotechnical characteristics, including underlying C and D hydrologic soil types as well as stability concerns, limited the feasibility of infiltration,
- Integrating vegetated landscape as integral elements of streets.

The regulatory requirements considered include the Clean Water Act, Section 303(d) water quality impairment listings and TMDLs. The receiving waters include a TMDL for bacterial indicators and 303(d) listings for pesticides, nutrients, selenium, and toxicity. Infiltration BMPs were not feasible at the site because of the poor draining type C and D soils.

Results

The LID options were limited by the above; however, LID facilities were designed to be implemented to the maximum extent feasible to accommodate for the ultimate condition of the project. Bioretention basins with underdrains were chosen because these would offer better treatment efficiencies for the pollutants of concern than other treatment options such as vegetated swales and extended detention basins. The cumulative detention capacity of all four bioretention systems is 90,000 cubic feet and is associated with a cumulative BMP footprint of 42,400 square feet. The vegetation used will be annual grasses and forbs to take advantage of the project area climate's moisture cycles and to increase infiltration by loosening the soil surface. The bioretention basins were estimated to at $875,000. An overview of the project layout and the location of bioretention systems is provided in Figure 1.

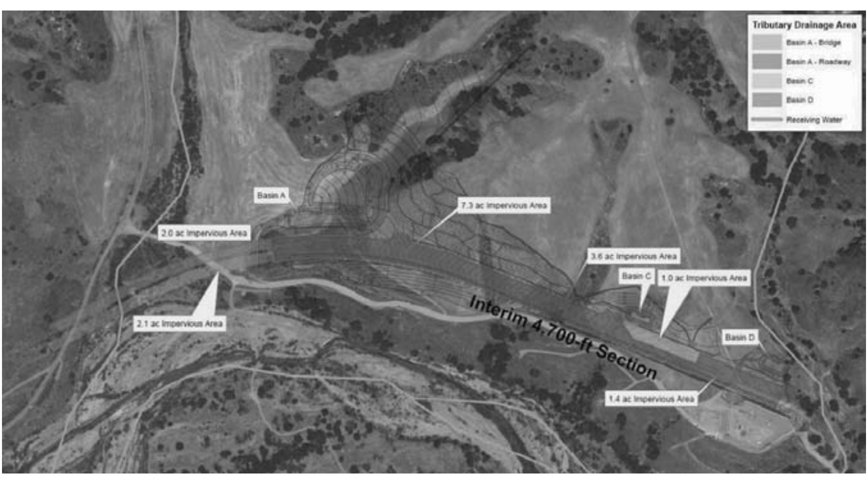

Figure 1 – Overview of New Project Drainage Area and LID Features

Retrofitting an Existing Roadway with Green Infrastructure

The second case study considers the integration of green street elements during a retrofit project for an existing roadway in Orange County, California. The technical feasibility analysis approach was applied to this typical roadway improvement project. The capacity improvement project proposes to widen an existing four-lane avenue to accommodate two additional lanes for a total of six lanes, as well as retrofitting an existing railroad crossing at grade into a vehicular underpass structure. The purpose of the proposed improvements is to alleviate the existing traffic congestion and delays occurring at the railroad crossing and to reduce the high accident potential at the crossing. Other project features include a stormwater pump station, extension of the major storm drain facility, and a temporary railroad shoofly to detour train traffic during construction, and corresponding utility relocation.

The 15-acre project area currently has 7 acres of impervious area. Widening the roadway will result in an increase of impervious area to 8.5 acres. The project drains southward into a succession of conveyance systems that are non-susceptible to hydromodification. Onsite structural LID BMPs are only designed to mitigate the 85th percentile storm event.

Challenges

There are numerous potential challenges to implementation of green components into the existing built environment. These include constraints during the construction phase, such as parking, trees, geotechnical and structural concerns, utility conflicts, physical constraints, slope, infiltration feasibility, and municipal codes.

The elements of technical feasibility that were analyzed include:

- Regulatory requirements,
- Site characteristics, and
- Infrastructure and project specific characteristics.

In terms of the regulatory requirements, there are no known CEQA concerns, no Environmentally Sensitive Areas (ESAs) in the vicinity of the project, and no Area of Special Biological Significance (ASBS) within 200 feet of the project. The receiving waters are, however, identified as impaired due to several pollutants including metals, nutrients, and bacteria. Onsite treatment BMPs considered should be effective for these pollutants.

The site characteristics limited the feasibility of infiltration. Geotechnical investigations at the site indicate the presence of loamy sand soil, which is typically favorable to infiltration. However, infiltration was ruled out because it could impact slope stability at the railroad subgrade, and contribute to the migration of an existing TCE-contaminated plume. During the investigations, groundwater has been observed 50 feet below grade but excavation will be limited to 30 feet. Geotechnical investigations have shown that the site is not a major contributor of bed sediment to the receiving stream.

Infrastructure and project-specific characteristics highlight the physical constraints set by the existing and future built environment, notably by the 12-foot width of travel lanes based on local standard plans and the requirement for a minimum setback as established by railroad regulator. The average annual daily traffic is expected to exceed 72,000 trips, the depth of the underpass structure was reduced to 15 feet to optimize the maximum allowable speed, and design of the roadway was adjusted to meet AASHTO HS-20 standards. Numerous utility lines, including oil, high pressure gasoline, fiber optic, and cable lines are located along the railroad and require to be permanently relocated under the depressed roadway. Funding originates from the municipality and the regional transportation agency, which do not restrict the use of dedicated funds for treatment BMPs.

Consistent with these observations, the application of LID principles onsite is limited to design of drainage structures and construction that allows pervious areas to receive runoff from impervious areas. However, the intent was to include LID facilities to the maximum extent feasible. As identified in the feasibility study, the improvement project adds traffic capacity in a confined right-of-way, which limits the opportunities to conserve natural areas and minimize the impervious footprint.

Results

As part of the design of the project, a landscaped bioretention was integrated at grade to the southwest side of the bridge. The 7000-cubic feet bioretention area has the capacity to treat 3.2 acres, which essentially consists of the roadway section that gravity-drains to the bottom of the underpass structure. A subdrain system along with pumping system capture and convey the stormwater runoff to the bioretention system at grade. Other sections of the roadway are treated by 15-foot wide biostrips that extend along the roadway. Biofiltration systems comply with the requirements of the NPDES permit and offer high removal performance for the identified pollutants of concern. An overview of the project LID features is provided in Figure 2.

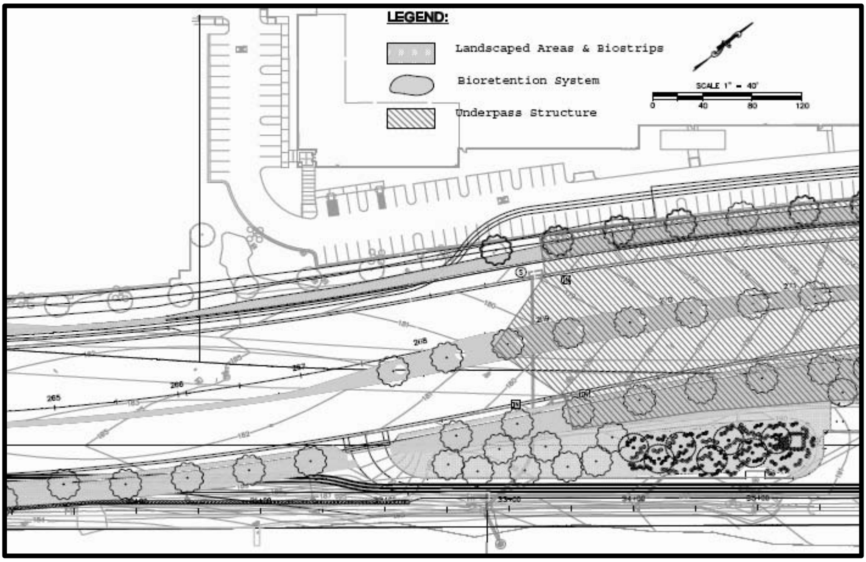

Figure 2 - Southwest Overview of Project LID Features

The costs associated with the incorporation of the bioretention system and the sump pump system are estimated at $270,000. The total capital costs of the project are $25 million. Maintenance and operation costs and will be driven by the usage of the sump pump and, as a result, by the frequency of storm events as no dry-weather flow is expected at the site.

Conclusions / Lessons Learned

Understanding the specific water quality regulations for LID and HM requirements in Southern California is challenging, but essential to meet MS4 permit requirements for roadway projects in the region. Using a water quality model can help simplify the process of determining the necessary size of basin required to meet LID and HM requirements in Southern California. One of the most difficult challenges of meeting the LID and HM requirements is locating sufficient right of way for mitigation devices. This is especially challenging where underlying soils are poor draining. These requirements make it increasingly critical to consider the required water quality mitigation at an early stage of the conceptual design and rough grading of the site.

This paper focuses on the use of the feasibility analysis to identify mitigation strategies to comply with LID and HM requirements for roadway projects in Southern California. However, the methodology would work for other types of development projects, as well. Adjustments would be required to run the model for other regions. The model was developed specifically for Southern Orange County in California, but runs on an HSPF framework that can be adjusted to reflect the characteristics of other areas.

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Keys to Green Streets: Collaboration and Sound Engineering

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Abstract

The Plainfield Avenue Bioretention Islands project in Grand Rapids, Michigan is an example of how public agencies and the private sector can effectively work together to accomplish green initiatives. This project utilized federal, local and private funds to finance street improvements that included innovative storm water management techniques. Michigan's Complete Streets legislation, the Michigan Department of Transportation's Context Sensitive Solutions process and the City of Grand Rapids' Complete Streets Resolution are public policies driving awareness of sustainable infrastructure practices, but they do not provide best practices or funding mechanisms. However, the collaborative efforts between stakeholders involved in the Plainfield Avenue project creatively generated sufficient funding to implement this multifaceted pilot project.

Introduction

Plainfield Avenue is a major transportation artery running through a potential historic district. The Creston Neighborhood Association and the Creston Business Association proposed combining their financial resources to create a boulevard streetscape on Plainfield Avenue as part of a master plan for the area. During this time, local concerns for the water quality of the Grand River were growing. The City of Grand Rapids collaborated with community leaders to implement low impact development techniques in the road design to manage storm water. A city engineer created a unique "bioretention island" concept that would improve both area water quality and aesthetics. The Michigan Department of Transportation took interest in financially partnering with the city on the place-making idea in order to use it as a pilot project for treating storm water within a roadway, instead of outside. The MDOT grant was used by the city to leverage funds from local foundations, while community leaders used it to leverage funding from the rest of the community. The city engaged the consulting firm Fishbeck, Thompson, Carr & Huber, Inc. to redesign the street and integrate the water quality improvements. The resulting design included seven bioretention islands constructed within the roadway median.

"Vital business districts are critical components of a livable city and a strong economy. Great neighborhoods and vital business districts go hand-in-hand; one cannot succeed without the success of the other. The choices that are made in

locating and designing business districts are also important factors in creating a walkable city and supporting transit." ~ City of Grand Rapids Master Plan 2002

Public Policy

The Plainfield Avenue Bioretention Islands project in Grand Rapids, Michigan is an example of how public agencies and the private sector can effectively work together to accomplish green initiatives. A number of events set the stage for the successful funding and implementation of this pilot project at the state and local levels. Beginning in 2003, the State of Michigan defined Context Sensitive Design as "a collaborative, interdisciplinary approach involving stakeholders for the development of a transportation facility that fits its physical setting and preserves scenic, aesthetic, cultural, and environmental resources, while maintaining safety and mobility." *1. (Michigan Department of Transportation Commission, 2005, Page 1)* In 2005 the Michigan Department of Transportation (MDOT) determined to "…pursue a proactive, consistent and Context Sensitive Solutions (CSS) process in keeping with its mission to provide the highest quality integrated transportation services for economic benefit and improved quality of life." *1. (Michigan Department of Transportation Commission, 2005, Page 1)* CSS principles include: early and continuous public involvement, effective decision-making, reflecting community values, achieving environmental sensitivity and stewardship, ensuring safe and feasible integrated solutions, protecting scenic resources and achieving aesthetically pleasing solutions. MDOT also decided that "A successful CSS program will require mutual commitment on the part of both transportation agencies and stakeholders to identify appropriate opportunities to plan, develop, construct, operate and maintain infrastructure in accordance with CSS principles…" *1. (Michigan Department of Transportation Commission, 2005, Page 1)* MDOT uses CSS as a planning, development and implementation process used for the whole life cycle of a project, and CSS is used on every project, regardless of type or size. In 2010 the Michigan Legislature passed legislation calling for Complete Streets, which are roadways designed with all users in mind, including motorists, bicyclists, public transportation riders and pedestrians of all ages and abilities. *2. (Michigan Legislature, 2010)* The law established a Complete Streets Advisory Council and charged it with educating and advising all levels of government, interest groups and the public on the development, implementation and coordination of Complete Streets policies.

The City of Grand Rapids has a tradition of working to support multiple transportation modes, thereby creating a street environment that accommodates motorists, pedestrians and cyclists. To demonstrate its continued commitment to the work of creating Complete Streets, the city passed a Complete Streets resolution in March 2011. The city committed to "design and construct Complete Streets wherever feasible, and staff will conduct a review of pertinent policies, ordinances and design specifications that affect the public right-of-way to ensure cohesive Complete Streets implementation." *3. (City of Grand Rapids City Clerk's Office, 2011, page 118)* The 2002 Grand Rapids Master Plan was updated in 2012. The update, called Green Grand Rapids, made recommendations for balanced, safe transportation and green corridors. This served as a foundation for support of the Plainfield Avenue Bioretention Islands project. *4. (City of Grand Rapids, Planning Department, 2012)*

Collaboration

The Creston neighborhood is located in the northeast quadrant of Grand Rapids, and is home to the Creston Neighborhood Association (CNA). Beginning in 2003, the CNA began to focus its neighborhood improvement work on its commercial corridor of Plainfield Avenue. Business owners in this low-to-moderate income area felt the general decline in commercial property conditions and the high number of vacancies needed the attention of the wider community. The resident members of CNA, in collaboration with the Creston Business Association (CBA), the City of Grand Rapids and other community stakeholders, began a formal process of evaluation of the neighborhood's socioeconomic profile and land use. In 2006 and 2007, over 100 individuals engaged in a design charette, the creation of the Creston Neighborhood Master Plan and the Creston Corridor Work Plan. Since 2006, CNA's Creston Corridor Initiative program has raised funds for façade improvements, public art murals and the placement of mosaic benches in public spaces. The Creston Car Show has become an annual marketing event for the neighborhood. These were all helpful toward positive place-making. However, with the 2008 financial downturn and a change in CNA leadership, the plans were shelved. In 2011, CNA's executive director and area business owners began work on the creation of a state-authorized Corridor Improvement District (CID), now named the North Quarter. The intent was to capture taxes which could be used to improve the three area commercial districts. All these planning efforts would soon become vital.

Plainfield Avenue was scheduled to be resurfaced in 2012 by the City of Grand Rapids with funding provided by the federal Surface Transportation Program and City of Grand Rapids capital improvement funds. Early in the design process, the city sent a data-gathering letter to homeowners and businesses along Plainfield Avenue, and to the CBA and the CNA, notifying them of the proposed work effort. The letter requested information related to the condition of the street and site observations (i.e. inadequate water pressure, road flooding, basement back-ups, etc.) During this initial stage, a local business owner expressed interest in a boulevard concept for the street, with trees and plantings, as noted in the Creston Master Plan. He cited this place-making vision as one incentive for his investment in the district.

The approaching project prompted the neighborhood and business associations to request a meeting with city engineers and their city commissioner to explore plans to enhance the road project with some type of planted boulevard. While the city agreed to review some areas where boulevards might fit, it was made clear that there was not sufficient funding available for the proposed place-making enhancements. It became obvious that while state and local public policy was leading to better projects, there were still two challenges: to identify best practices for these types of enhancements and to identify funding mechanisms.

Undaunted, the group asked the City Manager to attend one of the monthly CBA meetings. In front of a large group of stakeholders, he explained the city's unfortunate funding situation, but promised to search for any money left over from the previous year's construction contracts. The city found $30,000 and estimated that, if coupled with fundraising from the businesses, it might be enough to cover the cost of one or two traditional landscape islands.

The Second Ward Commissioner for the City of Grand Rapids had previously been involved in the design charette for Plainfield Avenue, as well as the meetings to form the tax increment finance district. The commissioner attended a Healing Our Waters Conference on the Great Lakes, which focused on the need to capture storm water on-site. Storm water is the number one cause of pollution in the nearby Grand River, which empties into Lake Michigan. Contaminants range from fine sediment, heavy metals and oils to debris, such as cigarette butts and soda bottles. The Grand River is only a few blocks away from the Plainfield Avenue business corridor.

Postponement of the resurfacing project to allow time to raise money was rejected because it could set the project back by years. However, the group was excited to learn that one of the city engineers had drawn up innovative plans for boulevard islands that would direct storm water beneath the road's surface toward concave planting areas in the roadway median. The water would surface in the "bioretention island" and flow by gravity along its length, irrigating the plants inside. The city engineer was reluctant to show the group his plans because he was not sure the idea could leverage a federal grant. However, the group immediately recognized that this design could capture the imagination of potential funders.

While this was happening, the local environmental action council launched a campaign to educate the Grand Rapids community about the need to capture storm water to prevent it from flowing into the Grand River. A newly-revised city master plan, Green Grand Rapids, included green initiatives similar to those reflected in the Creston Neighborhood's plans, setting the stage for a fundraising campaign.

The Second Ward Commissioner asked the City Manager to consider allowing donors to contribute over a 10-year period of time to make it feasible to raise more substantial amounts of money. The request was granted and the group immediately began going from business to business, reaching out to residents and contacting local foundations.

By November 2011, the city was working on a grant request to MDOT. City staff believed they had an operational design for bioretention islands that was worth consideration of a federal Transportation Enhancement (TE) grant. They defended the unique engineering design and convinced MDOT engineers and water quality experts that it would be effective and safe. The total project cost was expected to be about $330,000 for seven islands, enough to make a real difference in the local watershed. The city's place-making efforts were recognized as a good local example of MDOT's Context Sensitive Solutions process. The addition of bike lanes would

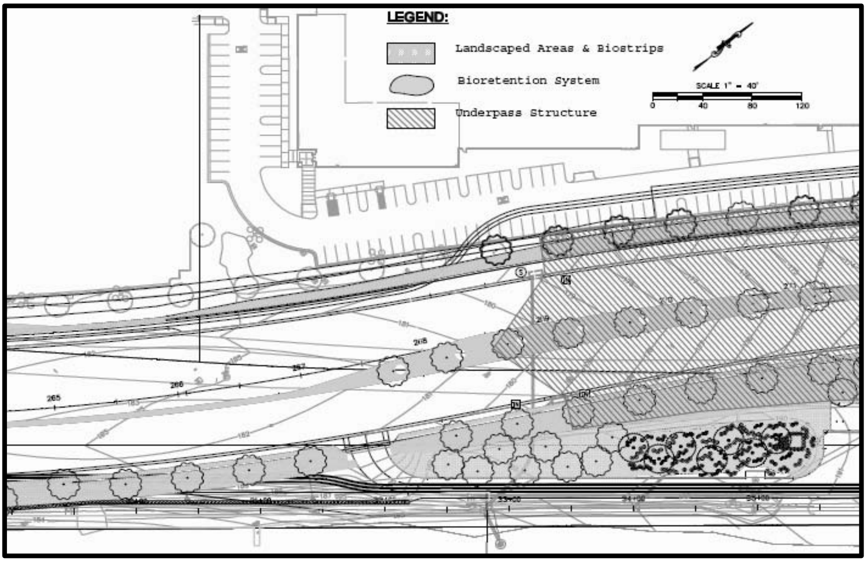

Figure 2 - Southwest Overview of Project LID Features

The costs associated with the incorporation of the bioretention system and the sump pump system are estimated at $270,000. The total capital costs of the project are $25 million. Maintenance and operation costs and will be driven by the usage of the sump pump and, as a result, by the frequency of storm events as no dry-weather flow is expected at the site.

Conclusions / Lessons Learned

Understanding the specific water quality regulations for LID and HM requirements in Southern California is challenging, but essential to meet MS4 permit requirements for roadway projects in the region. Using a water quality model can help simplify the process of determining the necessary size of basin required to meet LID and HM requirements in Southern California. One of the most difficult challenges of meeting the LID and HM requirements is locating sufficient right of way for mitigation devices. This is especially challenging where underlying soils are poor draining. These requirements make it increasingly critical to consider the required water quality mitigation at an early stage of the conceptual design and rough grading of the site.

This paper focuses on the use of the feasibility analysis to identify mitigation strategies to comply with LID and HM requirements for roadway projects in Southern California. However, the methodology would work for other types of development projects, as well. Adjustments would be required to run the model for other regions. The model was developed specifically for Southern Orange County in California, but runs on an HSPF framework that can be adjusted to reflect the characteristics of other areas.

Rapids Community Foundation, the Frey Foundation, the Meijer Foundation, the Kiwanis Foundation, the Morrison Family Foundation and the James and Shirley Balk Foundation. Additional individual private donations comprised an astounding $84,000, exceeding the total funding goal.

In a period of just a few weeks, at the busiest time of year, the Plainfield Avenue Bioretention Islands project was conceived and funded. Design of the islands was completed over the next two months and construction was completed in the summer of 2012. A ribbon-cutting ceremony in September featured a bus tour of the seven islands to explain how they work and highlight the drought resistant plants used to beautify the streetscape. Educational signage and a bronze plaque honoring donors will be installed in the corridor in 2013.

Sound Engineering

Plainfield Avenue from Leonard Street to Ann Street is a principal arterial route approximately 0.90 miles long and located in the northeast quadrant of Grand Rapids, Michigan, as shown in Figure 1.

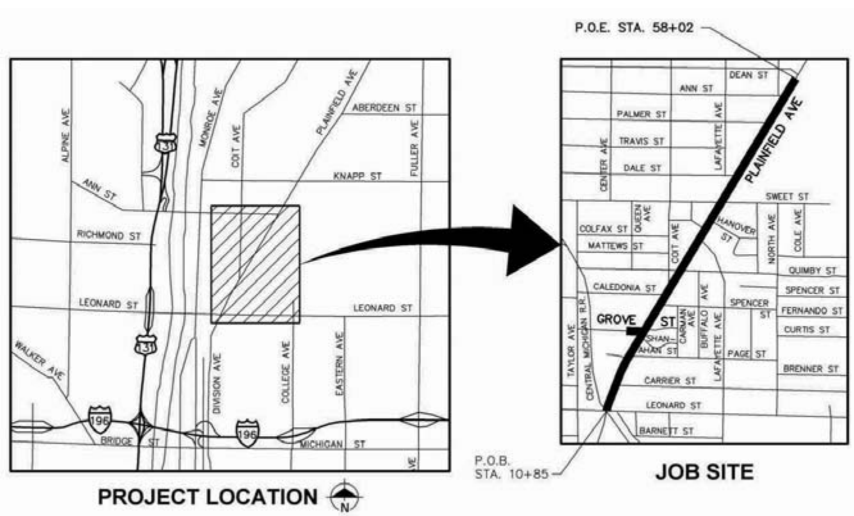

Figure 1: Plainfield Avenue Project Location

During the initial scoping stages of the project in September 2011, various stakeholders and city departments reviewed the private and public utility improvements needed within the project limits and discussed the impacts of these changes. City departments represented at these meetings included: Traffic Safety, Planning, Environmental Services, Water, Street Lighting, Parks and Recreation, Parking Services, Fire, Police and others. Combined sewer overflow (CSO) work along Plainfield Avenue between Grove Street and Spencer Street was required to complete one of the final contracts for a 20-year phased infrastructure project. The CSO project has eliminated 99.9 percent of the combined sewer overflows to the Grand River. Water main replacement and roadway reconstruction was also proposed in the affected section of Plainfield Avenue.

Green Grand Rapids is a planning document created in October 2011, which inventories and targets the implementation of green infrastructure throughout the city. Targets include balancing automobile transportation and bikeway networks with the greening of priority streets. The document outlines goals to create a community that enriches people and is balanced with nature. In Green Grand Rapids, Plainfield Avenue was identified as a "major street" with a limited tree canopy. Its canopy cover ranged between 3 and 11 percent, which is low in comparison to targeted goals.

The Grand Rapids Sustainability Plan identified several targets to provide services to the community while promoting economic prosperity, ensuring social equity and protecting the integrity of the natural environment for all citizens. *5. (City of Grand Rapids, Office of Energy and Sustainability, 2011)* This triple bottom line approach using city leadership, partnership with others and commitment to citizens is integral to all functions of the city.

The first target is to reduce greenhouse gas emissions (carbon footprint) and its impact on climate change by increasing the number of miles of on-street bike lanes. Plainfield Avenue was identified as a corridor in which to increase the use of bicycles and promote a north-south connection into and out of downtown Grand Rapids. Bike lanes had already been established along portions of Plainfield Avenue north of Sweet Street to Three Mile Road as part of a "roadway diet" completed in 2006. This effort reduced four travel lanes to two ten-foot through lanes, two five-foot bike lanes and a center turn lane. The impact did not reduce the capacity of the roadway, but it did reduce average travel speeds by several miles per hour.

A second target is to protect and maintain healthy ecosystems and natural habitat by increasing tree canopy in the city, increasing the use of low-maintenance grasses and native plants used in landscaping, and increasing the diversity of tree species planted. The addition of trees and other vegetation along the Plainfield Avenue corridor would help to achieve this goal.

Finally, it is the city's goal to improve water quality in the Grand River and its tributaries by reducing storm water discharge and pollutants. The city's National Pollutant Discharge Elimination System storm water permit requires the city to prepare a Watershed Master Plan that addresses problem areas and the Total Daily Maximum Load for established parameters that may affect storm water discharging to waters of the state (i.e. the Grand River). The city developed the plan and implemented this demonstration project as part of the effort.

The CBA and the CNA hosted a design open house to solicit input from the Creston community regarding the proposed road modifications. Designers from the city and Fishbeck, Thompson, Carr & Huber, Inc. (FTC&H) presented the preliminary designs for the bioretention islands, solicited input and discussed concerns. During interviews and surveys of local residents and businesses, several themes emerged, including the need to revitalize the local business community. Business owners wanted to create an environment which was inviting for retail customers. They wanted to see vacant stores occupied with vibrant new businesses. They wanted to establish the community with place-making in mind, where destinations are created, sociable and transformative.

A theme that developed was to beautify a highly urban neighborhood by providing green space. The impacted Plainfield corridor contained few shade trees and sparse landscaping, especially at the southern end. The overall area is characterized by older businesses and homes, many of which are located within close proximity to the roadway. The islands provided an opportunity to integrate the beneficial functions of plant material into this highly developed environment, including: interception and uptake of rainwater, microclimate cooling (thus combating the heat island effect), and providing an aesthetically pleasing asset to the neighborhood. These impacts may have secondary effects of increasing property value, improving the general perception of the neighborhood as a desirable destination, and attracting new businesses and residents.

Another theme that emerged was the problem of the fast pace of traffic through the center of the community. Although the volume of traffic on Plainfield Avenue was high (estimated to be over 16,000 vehicles per day), businesses wanted to allow these levels in order to maintain retail exposure. A three year traffic analysis from 2008 through 2010 was conducted along the corridor by the city's Traffic Safety Department. This study did not elucidate any significant trends or patterns for any specific type of crash. Parking was important and therefore its removal to provide additional green space was not supported. Removal of parking was also not feasible given the already narrow sidewalk areas along store fronts. What emerged was a goal to use a context sensitive design which could maintain or improve the current level of traffic service at all of the intersections while reducing average traffic speeds.

Leonard Street is just south of the Plainfield Avenue project area, with a small section under the jurisdiction of MDOT (Business Loop U.S.-131). Plainfield Avenue north of Leonard Street has five lanes of traffic, including four through lanes and a left turn lane. Protection of this geometric configuration was required to maintain the current level of service for the roadway. Introduction of bike lanes in this section would not be possible without significant right-of-way acquisition and roadway widening. However, to the north, from Carrier Street to Grove Street, a "road diet" was proposed with 5-foot bike lanes, a 10-foot left turn lane and the elimination of two parking spaces just north of Page Street. From Grove Street to Sweet Street the roadway was generally 46 feet wide, and the road diet was continued with the addition of a 10-foot left turn lane and the reduction of the through lane widths from

15 feet to 10 feet, along with two 8-foot parking lanes. The section north, from Sweet Street to Ann Street, remained the same with a 10-foot center turn lane, two 11-foot travel lanes and two 5-foot bike lanes. Adjusting 125 feet of curb just north of Ann Street on the east side of the roadway was necessary to provide the 11-foot travel lanes, a northbound 5-foot bike lane, a center turn lane and 8-foot parking on the west side.

Although the American Association of State Highway and Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets 2011, 6th edition, specifies that 10-foot lanes may be used where truck volumes are low and speeds are less than 35 miles per hour, MDOT guidelines require minimum travel lanes of 11 feet. *6. (American Association of State Highway and Transportation Officials, 2011)* Therefore, it was necessary to secure a design exception for the use of 10-foot travel lanes through this corridor. The city's Traffic Safety and Engineering Departments met with MDOT to provide information necessary to receive a design exception to allow the 10-foot travel lane widths.

While preliminary design concepts and cost estimates were developed through the fall of 2011, the design of the seven bioretention islands did not begin in earnest until December, after MDOT provided the Conditional Commitment for a TE grant. However, the scope of the project still could not be identified in full until there was commitment from local foundations, as well as the local business and neighborhood associations, for the necessary local match funding and maintenance funding. The design of the bioretention islands along Plainfield Avenue was a joint effort between the city's Engineering Department and FTC&H.

The islands vary in length from 60 to 220 feet and span approximately one mile. The available width of the islands was determined by the roadway design, which included 10-foot left turn lanes. MDOT Local Agency Programs Guidelines for Geometrics require a minimum of one foot of separation between the edge of the travel lane and any curbing. *7. (Michigan Department of Transportation, 2008)* Therefore, a 1-foot inverted gutter pan with a 6-inch wide curb head was selected. The inside island width was limited to a maximum of seven feet. An initial concept for draining storm water runoff from the sides of the road into the island was to discharge the storm water through a shallow gravity pipe system. However, the final vetted concept was modified with a siphon type system connecting the new catch basin connections to an inlet structure at the center of the islands (see Figures 2 and 3).

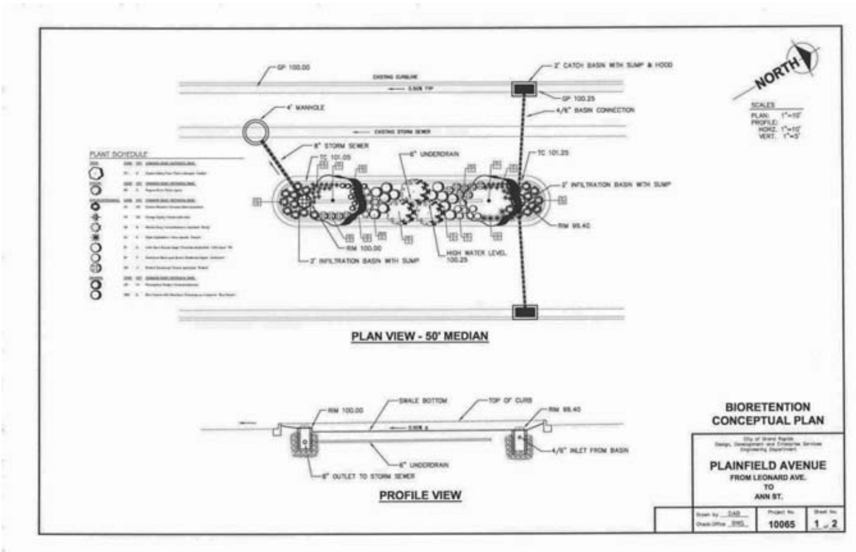

Figure 2: Plan View - Bioretention Conceptual Plan

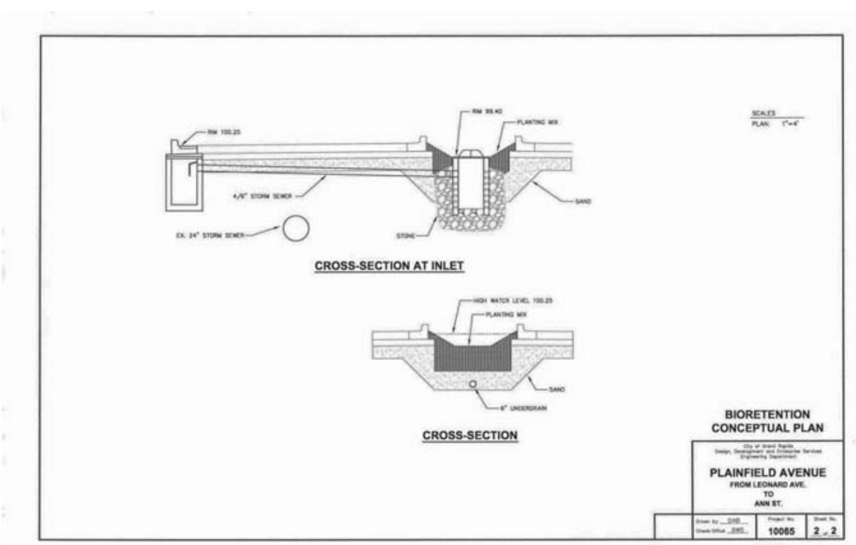

Figure 3: Section View - Bioretention Conceptual Plan

As Figure 4 illustrates, a 1-foot infiltration hole in the bottom of the inlet structure was provided to allow water to infiltrate into the ground after rain events. Each inlet casting rim was set at approximately 0.85 inches below the lowest gutter grade of the new catch basins at the outside edge of the roadway. The longitudinal slope of the island generally matched the slope of the roadway, but at no less than 0.5 percent. An outlet overflow structure was designed at the downstream end of each island, and the rim elevation was set to begin to discharge storm water back into the storm sewer if depths in the basin reach 0.25 feet below the lowest gutter grade. This was to ensure that the overflow structure would be in operation before any overflow could occur from the island to the street. In addition, if the island overflow system became plugged, the storm water in the gutter would bypass the new catch basins connected to that island and flow to the existing catch basins connected to the existing storm sewer system.

Soils play an essential role in fulfilling the water treatment goals of the islands and supporting plant establishment. The existing roadbed and underlying soil were excavated to a depth of approximately four feet, then backfilled with one and a half feet of sand and a minimum of two feet of special planting soil. The sand layer was placed to ensure good infiltration directly below the growing medium. A 6-inch underdrain was placed below the sand to collect groundwater and discharge it into the existing storm sewer to ensure that saturated conditions beneath the roadway do not persist for long periods of time. The planting mix is composed of 50 to 60 percent sharp sand, 20 to 30 percent topsoil and 20 to 30 percent compost. The sand component ensures good infiltration, while the topsoil and compost components provide a nutrient-rich medium to support plant establishment. In addition, the high cation-exchange capacity of the clay and organic fractions capture dissolved metals and other contaminants, removing them from storm water.

Island curb ends were designed with a special rolled curb end and reinforcing steel bars to prevent damage to the curb head from street snow plows. The depth of the curb was made to be two feet, two and a half inches, and three reinforcing bars were included in the curb to provide sufficient mass to set the curb in place and prevent movement with the limited and unconsolidated soil located behind the curb. Side slopes were set to a maximum of 1:2 vertical to horizontal. A 6-foot flat area was designed within the ends of each of the island areas to provide a more visible space for plantings. Two 4-inch conduits with caps were run under the roadway to each island for potential future installation of irrigation or electric service for holiday lighting. At the time of design, there was not sufficient funding for these improvements. However, installation of the conduits to prevent future damage to the street was considered wise.

Water quality improvements were expected to result from the project. The contributing area to all of the bioretention islands is 3.3 acres, or 143,748 square feet. The corresponding water volume generated from this area (based on the criteria of one inch of runoff from the impervious areas) is 11,979 cubic feet, or 89,609 gallons of storm water. No significant pervious areas were estimated in this calculation.

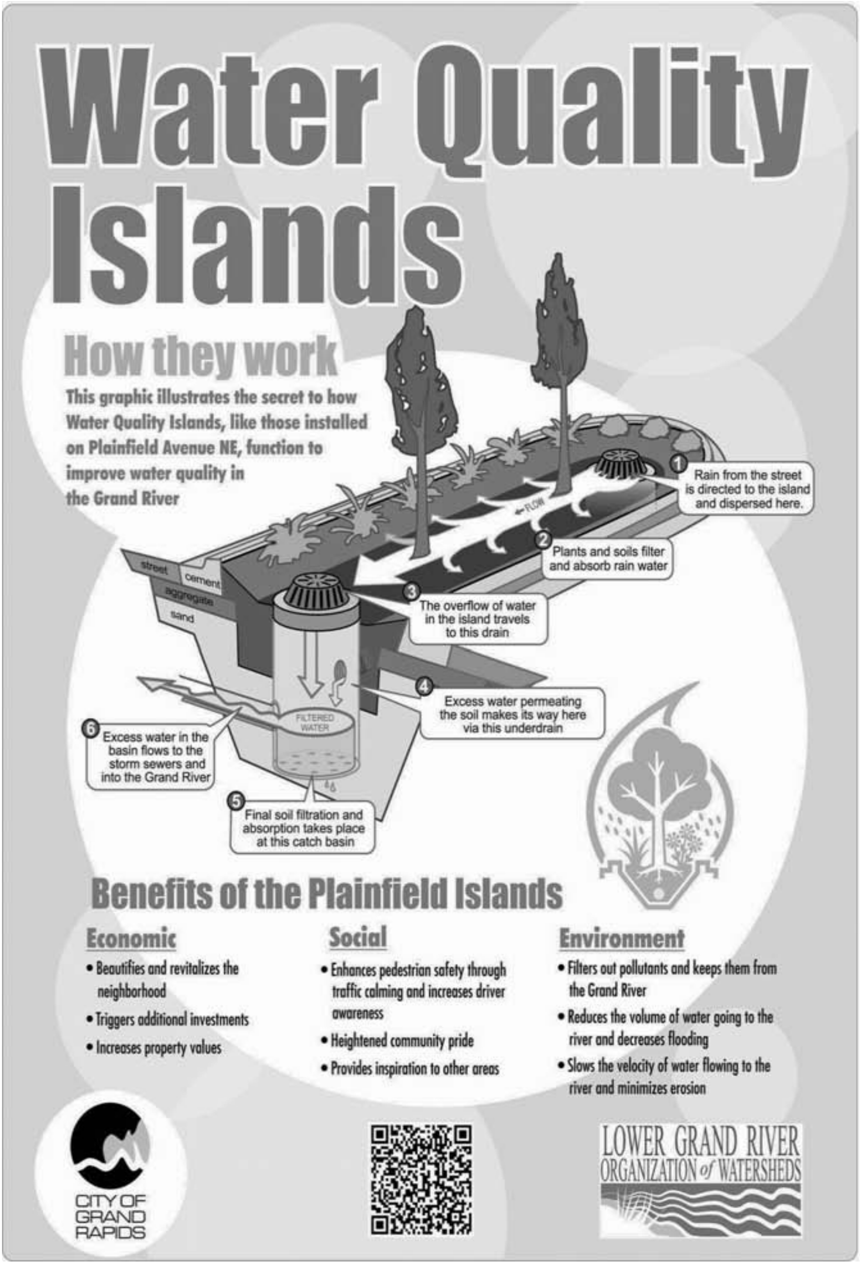

Figure 4: Water Quality Islands – How They Work

The infiltration rate of the bioretention islands was assumed to be 12 inches per hour. The rating for total suspended solids removal was estimated to be high. Groundwater is well below the roadway in this area and underlying soils are generally sandy. It was anticipated that much of the storm water would infiltrate into the soil and recharge groundwater.

The plant material utilized in the islands was selected to withstand a harsh urban environment. The selected species are drought, heat and salt tolerant. They are also tolerant of shallow inundation for short periods of time. The designers worked with the city forester to ensure trees and shrubs were compatible with the city's urban forestry goals. The forester desired that trees be incorporated into the design due to their effectiveness in intercepting storm water. The southern islands contain Accolade elm (*Ulmus japonica x wilsoniana* 'Morton'), the Society of Municipal Arborists' 2012 Urban Tree of the Year. This large shade tree species was placed in this area due to a lack of shade trees. Smaller ornamental Capital callery pears (*Pyrus calleryana* 'Capital') were utilized in the northern islands. These trees provide year-round visual interest and have a narrow growth habit, so they will not grow into traffic lanes. Flowering shrubs, taller ornamental grasses and taller perennials were placed in the center of the islands, with cultivars two feet or less in height planted at the perimeter and ends of the islands. This ensures clear visibility for vehicles in turning lanes. The diverse array of vegetation provides a colorful display throughout the growing season, while providing valuable storm water treatment.

A cost benefit analysis was conducted for the bioretention islands in comparison to the conventional catch basin inlet devices, hydrodynamic separators and leaching basins. Catch basins are a cost effective method to control total suspended solids at $21,408 per ton removed. Therefore, a minimum of two additional catch basins were provided at each island location. The existing catch basins were maintained in place as back-up and for larger storm events which exceed the capacity of the inlets to the bioretention islands. Although the islands were the most costly of these best management practices (BMP), they provide other benefits not provided by the other BMP's. These benefits include:

- **Reduced storm water runoff:** stores and filters storm water, which minimizes downstream bank erosion, reduces flood impacts and prevents the storm water from polluting local waterways
- **Increased groundwater recharge:** has the potential to increase groundwater recharge by directing water into the ground instead of pipes
- **Improved air quality:** improves air quality through uptake of air pollutants and the deposition of particulate matter
- **Reduced atmospheric CO_2:** reduces carbon dioxide emissions through direct carbon sequestration
- **Reduced urban heat island:** through evaporative cooling and reduction of surface albedo, the bioretention works to reduce the urban heat island effect and reduce energy use in the community.

A maintenance plan was developed for the islands. The plan was prepared to evaluate the estimated cost for maintenance and to develop a sustainable financing structure to ensure the islands would be maintained with limited city involvement. Maintenance tasks include:

- Inspect for and remove weeds and undesirable plants
- Inspect soil and repair eroded areas
- Mulch void areas
- Prune woody vegetation and remove herbaceous dieback at the end of the growing season
- Identify and treat diseased trees and shrubs
- Remove and replace dead and diseased vegetation
- Remove litter and debris
- Inspect and maintain the underdrain system to keep it functioning properly
- Inspect and remove accumulated sediments if buildup reaches 25% of the ponding depth
- Repair and replace damaged curbs and damaged signs
- Irrigate vegetation during times of extreme drought after the establishment period to provide one inch of water per week

The total estimated cost ranges between $1,200 and $2,900 per year. Assuming an initial fund of $30,000 and a return on investment of five percent, approximately $1,500 could be used for maintenance each year without additional resources required by the community. The city agreed to catch basin cleaning. The Creston Business Association acknowledged full responsibility for all other maintenance of the islands. The North Quarter Business Improvement District has recently been approved, which will provide additional options for care and maintenance of the islands in the future.

Conclusion

Public policy in support of green streets creates a foundation, but effective project development and implementation further requires both best practices and funding mechanisms. Faced with the challenges of a pilot project and a funding gap, the firm determination of all the stakeholders to work in partnership created a scenario that yielded positive results, with both immediate and long-term impacts.

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Benefits of Proactive Monitoring of Traffic Signal Timing Performance Measures – Case Study of a Rapidly Developing Network

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ABSTRACT

Some insight into the benefits of regularly and frequently maintaining traffic signal timings within and across jurisdictional boundaries is provided. The rapidly growing Cranberry Township located at the crossroad of two interstate highways (Pennsylvania Turnpike (I-76) and I-79) in the state of Pennsylvania, twenty miles north of Pittsburgh is used as a case study. Environmental and economic costs due to the absence of monitoring and updating traffic signal timings are estimated. While traffic signal timing optimization and coordination is a cost effective strategy to reduce travel time and its consequential air emissions along corridors, implementing such timing plans are only effective at and around the time of implementation, while travel demand remains constant. As times passes, with the fluctuation of vehicular demands, especially in rapidly developing areas, timing plans need to be monitored and modified. In Cranberry Township such developments and travel demand fluctuations result in significant increase in costs of travel (time and fuel) and external environmental costs. Estimates show that timing plans that were at their optimal level at the time of implementation, in less than two years result in 18 percent increase in the cost of fuel, 13 percent increase in the cost of travel time and 11 percent increase in the external environmental costs, if left unmodified.

INTRODUCTION

To ensure that a traffic signal network is working at its highest efficient level and traffic is flowing safely and smoothly, regular monitoring of traffic demand and travel patterns is necessary. Frequent evaluation of traffic volumes and signal timings followed by updating of already implemented strategies and incorporating new strategies is critical for rapidly growing cities and networks. The updates of implemented timing strategies may include new timing plans, phasing, and offsets to better address the level of demand. Timing plans, phasing, cycle lengths and offsets are essential for the operation of traffic signals and signalized intersections.

Proactively monitoring and evaluating the operation of traffic signal systems and strategies can be labor intensive. Because of budget constraints and labor shortages, many jurisdictions are not able to operate their traffic signal systems to provide optimal traffic flow and roadway capacity at all times, resulting in increased traffic congestion, delays and emissions along their networks. Consequently, imperfect conditions along arterial networks can increase some of the secondary negative impacts such as accidents, noise and reduced safety.

This paper estimates costs (direct and external environmental costs) associated with traffic signal systems if they are not monitored, evaluated and maintained on a regular basis for the level of vehicular and pedestrian demands. Implementing traditional measures, such as signal timing optimization and coordination, to alleviate the environmental problems can be cost effective if they are maintained and monitored properly and operate efficiently (ITE 2012). While it seems intuitive that not updating traffic signal timings on a regular basis would lead to a suboptimal level of network operation, the results of this work illustrate that costs associated with the lack of frequent evaluation of performance measures can be substantial. The objective is to encourage jurisdictions and traffic operation teams to develop a system monitoring program to allow each signalized intersection in their network to operate as efficiently as possible, at all times. Traditional signal timing based on time of day (TOD) operation may only be at an optimal level on the day that the timings were implemented and fine-tuned since vehicular demand and travel patterns might change soon after the implementation of the timings. Growth in population, fluctuations in volume, changes in travel patterns, and developments in the area all can reduce the efficiency of the implemented signal timings. The degree of such impact is clearly demonstrated in this paper using scenario-based analysis. The cost of fuel and time as well as the external air pollution cost of not monitoring and updating signal timings are estimated for signals along a traffic signal network in Cranberry Township, Pennsylvania.

In this paper, we estimate the external air pollution costs of not monitoring and updating signal timings in Cranberry Township, Pennsylvania utilizing air pollution valuation data (Muller 2007). Cranberry Township took an enormous step in improving traffic operations by implementing new signal timings and updating their software and hardware systems within the past couple of years in order to address the high level of growth happening throughout the Township. The combination of a number of factors including newly implemented signal timing plans, newly implemented hardware and software traffic signal systems throughout the Township, the geographic location of Cranberry Township and its rapid economic and population growth, makes Cranberry Township a feasible case study to illustrate costs associated with the lack of proactive monitoring of traffic signal timing performance measures.

EXISTING TRAFFIC SIGNAL RETIMING COST AND BENEFIT ASSESSMENTS

The benefits and measures of effectiveness of traffic signal retiming have been quantified and evaluated in the literature, most of which focus on U.S. case studies. Based on an analysis conducted on the Maryland Department of Transportation retiming project of 215 signals in the Washington DC area, travel delay was decreased by 13 percent and number of stops by 10 percent (ITE 2004) by implementation of new timings. The same paper lists more examples of successful signal retiming projects including a Lexington, Kentucky retiming project that reduced delays by 40 percent; the Traffic Light Synchronization Program in Texas reduced delays by 14 percent; and a Jacksonville, Florida retiming project decreased travel time by 7 percent (ITE 2004). According to the Institute of Traffic Engineers (ITE 2012), traffic signal retiming can result in 7-13 percent reduction in overall travel time, 15-37 percent reduction in overall traffic delay, and 6-9 percent in overall fuel savings.

While many studies report on typical measures of effectiveness such as number of stops, delay, speed, travel times and fuel consumption, only a few quantify benefits and costs of signal retiming in terms of environmental impacts and user costs (Day 2010). This work examines cost savings of the traditional signal monitoring and retiming in terms of time and fuel, environmental damages, mortality and morbidity.

PROJECT BACKGROUND

Cranberry Township, Pennsylvania is located at the crossroad of two interstate highways, the Pennsylvania Turnpike (I-76) and I-79, twenty miles north of Pittsburgh in neighboring Butler County. Its proximity to the major interstates as well as the city of Pittsburgh has encouraged many businesses and corporations to move their headquarters and offices into the Township resulting in major and rapid growth and economic and social changes over the last decade.

To address this growth, Cranberry Township took an enormous step in improving traffic operations by implementing new signal timings and updating their software and hardware systems within the last two years (since 2010). The combination of a number of factors including these newly implemented signal timing plans, and newly implemented hardware and software traffic signal systems throughout the Township, along with the geographic location of Cranberry Township and its rapid economic and population growth, makes Cranberry Township a feasible case study to illustrate costs associated with the lack of proactive monitoring of traffic signal retiming performance measures.

Cranberry Township currently operates and maintains a total of 44 traffic signals, 37 within or partially within the Township limits, while the rest are in Adams and Marshall Townships, as well as one in Seven Fields Borough in Butler County, Pennsylvania. Two major corridors in Cranberry Township are Route 19 and Route 228. Route 19 is significant to the traffic network systems as it runs parallel to the Pennsylvania Turnpike (I-76) at the junction with I-79. Route 228 and Route 19 provide access to both these interstates. Figure 1 illustrates the location of Cranberry Township, its signalized intersections and the boundary of this analysis.

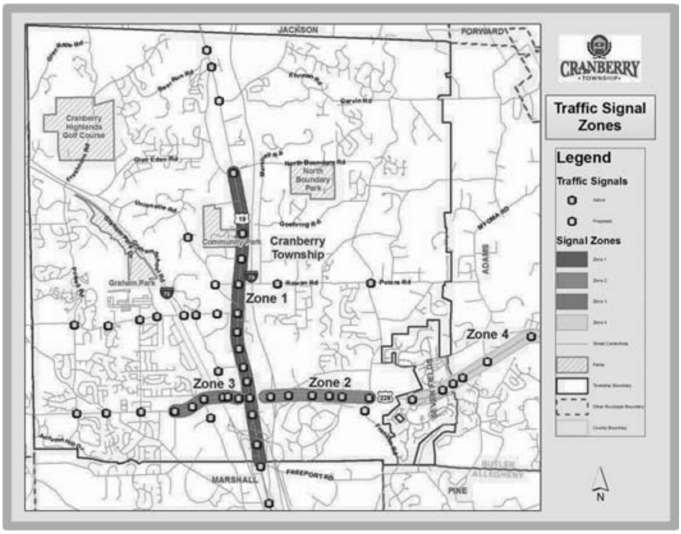

Figure 1: Map of Cranberry Township Traffic Signal Zone, Source: Cranberry 2012

During the Fall of 2010, Cranberry Township opened a state-of-the-art Traffic Operation Center (TOC), currently responsible for the operation and maintenance of the signalized intersections owned and/or operated by the township. Cameras are currently installed at fifteen key intersections, and most signalized intersections are part of a centrally based system communicating through a fiber optic network. Cranberry Township has a mix of NEMA TS2 Type 1 operation, Econolite ASC/3 Controllers, Aries Closed Loop Operating System, and Econolite's Central Based Centracs System.

To improve operations, Cranberry Township implemented coordinated timing plans for all its signalized intersections in April of 2011, using vehicular traffic counts collected in 2009. All signalized intersections are currently running time of day (TOD) coordination plans. TOD coordination plans mean that timing plans vary for each peak period (i.e. AM, Midday, and PM) depending on the level of demand. In Cranberry Township, there are four different TOD plans AM, Midday and PM timing plans as well as Saturday timing plans. There is no gap between the timing plans, hence at no time between the AM, Midday and PM periods the intersections run under a free operation scenario. Each route runs a different coordination plan time. Table 1 shows the hours associated with each plan and the cycle lengths run during each plan.

Table 1: Cycle Lengths and Peak Periods in Cranberry Township

Time	*Cycle Length (sec)*
AM Peak (5:00AM – 10:00AM)	130
Midday (10:00AM – 3:00PM)	140
PM Peak (3:00PM –10:00PM)	140

METHOD

To evaluate the timings implemented in Cranberry Township and to measure their cost effectiveness, new manual counts at the key intersections were collected throughout the Township. These counts were compared with the original counts, collected in 2009, used for the development of the already implemented timing plans.

Synchro/SimTraffic optimization software (Trafficware 2012) was used for modeling the network and timing plans. The model was validated based on travel times measured while driving the corridors in the field. In order to have a reasonable sample size for calibration, four travel time runs were conducted along each corridor in each direction. Then the model and timings were adjusted using the new vehicular counts collected at nine intersections. Counts show significant fluctuation throughout the corridor consistent with growth as well as changes in travel patterns compared with the 2009.

Measures of effectiveness including travel time, speed and number of stops were compared between the two sets of vehicular counts keeping the timing plans unchanged. To evaluate costs associated with the timing plans in place, direct costs (including costs of time and fuel) and indirect costs (external environment) were estimated using measures of effectiveness such as travel time and speed. It is important to distinguish that direct costs are typically incurred by those driving along the corridors while indirect cost are incurred by the society at large.

To estimate the direct and indirect costs, travel time savings and speeds were converted into miles saved in terms of vehicle miles traveled (VMT) and then converted into the cost of fuel. The price of gasoline was assumed to be $3.5 per gallon. Travel time difference resulted from the new counts vs. the old counts were also converted to the cost of time. The average value of time was assumed to be $16 per hour (TTI 2011).

To estimate the fuel energy and cost of fuel, vehicle emission factors were determined using EPA's Mobile 6.2 (MOBILE 6) emissions modeling tool. The model estimates emissions from fuel combustion, evaporative losses, tire wear, break wear for all types of vehicles including passenger vehicles, trucks, buses, etc. (EPA 2003). Fuel use (FU) is a function of fuel energy (FE) and daily vehicle miles traveled (DVMT) and fuel cost (FC) is a function of fuel use and the price of gasoline.

$$FU = FE \times DVMT \quad (1)$$

$$FC = (FU \times P)/C \quad (2)$$

where:

FU = Fuel use (Mega Jules(MJ)/day);

FE = Fuel energy (MJ/km);

FC = Fuel cost ($/day);

P = Price of gas ($3.5/gallon);

C = 121.3 MJ/gallon of gasoline

$DVMT$ = Daily vehicle miles traveled (miles/day)

To estimate the cost savings of external air emissions, the Air Pollution Experiments and Policy (APEEP) analysis model was used (Muller 2007). APEEP connects county level air emissions through air quality modeling to exposures, physical effects and monetary damages (NRC 2010). For each pollutant, the model estimates cost of mortality, morbidity, and environmental damages which includes timber loss, visibility, and forest recreation to name a few. Six million dollars was assumed to be a value of statistical life for estimating the cost of mortality in APEEP. CO2 equivalent cost of 30 dollars per ton was used for the estimation of carbon dioxide (NRC 2010) and 520 dollars per ton was assumed for the cost of carbon monoxide (Matthews 2001).

Estimating the extra miles traveled resulting from the use of new vehicular counts and joining them with the MOBILE 6 emission factors in grams per mile and APEEP costs in dollar per gram, the external environmental cost savings were estimated for carbon dioxide, sulfur oxides, nitrogen oxides, ammonia, carbon monoxide and particulates.

$$C_i = DVMT \times EF_i \times C \qquad (3)$$

where:

C_i = Cost of pollutant i ($/day);

$DVMT$ = Daily vehicle miles saved (miles/day);

EF_i = Emission factor for pollutant i (gram/miles); and

C_i = Cost factor for pollutant i ($/1000gram)

RESULTS

The results of this study show that if timing plans that were implemented in April 2011 in Cranberry Township were not updated to meet the current (2012) travel demand, the average speed throughout the network would decrease by about 13 percent, cost of time due to travel delay would increase by 13 percent, cost of fuel would increase by 18 percent and the external environmental costs which include costs due to health impacts of air pollutants would increase by about 11 percent. Annual cost of fuel for the whole network would increase from about $3.4 million to $4 million, while the total cost of driving would increase by about $2 million a year. It is important to note that original vehicular counts were collected in 2009, and timing plans were implemented in 2011, approximately a year and a half later. Since, in the field of traffic signal timing and traffic engineering, it is customary to fine-tune the implemented timings in the field after design and deployment, I assumed that the timings implemented in 2011 were adjusted at the time of implementation to accommodate for the volumes at the time of deployment (April 2011). In other words, the 2009 counts only served as a basis for the analysis and design. It is therefore incorrect to assume that timing plans implemented in 2011 used two year old vehicular counts; instead they have been adjusted for the demand at the time of implementation in 2011. Knowing this, the analysis presented here, compares the timings resulted from the demand in 2011 with the demand of 2012. The estimates provided hereafter do not include other external costs incurred by the users such as accident or maintenance costs. Table 2 shows the actual costs associated with each of the categories.

Table 2: Total Direct and Indirect Annual Costs Associated with Driving Along Arterials in Cranberry Township

Urban Area	At the Time of Implementation (2011)	Now (2012)	Percent Increase
Direct: Annual Cost of Fuel (Million $)	3.4	4	18
Direct: Annual Cost of Time (Million $)	15	17	13
Indirect: Annual External Environmental Cost ($)	720,000	800,000	11
Total (Million $)	19	21	14
Total Cost (Million $1000/Signal)	430	490	14

Table 3 shows the total external emissions cost of driving by pollutant in Cranberry Township. Costs of CO_2, VOC and CO show more of a significant change compared with the rest of the pollutants.

Table 3: External Emissions Cost of Driving per Pollutant (1000$/Year)

	CO_2	NOx	VOCs	CO	SOx	PM	NH3
Total Cost of Driving (2011)	$280	$30	$110	$180	$2	$9	$110
Total Cost of Driving (2012)	$330	$33	$120	$190	$2	$9	$110

DISCUSSION

The increase of 14 percent in total cost of driving for timings that have been implemented in April 2011 is rather significant. As demand increases the total cost of driving will also further increase. Cities cannot rely on timing plans that are implemented in their jurisdictions for a long period of time when monitoring and reevaluating of the timing plans are crucial to the efficiency of their travel networks; otherwise the system will be running at a suboptimal level. In many cases, with the fluctuation of vehicular traffic volumes and demand, if an agency does not have funding and resources to retime their signals, running the traffic signals on free mode vs. coordinated timing plans may result in less of a negative impact. In the case of Cranberry Township for instance, during the AM peak period, using the 2012 counts and running the network in free mode, resulted in 10 percent lower delay throughout the network compared with the status quo. Conducting a benefit cost analysis for the timing plans may warrant running the signals in free operation mode. For cities where the traffic patterns and volumes remain mostly constant, the negative impacts might be minimal, and timing plans can remain effective for longer periods of time. The recommended traffic signal retiming interval is two to three years. However, most agencies exceed this time interval and retime their signals within a five year period, because of limited resources in most cases (NCHRP 2010). In the case of Cranberry Township, assuming linear demand increase, retiming the traffic signals after five years from the original time of implementation in 2011 could result in up to 70 percent increase in total cost of driving in the Township.

Assuming a cost of signal retiming of $3,700 for each signalized intersection (NCHRP 2010), retiming of all signals within the network would cost Cranberry Township about $160,000 annually (based on 44 intersections). This cost is only about 7 percent of the total cost of driving, which turned out to be about $50,000 per signal. Therefore, economically and environmentally, it makes sense for the Township to proactively monitor and retime its signalized intersections annually.

It can be argued that costs estimated above are mainly paid by the users (drivers pay for the cost of time and fuel) and are not a direct cost to the authorities. Social and environmental costs of not maintaining the signals were estimated to be a total of $80,000 in Cranberry Township, which translates into about $1,800 per signal. The social benefit cost ratio in this case is 0.5. This added to other social benefits of proactive signal timing maintenance such as safety should encourage the government agencies to provide timelier and more frequent funding for this congestion management measure.

In summary while signal re-timing seems like a basic strategy in the world of traffic operations and management, depending on the jurisdictions' level of travel demand growth, waiting too long before updating the timings can be significantly costly and counter effective. In fact, proactive retiming of signal systems can be one of the most cost effective strategies, often overlooked and ignored, to achieve travel time and environmental benefits.

CONCLUSION

In this paper, external air emissions costs associated with obsolete signal timing plans especially in rapidly developing areas were estimated. These estimates can be used in benefit cost studies to assess the benefits of proactive signal monitoring and retiming in various geographic areas. Although costs of time and fuel are larger in magnitude, the external environmental costs resulting from timing plans that are outdated shortly after their implementation remain considerable. To promote environmental and economic sustainability, responsible agencies and funding sources need to give a substantial attention to the timely evaluation and maintenance of signal timings.

In lieu of manually evaluating and re-timing traffic signal timings other methods and strategies such as implementing adaptive signal control systems can be considered. While this paper did not consider any strategy that promotes dynamic adjustment of signal timing plans, we acknowledge their potential usefulness in effectively and dynamically retiming signal systems based on real time or close to real time demand.

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Fuel Conservation Through Freeway Work Zone Traffic Diversion Planning

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Abstract:

Construction activities and numbers of related work zones on urban freeways have grown significantly. The most problematic work zones occur on roads that are already fully loaded, and impacts of work zones on mobility and fuel efficiency make success of the traffic control plan vital. Full freeway closures are sometimes implemented to expedite project completion and thereby reduce the cumulative impact of construction on travelers, however, full closure can cause significant freeway congestion. Congestion cost American drivers more than $100 billion each year in wasted fuel and lost time. Reducing work zone congestion can be an effective energy conservation technique not only saving fuel but also saving traveler time. If a work zone plan includes freeway closure, an effective diversion plan that makes drivers aware of delays and available alternate routes can help minimize congestion. Construction on the SH-71/IH-35 interchange required complete closure of all IH-35 main lanes. IH-35 is an important business corridor, conveniently connecting four large Texas cities, as well as, facilitating trade between Mexico and the United States. A parallel route, the SH-130 toll road, was made free to travelers during those closures. The purpose of this paper is to investigate driver route switching behavior during the IH-35 closure, how that behavior reduced fuel consumption and explored options for relieving delays on IH-35 during future closures. The findings indicate that changes in traffic volume on SH-130 during the closure were statistically significant although usage of SH-130 was less than anticipated, and there was significant queuing on IH-35 at the work zone. Analysis was based on integrating data from all available sources. Traffic conditions of a non-closure weekend were compared to the closure weekends and fuel consumption was estimated.

Keyword: Freeway construction, Fuel efficiency, Traffic diversion, Traffic management, Driver route switching behavior, Freeway closure

INTRODUCTION

As the aging transportation infrastructure increasingly requires repair and renewal, construction activities and related work zones on urban freeways have grown significantly. An effective diversion plan can play a critical role to control traffic in work zones. However, diversion plans do not provide a means of controlling the quantity of traffic choosing alternate routes and are sometimes employed without proper consideration of the potential effect of the diverted traffic on the alternate route. Careful analysis of diversion strategies is needed to develop more efficient and effective strategies.

To properly manage traffic flow in a way that improves road safety and decreases congestion, accurate estimation of work zone capacity is critical [Weng, Jinxian, 2012]. Capacity reduction is the most significant factor that influences traffic delays. Several studies [Dudek and Richards, 1982; Rouphail and Tiwari, 1985; Krammes and Lopez, 1994] found that capacity at freeway work zones was mainly affected by: location (lane closure configuration and on-ramp/off-ramp proximity), traffic control plan (work zone duration, work time, lane narrowing, physical barriers, additional warning signs, and reduced speed limit), percentage of heavy vehicles in the traffic stream, and road grade.

There have been few studies of disequilibria and the adjustment process due to work zone traffic diversions. In practice, most work zone traffic impact studies either use the existing daily travel demand pattern or modify demand by arbitrarily assuming a diversion rate [Lee et al, 2005; Chu et al, 2005]. Some psychometric studies analyzed the diversion behavior of travelers in the presence of temporal road capacity reductions and traveler information systems [Khattak et al, 1993; Khattak et al, 1994; Peeta et al, 2000; e.g.,], but these studies did not substantiate their models with actual data.

Work zones pose a risk to the road users in terms of safety. The frequent involvement of heavy trucks in work zone crashes makes them a major work zone safety concern. Studies have found that the percentage of crashes involving trucks is much higher in work zones [AASHTO, 1987; Pigman et al, 1990; Schrock et al 2004]. Numerous studies have been conducted to enhance work zone safety and traffic control.

Highway work zones use temporary traffic control (TTC) devices to provide continuous safe and efficient traffic flows during road work. Helmuth (2002) shows that misapplying TTC devices and portable changeable message signs (PCMS) commonly causes confusion and anxiety in drivers [AASHTO, 1987].

Provision of advance information to travelers regarding alternative routes and temporary facilities are ways to reduce congestion during roadway construction. Accurate and timely reporting of traffic information is a valuable factor for managing a work zone. Advance notice to the public via radio, television, newspapers, changeable message signs, and traveler information systems can encourage drivers to use alternate routes or travel at off-peak times [MassHighway Chapter 17, 2006].Changeable message signs (CMSs) are playing increasingly important roles in attempts to improve highway safety, operations, and use of existing facilities. CMSs are traffic control devices used for traffic warning, regulation, routing and management, and are intended to affect the behavior of drivers by providing real-time traffic-related information.

MORE INFORMATION ON TRAFFIC CONTROL CONCEPTS

A summary of available information on work zone traffic control concepts with emphasis on Changeable message signs and lessons learned from full highway closure experiences is presented in this section.

PCMSs can be used to notify drivers of future changes in traffic conditions in the work zone. However, generic messages can cause PCMSs to lose effectiveness with motorists. Previous studies of several work zones on high-speed roadways in

Texas suggest that misapplications of PCMSs in work zones often contribute to driver confusion and anxiety about their appropriate travel paths [Dudek, 2004]. To be effective, a PCMS must communicate a meaningful message that motorists can read and comprehend within a very short time. Proper PCMS message design and use requires application of both human factors and traffic engineering principles. PCMS design and use guidelines have been developed through extensive research and field validation [Dudek, 1979; Dudek, 1997; Dudek, 2004; Dudek et al, 1978; Dudek et al, 2000; Ullman et al, 2005]. Unfortunately, personnel who are expected to operate the PCMS come from a variety of educational backgrounds and types of experience. Those personnel who are given PCMS responsibilities (or inherit them by default) in the field often do not have adequate levels of training in PCMS message design and application [Halloin, 1996]. The Manual on Uniform Traffic Control Devices (MUTCD) provides a number of basic guidelines about PCMSs in sections 2A.07, 2E.21, and 6F.55 [MUTCD, 2003]. The Portable Changeable Message Sign Handbook is a 2003 FHWA document prepared to supplement the MUTCD and provide additional guidance regarding PCMS use [PCMS Handbook, 2003].

Developing a management strategy for work zone operation is highly dependent on the duration, time of day, and type of construction. Full Road Closure is often considered by transportation agencies as an effective way to balance the conflicting needs of mobility and safety in the work-zone. By definition, full road closure is "the removal or suspension of traffic operations either directionally or bi-directionally from a segment of roadway for the purpose of construction activities." [FHWA, 2003]. Short-term full freeway closure is a work zone strategy that is receiving more consideration by state DOTs because it can often reduce project duration and cost. These positive effects usually lead to increased public acceptance, and potentially reduce both short- and long- term user costs [FHWA report, 2004]. While there is a wealth of literature on work zone safety, capacity, speed reduction, driver behavior, and changeable message signs, less has been written on traffic operations associated with full freeway closure. Some case studies have been published

FHWA ROAD CONSTRUCTION CASE STUDY

Case studies have been published by the Federal Highway Administration (FHWA) that provides information about essential planning measures, benefits and impacts of full freeway closure [FHWA report, 2003]. The cost and duration of construction in most cases was reduced (for example Columbus, OH, Detroit, MI, and Portland OR). Tables 1 and 2 provide major characteristics of these closures.

There are six long-term full closure projects and five weekend full closure projects presented in the tables. Most projects which used the weekend full closure method involved only re-paving or other roadway repair activities. While longer periods of full road closure usually involved reconstruction projects such as road widening and bridge repair, in the TH- 36 project, full closure reduced the construction duration from close to two years to 7 months (4 months of full closure and 3 months of partial and intermittent closures) [MnDOT report, 2006].

Although the ADT's at the construction project sites cover a wide range, from 30,000 to 240,000, most projects involved roads at, or close, to capacity. As seen in the table, eight of eleven projects are Interstate freeways and carry over 60,000 vehicles per day. Most of projects reported more than a 60 percent reduction of construction duration. The significant reduction of duration could mitigate the traffic impacts and save user costs.

The Washington State DOT [Dunston et al, 1998] studied full highway closure extensively during the I-405 full weekend closure. They examined travel time and purpose of trip and found that a large number of drivers did not cancel planned trips because of the closure. Alternate routes are critical elements in traffic control plans for full closure because they help carry diverted traffic and reduce congestion. Most projects, except the I-405 project, had proposed detours that were parallel to the segment under construction using high-grade roadways such as freeways or major highways. Some cases cited that the projected congestion impacts typically were overestimated because the actual demand during construction was less than expected. Some studies assumed that diverted traffic would follow the proposed detours during the construction but many drivers found other routes. Effinger J., et al. (2011) presented a case study quantifying driver diversion and its impacts during the I-43/I-894 full freeway closure event in October 2010 in Milwaukee [Effinger et al, 2011].

A recent full closure happened on Interstate 5 near downtown Sacramento, California. The project construction plan for I-5 was to periodically close one direction near downtown Sacramento during a two month construction process, which decreased the construction time from the planned 190 days with a regular partial closure to the actual 35 days with full closure. They also significantly reduced the travel demand on I-5 near the closure section, due to a major freeway detour route for through traffic, and the abundance of local arterial routes to serve as alternative paths [Zhang et al, 2012].

	Seattle, Washington, I-405	Louisville, Kentucky I-65	Kennewick, Washington, SR 395	Wilmington, Delaware, I-95	Portland, Oregon, I-84
Facility Type	Interstate	Interstate	Arterial	Interstate	Interstate
ADT		130,000	30,000	100,000	180,000
Closure Duration	2 weekends	2 weekends	1 weekend	7 months	2 weekends
Land Miles	2	6	3 intersections	24.4	33
Cost		$4.1M	$0.5-1M	$23.5M	$5 M
Traffic Model	No	No	No	Yes	Yes
Project Date	1997	2000	2000	2000	2002

Table 1: Characteristics of Full Closure Sites by Location

	Detroit, Michigan, M-10	Columbus, Ohio, I-670	North St. Paul, Minnesota, TH 36	Tennessee DOT, I-40	Maine DOT, I-295	California, I-405
Facility Type	State Highway	Interstate	Trunck Highway	Interstate	Interstate	Interstate
ADT	97,000	62,000	39,000	-	-	240,000
Closure Duration	2 months	18months	4 months	13 months	3months NB, 15months SB	53 hours
Land Miles	7.6	8	2	-	24	10 NB, 4 SB
Cost	$12.5M	$36.7M	$27M		$35.3 M	
Traffic Model	No	Yes	No	Yes	-	-
Project Date	2002	2003	2007	2008	2008	2011

Table 2: Characteristics of Full Closure Sites by Location, Continued

CASE STUDY: CONSTRUCTION ON THE SH-71/IH-35 INTERCHANGE

IH-35 is an important business corridor, conveniently connecting four large Texas cities, Austin, Dallas, Fort Worth, and San Antonio, as well as, facilitating trade between Mexico and the United States. For the 5 level stack construction on the SH-71/IH-35 Interchange, three main lane closures happened during three weekends in 2011.

At the commencement of this study, several data items relevant to developing the diversion plans were collected from a number of sources and these are presented in next section.

Data Collection

To analyze how traffic patterns changed during the IH-35 weekend closures, it is a prerequisite to establish a typical weekend pattern. However, traffic count data on IH-35 was available only for two locations (one located 0.3 miles south of FM1626, south of and in the vicinity of the closure and the other one located near San Marcos 0.9 miles south of FM 2001, roughly 30miles from the closure)

While IH-35 data was limited to counts provided by permanent counting stations, SH-130 data included hourly toll transactions at the series of toll stations along the length of the facility. These data were used to estimate the success of the diversion plan.

To predict typical hourly SH-130 traffic, the most recent five-months of transaction data (Jan-May 2011), were used. Although 12 months of historical transaction data for SH 130 was available, transaction totals were changing rapidly during the earlier months compared to the Jan-May totals that were relatively stable. Because all the closures were encompassed by the time frame late evening on Friday until midnight Sunday, we analyzed this period of time. The days and times of the three main lane closures on IH-35 due to construction of flyovers at the IH35/Ben White Boulevard interchange are shown in Table 3. The transaction data on SH-130 is directional, defined by segments corresponding to toll collection stations. The data related to each station ID is the cumulative number of transactions on main lanes and exit ramps located in the same segment. It is divided into five segments, as shown in Figure 1.

The Toll Status

During the SH-71/IH-35 interchange construction, two diversion plans were defined to control the traffic: local detour and network diversion. The local detour plans were designed to detour the proportion of traffic not diverted but remaining on IH-35. The network diversion plan, which was the main interest of this project, was designed to divert traffic to the SH-130 toll road. The SH-130 toll road is a parallel route to IH-35 and the toll status during the full closure was changed to free to reduce traffic congestion at the construction zone. Clearly driver understanding of the free status played a vital role in the potential success of the diversion plan.

To achieve this goal, TxDOT provided both pre-trip and en-route information about the closure and free toll road status hoping to reduce divert significant numbers of travelers during the construction. To inform travelers passing through Austin about the closure and the existing alternative (SH130 was toll free), they used radio, TV, portable message signs (PMS), and dynamic message signs (DMS). They even collaborated with Dallas and San Antonio TxDOT district personnel.

In this traffic control plan, a message providing the time and location of the closure was posted three days before the beginning of each closure. Based on the location of the construction (south of the City), there were more options for the southbound commuters to choose an alternative detour route.

Data Analysis

TXDOT provided prior notice to travelers about the closures hoping to reduce numbers of unnecessary trips and stimulate path changes during the closure. To analyze how traffic patterns changed during the closures and to find how successful they were at achieving their goal, we compared hourly traffic on typical weekends with hourly traffic during each closure. However, traffic count data on IH-35 was available only for two locations in the vicinity of but not precisely where counts were needed. On the other hand, we had access to one-year directional hourly traffic data from all toll stations along SH-130, which were classified by axles (from Jun 2010 to May 2011). To predict typical hourly traffic on SH-130, we used the most recent five-month data (Jan-May 2011).

Average Hourly Base Data Analysis: Based on IH-35 limited count data, to analyze how traffic patterns changed during the closures, hourly traffic on typical weekends were predicted and compared with hourly traffic during each closure. We tested a null hypothesis (H0) that the closure had no impact on IH-35 traffic volumes as monitored by the permanent count stations in South Austin and San Marcos. The analysis shows that South Austin was affected by the IH-35 closure, but San Marcos was not. Traffic data collected at the south Austin detector indicates that traffic flow decreased during closures on both north and south bound lanes. Clearly, TxDOT was successful in encouraging drivers to avoid some unnecessary trips.

SH-130 hourly traffic transaction counts were the second available data source. The transaction data on SH-130 is directional, defined by segments corresponding to toll collection stations (Figure1). The data related to each station ID is the cumulative number of transactions on main lanes and exit ramps located in the same segment. To see the how successful the diversion plan was, we ran tests on SH-130 data. Table 3 shows the directional average hourly traffic during each closure for each segment. Data for the first and second closures are not available in segment SH-45. And “typical” weekend average hourly traffic for the closure times is shown in Table 4. Typical conditions were based upon approximately 5 months of transaction data.

These tables show that northbound traffic is slightly heavier than southbound traffic on both typical weekends and during closures. The volumes are generally larger during closure times than under typical conditions. Using this information, we performed a test to determine the statistical significance of the differences between typical and closure traffic volumes on SH-130 based upon average hourly volumes. We hypothesized that closures did not have any impact on driver route choices and that drivers did not use the toll road as an alternative, even if it was free. Test results

North Bound Average hourly traffic during closures	Type of Vehicle	Stations					
		SH130					SH45
		305	306	307	308	Ave	SH45
2/11/2011 Closure	Car	349	847	597	463	564	-
2/25/2011 Closure		326	886	627	479	579	-
5/20/2011 Closure		318	864	561	398	535	377
2/11/2011 Closure	Truck	58	69	70	68	66	-
2/25/2011 Closure		86	102	101	99	97	-
5/20/2011 Closure		43	53	51	48	49	51

South Bound Average hourly traffic during closures	Type of Vehicle	Stations					
		SH130					SH45
		305	306	307	308	Ave	SH45
2/11/2011 Closure	Car	286	789	489	350	479	-
2/25/2011 Closure		235	706	448	315	426	-
5/20/2011 Closure		305	793	459	314	468	268
2/11/2011 Closure	Truck	54	71	70	66	65	-
2/25/2011 Closure		40	57	54	51	50	-
5/20/2011 Closure		46	51	48	46	48	44

Table 3: SH-130 average hourly volumes by segment during closures for NB and SB.

North Bound Average hourly traffic for typical weekend	Type of Vehicle	Stations					
		SH130					SH45
		305	306	307	308	Ave	SH45
First Closure	Car	207	526	305	182	305	-
Second Closure		305	709	430	276	449	-
Third Closure		234	600	343	208	348	166
First Closure	Truck	17	22	19	17	9	-
Second Closure		51	57	53	51	14	-
Third Closure		25	31	27	25	11	9

South Bound Average hourly traffic for typical weekend	Type of Vehicle	Stations					
		SH130					SH45
		305	306	307	308	Ave	SH45
First Closure	Car	199	494	261	159	277	-
Second Closure		245	599	317	195	342	-
Third Closure		286	645	361	240	394	230
First Closure	Truck	26	30	26	25	9	-
Second Closure		36	40	36	34	11	-
Third Closure		50	55	50	49	13	11

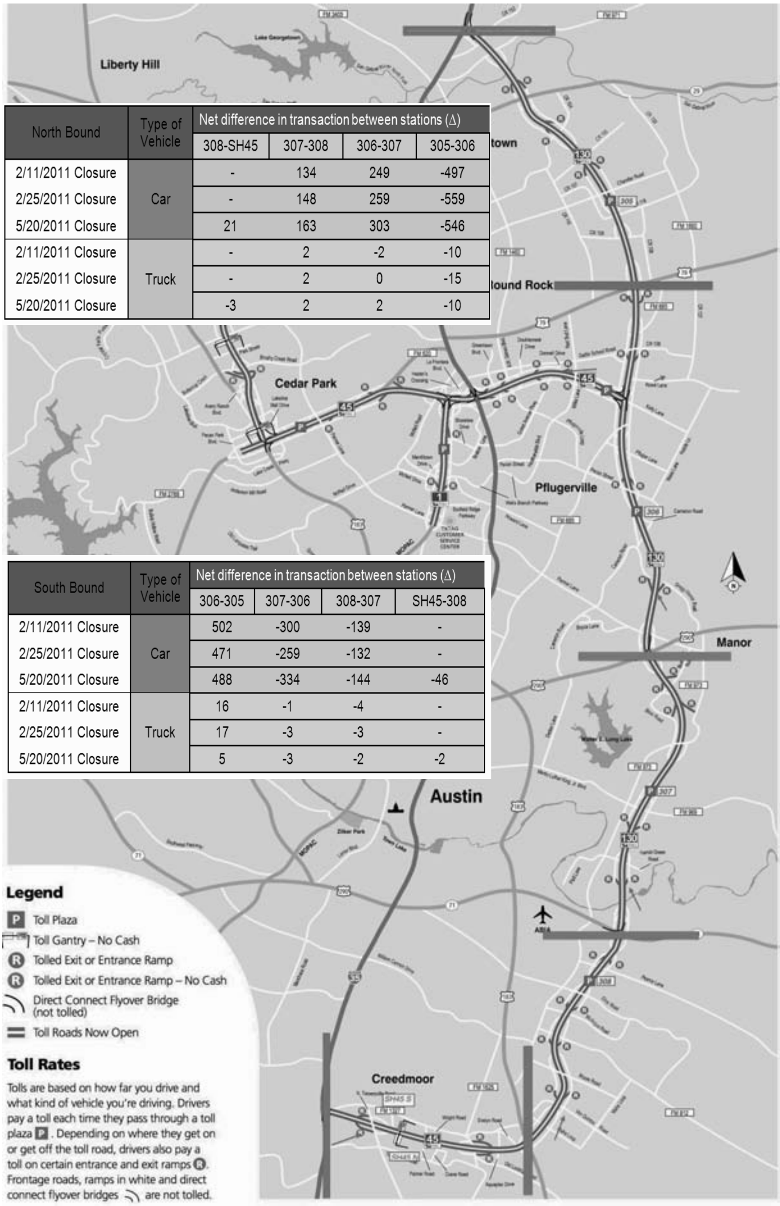
Table 4: Typical hourly transaction on SH-130 for closure days/times.

show a significant increase in traffic flows in both directions for all stations was observed. Although this is evidence of diversion, one cannot quantitatively state how much diversion because more detailed data on IH-35 is needed to conduct the analysis that can help answer the question. Unfortunately, such detailed IH-35 traffic data is not available.

Estimation of Entry/Exit Locations for SH-130 Traffic during Closures:
Furthermore, from the toll road average hourly transaction data, one can obtain a net difference in transaction volume between successive stations allowing estimation of net changes in SH-130 traffic volumes that can be interpreted as an estimate of entry/exit volumes.

Using the segment transaction net differences (Figure 1), one can roughly calculate that 80 percent of north bound traffic that entered SH-130 from feeder highways south of the most northern segment exited SH-130 in the most northern segment and 90% of south bound traffic that entered from feeder highways north of the most southern segment exited SH 130 in the most southern segment. That is, about 20 percent of the northbound traffic that entered from feeder highways traveled through to points north of Austin and about 10 - percent of the southbound feeder highway traffic was likewise through traffic. Regarding estimation of traffic that was northbound on IH-35 and chose to divert to SH-130, the first available northbound transaction station is 308 located north of the IH-35 and SH-130 interchange. Between the interchange and the toll station there are a number of feeder highways including US-183 and FM 812, so one must logically assume that a non-zero fraction of the transactions at station 308 are vehicles that entered from the feeder facilities instead of from IH-35.

However, the maximum volume that could have come from IH-35 is the total volume of station 308, with an average of 446 transactions per hour across the three closures. The average number of transactions processed at the northern most toll -



North Bound	Type of Vehicle	Net difference in transaction between stations (Δ)			
		308-SH45	307-308	306-307	305-306
2/11/2011 Closure	Car	-	134	249	-497
2/25/2011 Closure	Car	-	148	259	-559
5/20/2011 Closure	Car	21	163	303	-546
2/11/2011 Closure	Truck	-	2	-2	-10
2/25/2011 Closure	Truck	-	2	0	-15
5/20/2011 Closure	Truck	-3	2	2	-10

South Bound	Type of Vehicle	Net difference in transaction between stations (Δ)			
		306-305	307-306	308-307	SH45-308
2/11/2011 Closure	Car	502	-300	-139	-
2/25/2011 Closure	Car	471	-259	-132	-
5/20/2011 Closure	Car	488	-334	-144	-46
2/11/2011 Closure	Truck	16	-1	-4	-
2/25/2011 Closure	Truck	17	-3	-3	-
5/20/2011 Closure	Truck	5	-3	-2	-2

Figure 1: SH-130 segment/station descriptions and Net changes in southbound SH 130 traffic transactions among successive toll stations during closures

station, station 305, averaged 331 per hour across the three closures. As an extreme but unlikely estimate of the fraction of traffic that originated on IH-35 and traveled through to points north of Austin, 331/446 or 74% could possibly have traveled through to points north of Austin or 26% were destined for Austin. For the southbound direction, toll station 305 provides the first counts after the SH130-IH35 interchange and this volume averaged 275 per hour across the three closures. At the southern end of SH 130, toll station 308 averaged 326 per hour across the three closures or roughly 118% of the first southbound counts at station 305. Using the previously described logic, then all of the possible southbound traffic was destined for points south of Austin.

Comparisons for Different Times of Day during the Closures: The previous analysis was based upon average hourly volumes across the closure times, but volumes and patterns vary significantly among the times of day during which the IH-35 closures were active. If one considered every hour of the day to be a distinctive case the result would be specific but rather difficult to understand. To simplify the analysis, the 24 hours of the day were combined into 3 time slices or groups: Time 1 (midnight to early morning 2300-0600), Time 2 (morning and late evening 0700-0900, 1900-2200), and Time 3 (mid-day through PM peak 1000-1800).

The reason to choose this grouping is that traffic volume patterns during weekends are different from week days. By looking at the data and performing multiple range tests, we determined that "rush hours" on weekends start later in the morning than weekdays and continue until early evening. To be able to see the changes during the closure compared to typical conditions, typical hourly traffic volumes were developed for the three generalized time frames. Analysis shows that the number of trucks using SH-130 during closures increased by more than three times the typical volumes. Car transactions also increased significantly during all time groups for the closure conditions. Although patterns of entering and exiting traffic are similar across the three time periods, numbers of transactions or volumes are much greater during day time hours, that is Time 3 (1000 through 1800 hours). That is, in the northbound direction there are net increases in traffic volume through all stations until the northern most station 305 where the net decrease is approximately equal to the sum of the net gains across the previous stations. This indicates a very large fraction of the SH-130 northbound traffic is destined for points in Austin rather than points north of Austin. In the southbound direction only the section between stations 305 and 306 shows a net traffic volume increase with the three more southern sections showing net volume decreases. Like the northbound direction, this seems to indicate that a very large fraction of the southbound traffic is destined for points in Austin rather than locations south of Austin.

Figure 2 presents numbers of transactions for the four toll stations along SH-130 for the daytime conditions (1000 to 1800 hours) for the northbound and southbound directions respectively. The Figures illustrate the same concepts stated in the previous paragraph, that is, northbound volumes reach a maximum at station 306 located just south of the SH-45 and US-79 exits. Stations 308 and 305 at the south and north ends of SH-130 have the smallest traffic volumes again, showing that the "through" traffic is a small fraction. Southbound volumes reach a maximum at station 306 just the south of SH-45 and US-79 entrances and decrease to the smallest level at station 308 the most southerly transaction station.

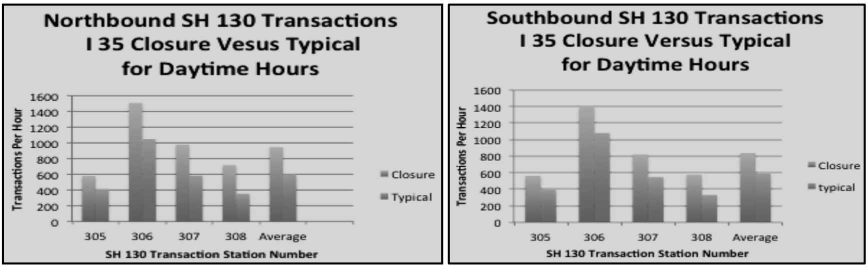


Figure 2: SH 130 transactions by toll station during daytime hours [Station 308 is most southerly, 305 is most northerly].

Fuel Conservation Analysis

More efficient traffic operational strategies that relieve roadway congestion can have a significant impact on fuel consumption by increasing fuel economy. The choice of route can significantly affect fuel consumption and emissions. As mentioned earlier, during the SH-71/IH-35 interchange construction, two diversion plans were defined to control the traffic: a local detour with total distance of 27 miles and a network diversion with total distance of 47 miles. In the local detour route, because of the large proportion of traffic not diverted that remained on IH-35, there was level of service F (LOS F: heavy traffic conditions) characterized by stop-and-go traffic with average speeds of 15 mph on IH-35. The network diversion plan, although a longer distance provided an average speed of 65 mph.

Stop-and-go traffic, characterized by repetitive cycles of complete stops for 5 to 20 seconds followed by movement at speeds of 5 to 15 miles per hour tends to increase fuel consumption. Since stop-and-go fuel consumption rates are different during different parts of the cycle, one might describe fuel consumption using a three term model. The first term might represent stopped vehicles with idle fuel consumption rates, the second term could describe fuel consumption for vehicles accelerating from a stop, and the third term might represent stochastic effects of vehicle movements which consume excess fuel. In general vehicles have the smallest fuel consumption rate during idling while stopped and consume more fuel after they start moving. However, when a vehicle is stopped and the engine left running, it is producing zero mpg. Consequently, idling could be considered as negative mpg since no work is being done.

In the IH-35 case study, to evaluate fuel consumption on two different routes, a general graph which illustrates fuel economy at different speeds and across different traffic conditions is required. The Transportation Energy Data Book (2010) is the best available source that has “Fuel Economy-Speed” data (Figure 3). This graph tends to indicate that with time, manufacturers have produced cars that exhibit greater fuel economy at higher speeds. The 1997 curve indicates best fuel economy at speeds of 50 to 60 mph. Since the latest graph is for 1997, one might expect that newer cars could produce greater fuel economy at higher speeds than 55 mph.

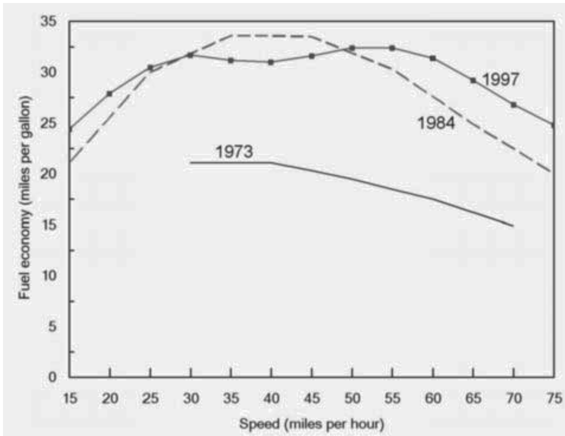


Figure 3: Fuel Economy (mpg) versus Speed (mph)
[Source: Figure 4.2 of the Transportation Energy Data Book, 2010].

Limited studies have been done on stop-and-go traffic to estimate general fuel consumption rates corresponding to vehicle acceleration/deceleration and idling. Silva et al. (2006) evaluated three numerical models to estimate fuel consumption of gasoline light-duty vehicles. Models were used to simulate fuel consumption across a variety of traffic condition. Cruise speed was compared with several stop and go situations (up to 9 stops). Their findings predict up to 67 percent increases in fuel consumption.

According to figure 3, fuel economy at constant speeds 15 and 65 mph are 25 and 30 miles per gallon, respectively. Considering the fact, that Figure 3 shows fuel consumption at steady state speeds, additional fuel consumption due to accelerating/decelerating and idling should be included in estimates of total fuel consumption for the IH-35 diversion route. Although the average speed was 15 mph, vehicles were spending large portions of time in queues idling and repetitively acceleration and decelerating to the stopped condition.

The likely fuel economy of stop-and-go operations on IH-35 was dramatically poorer compared to a 15 mph steady-state speed. One might logically infer that considering "lost" fuel due to idling during long duration stopped times and the measured 67 percent increase due to acceleration and deceleration, the very heavily congested stop-and-go situation on the I-35 diversion route could have produced fuel consumption rates as much as twice the steady-state speed condition on the alternate route. The distance for the alternate route is less than twice the IH-35 route. Considering these two facts, taking the longer but steady state higher speed alternate route could saved fuel and time.

CONCLUSION

During the IH-35/ Ben White Boulevard construction, the increase in SH-130 (as an alternative path) traffic volumes clearly indicates diversion from IH-35. However, the volumes diverted from an IH-35 path were small in both the northbound and southbound directions. For northbound, the SH-130 toll transaction station closest to SH-35 showed over twice the typical traffic volume during the closures; however, this increase was only about 350 car transactions per hour. In other words, even if all of the 350 vehicles per hour were diverted from IH- 35, it would still represent a very small fraction of one freeway lane. As for southbound, the station nearest to the beginning of SH-130 showed a maximum increase of about 165 vehicles per hour.

Based upon both volume and net difference tables, one might hypothesize that a large fraction or specifically more than half of the weekend traffic on SH-130 northbound and southbound appears to be destined for locations in the metropolitan area rather than locations north or south of the Austin area. In addition, the location of the construction zone could have had a significant effect on traffic pattern changes. Since the construction zone was located south of the metropolitan area, the south bound traffic was more likely to be informed about the closure. Considering these facts together, one can logically speculate that the volumes of traffic diverted from IH-35 paths were small for several reasons:

- If most IH-35 travelers were destined for metro-Austin they would not likely consider the SH-130 path, as it would cause them to travel "out of their way" to reach their destination.
- Travelers may have been unfamiliar with the many connections between SH-130 and their metro-Austin destinations.
- IH-35 travelers likely did not perceive the level of congestion that would develop on that freeway as the result of the main lane closures.

SUGGESTIONS

To ameliorate the lack of diversion from IH-35 to SH-130 the following suggestions are provided for future diversion efforts: 1) Provide comparative travel times for IH-35 and SH-130 through forecasts or through real-time information delivery means, including changeable message signs (CMS), highway advisory radio, television and other traffic condition outlets. 2) Provide information through CMS's, TV, and newspapers regarding the ease of connection from SH-130 to metro-Austin destinations. 3) If the diversion road is a toll road that is made free for the diversion plan, communication of the free status to travelers is vitally important. 4) For travelers who are not familiar with alternative paths (like SH-130) graphical signage showing schematic maps could be provided along the path leading to diversion routes. Finally, providing estimates of fuel consumption for alternative diversion paths could influence travelers in their route choice decision.

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Evaluating Community Transportation Emission Methodologies

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ABSTRACT

Many communities have committed to reducing their greenhouse gas (GHG) emissions. Fulfilling these commitments often includes: inventorying emissions, development of a local action plan, reduction targets and measuring progress from plan implementation. Using Waterloo Region as a case study, a comparative analysis of estimation methodologies for community transportation emissions was conducted. The transportation sector is often a large part of many local GHG emission profiles and can be difficult to effectively measure. Three commonly used methodologies were compared and evaluated, vehicle kilometers traveled (VKT), vehicle registration methodology and retail fuel sales. The evaluation considered accuracy of data inputs and outputs, resources required ability to replicate for future inventories, and the ability to reflect impacts from the implementation of local actions. It was concluded that the fuel sales method is the least arduous, is reasonably accurate to replicate and suitable for monitoring progress. Municipalities would benefit to obtain fuel sales data within their jurisdictional boundaries to estimate local transportation emissions for their inventory as it will also better reflect progress from implementing their reduction initiatives. Vehicle registration data can further assist with estimating potential reductions from the proposed action plan.

CONTEXT

Despite decades of international policy debate on climate change, atmospheric carbon dioxide (CO_2) concentrations have continued to rapidly increase towards levels of great scientific concern.[i] The Intergovernmental Panel on Climate Change has identified that anthropogenic greenhouse gas (GHG) emissions unequivocally have been the dominant influence on the forced change in our climate over natural influences during the past 60 years.[ii] Moreover, the signs of climate change and variability are becoming increasingly evident with impacts already felt in numerous parts of the world including Canada.[iii]

There is a growing body of international research on the role of local government and community action in climate change policy.[iv] With regard to GHG mitigation, urbanized areas have been estimated to consume two thirds of global primary energy resources and are responsible for 40% to 70% of the world's CO_2 emissions.[v] This will intensify as more than half of the world's current population already lives in towns and cities and urban populations are expected to grow to two thirds of the global population by the year 2030.[vi] Many cities are also already dealing with the effects of climate change. Furthermore, nearly all urbanized areas are at risk as they cluster both people and vulnerable infrastructure (i.e., water, transportation, energy) into relatively small areas. Therefore, actions at the community level can play a critical role in reducing anthropogenic influences on climate change.

Municipalities have a great opportunity to portray themselves as a legitimate player in the global effort to mitigate climate change if they can demonstrate accountability to their public GHG reduction commitments. In order to do this, local government and communities need to understand the relationship between the various data inputs and outputs within mitigation frameworks in order to effectively achieve and measure their progress towards established reduction targets. In Canada, some 240 municipalities are participating in the Federation of Canadian Municipalities Partners for Climate protection program which is a framework for local GHG mitigation.[vii] The upper tier Regional Municipality of Waterloo along with its three local city government bodies have all committed to this program in the past and have recently joined forces to develop and effective GHG reduction strategy. The ability to measure the effectiveness of implementing their strategy is founded in their methodological approach to developing the local emissions inventory and action plan. The Waterloo Region experience is a good backdrop to analyze the role that emission methodologies play in enabling municipalities to develop a sound base to their GHG reduction strategies which is critical for accountability in measuring progress towards reduction targets.

INTRODUCTION

Since the 1990's, local governments around the world have committed to reducing their greenhouse gas (GHG) emissions from both their municipal (corporate) operations as well as on a community-wide scale. Frameworks to fulfill these commitments often include an inventory of emissions borne from local activities, development of an action plan, establishing reduction targets relative to the baseline year and, measuring progress from implementation of the plan.

Efforts to measure, manage and reduce municipal corporate emissions are for the most part relatively straightforward due to clear ownership, access to data and numerous internal mechanisms to set and fulfill corporate GHG emissions reduction goals. For example, reducing emissions from the municipal fleet can be directly affected by the type of vehicles and fuel purchased, equipment installed and driver routes established. Community GHG emissions on the other hand, while geopolitically based, are influenced by a wide variety of stakeholders and therefore require significant coordination and collaboration to manage. Nevertheless, any community has to understand and address this challenge once they are committed to developing local climate action plans if they want to demonstrate progress towards achieving their GHG reduction goals.

Selection of emission estimation methodologies at the inventory stage can directly and indirectly affect the likelihood of success in terms of effectively measuring and achieving progress towards a local reduction target. This is particularly the case at the community scale where there are more data sources and wide spread influential control over the type of activities that cause GHG emissions at this scale.

Emission sources typically measured within community GHG inventories include:

- Residential, industrial and commercial stationary energy consumption (e.g. electricity and natural gas);
- Transportation (e.g. gasoline/diesel);
- Waste (e.g. methane from landfills) and;
- Agricultural activities in rural areas within a county or regional municipality (e.g. enteric fermentation in livestock).

Transportation emissions are often a large part of the community carbon footprint and one of the more difficult emission sources to effectively measure. This is also an emission source that can be influenced by a variety of land-use policy mechanisms, infrastructure investment and behaviourial change programs and incentives available to local municipalities.

Community transportation emissions are mainly derived from the combustion of fuel in personal and commercial/industrial vehicles used within a community. Tracking and reducing these emissions is difficult due to the lack of operational control in tracking variables such as; kilometers driven, personal preference of vehicles (e.g. type and make of vehicle), limited access to data sources (e.g. insurance, card-lock) along with the magnitude of data sources and the level of accuracy that can be captured. The identification of the objective (transportation planning or emissions measurement) is necessary as this defines which method or methods to capture and measure community transportation emissions should be used. By analyzing different emissions estimation methods in conjunction with different municipal and community objectives the relationship between data inputs, outputs and their interdependencies can emerge.

The Waterloo Region was utilized as a case study for conducting a comparative analysis of transportation estimation methodologies at the community scale. Three commonly used methodologies for estimating community transportation emissions were compared and contrasted on the basis of: accuracy, staff and financial resources required; ability to replicate methodology to compile future inventories; and the ability to reflect impacts from the implementation of various GHG reduction initiatives within local climate action plans. In addition to identifying advantages and disadvantages of each emission estimation method, a conceptual framework to consider the objective (policy or measurement), various data inputs and inputs and their relationship in the context of the stages associated with community GHG action planning is included. The article concludes with the proposed framework that would help municipal staff assess how and what methods would best enable them to set GHG related transportation policy or track progress towards community transportation emission reduction targets.

The preparation of this paper was undertaken to meet the following objectives:

- Better understanding GHG emissions from transportation at a community-wide scale.
- Enabling measurement of progress as local governments start to implement GHG reduction initiatives.
- Development of a framework for local governments to illustrate the inter-relationship between developing accurate emissions inventories and transportation related GHG reduction strategies.

Overall this article aims to provide municipalities and communities with a better understanding of their GHG emissions from transportation and enhance their ability to measure progress towards their reduction target as they implement local initiatives.

CALCULATING COMMUNITY TRANSPORTATION EMISSIONS

A community transportation GHG emissions inventory is a broad look at the community-at-large by sub-sectors unlike the specific facility and vehicle data commonly used at the municipal corporate scale. When calculating community transportation GHG emissions, there are three common methodologies that are typically deployed:

1. **Vehicle Registration Method. The method utilizes vehicle-in-operation data, fuel efficiency ratings as well as average distance traveled to estimate VKT and fuel consumption.**

The vehicle registration methodology uses vehicle-in-operation data collected from R.L. Polk Canada (Polk)[viii] as its main input to estimating vehicle kilometre travelled (VKT) and fuel usage based on fuel efficiency ratings. This approach is used in transportation modelling such as for policy or regulatory based emission studies. [ix]

The vehicle registration methodology is costly, complex and requires data from several inputs. This methodology is often very difficult to replicate in the future due to potential changes to data collection processes and sources. Data will need to be collected from various sources (specifically vehicle registration information and estimated distance traveled) for this methodology each time an inventory is completed. Additionally, data from Polk has a cost associated with data collection, adding to a municipality's expense for this emissions assessment.

$$VKT_{ij} = AADT_{ij} \times VIO_{ij}$$

Where:
- $VKT_{i,j}$ = Vehicle kilometer traveled for vehicle type i (e.g. car) and model year j (e.g. 2008)
- $AADT_{i,j}$ = Average annual daily traffic by vehicle type i (e.g. car) and model year j (e.g. 2008)
- $VIO_{i,j}$ = Vehicle in operation for vehicle type i (e.g. car) and model year j (e.g. 2008)[x]

The GHG emissions and the fuel use are derived from the VKT value, where GHG emissions for

$$Veh_{ijk} = FE\ veh_{ijk} \times ADT_{ij} \times VIO_{ijk} \times EFCO_2e\ veh_{ijk}$$

Where: GHG emissions for $Veh_{i,j}$ = GHG emissions for vehicle type i, model year j and fuel type k

$FE\ veh_{i,j,k}$ = Fuel efficiency rate for vehicle type i, model year j and fuel type

$EFCO_2e\ fuel_{,I,j,k}$ = CO_2e emission factor for vehicle type i and model year j and fuel type k

2. **Retail Fuel Sales Method. The method takes direct fuel sales data and fuel emission factors into consideration; fuel efficiency, or distance travelled are not data inputs for this methodology.**

This simplified methodology takes direct fuel sales data and fuel emission factors into consideration, fuel efficiency, or distance travelled are not data inputs for this methodology. It should be noted that commercial and card-lock systems are not included in this data set (e.g. largely diesel fuel pumps used by private fleets). This approach is more directly associated with assessing emissions calculations for GHG programs.[xi]

The fuel purchased method does not take fuel efficiency, or distance travelled into consideration. As such, it is a simpler methodology with fewer requirements for data collection. Although the data set is not complete in the case of Waterloo Region, in terms of filling the gap in townships fuel consumption data, estimations for the missing jurisdictions are considered to be relatively simple and are based on readily available population statistics. However, as stated earlier, all assumptions and estimates will affect the outcome of the data, and its ability to be compared to other municipalities. This is a more direct look at the quantity of fuel purchased within the municipalities as opposed to estimation based methods drawn from multiple sources. Although this is the simpler methodology, in terms of data collection and accuracy, it should be noted that it is also costly as data acquired must be purchased.

Calculating GHG for this methodology was simplified by multiplying the corresponding fuels with the appropriate GHG emission factor.

$$CO_2e = EFCO_2efuel \times Litres$$

Where: $EFCO_2efuel$ = CO_2e emission factor for gasoline/diesel fuel types

Litres = total litres of fuel type utilized

3. **Vehicle Kilometers Travelled (VKT) Method. The VKT method uses traffic counts and road lengths to estimate VKT and fuel consumption.**

The VKT methodology uses Average Annual Daily Traffic (AADT) counts and road length segments to calculate VKT. The AADT is an average calculated over a year of the number of vehicles passing a point in specific intersections each day. At a community-scale, this can include a large number of intersection counting points. However this is more typically used in a municipal transportation infrastructure management context for a variety of purposes other than emissions analysis.[xii]

Data is generally available from a local governments transportation department (road segment lengths can be determined using GIS). The VKT number is then applied to average fuel efficiencies and a general percentage breakdown of vehicle types. Based on these averages, fuel use is determined and multiplied by the fuel emission factors. Where data is not available, assumptions must be made to estimate VKT per kilometre of road, based on available data. In a two-tier municipal system, such as a Regional government, additional data collection from multiple sources is required in addition to significant compilation and analysis efforts.

$$\text{VKT}_a = \text{KM}_S \text{ x AADT}$$

Where: VKT_a = Annual vehicle kilometers traveled
KM_s = Road segment length in kilometers
AADT = Average annual distance traveled

To calculate the GHG, the total VKT is then broken down by national average vehicle type, and fuel type.[xiii]

Table 1 below summarizes the Region of Waterloo's total community transportation emissions as calculated by each of the proposed methodologies, and the percentage of the emissions in terms of the Region's overall community GHG emissions (including residential, commercial and industrial and community sectors). The VKT methodology is significantly lower in terms of tonnes of GHGs, as noted as a gap; the VKT methodology is only looking at AADT for Regional roads, and does not include figures from local municipalities.

Table 1. Summary of Calculation Methodologies used in assessing Region of Waterloo's GHG Emissions

Calculation Methodology	Total GHG (tonnes)	% of Total Community Emissions Profile	Data Gaps/Notes
VKT	830,445	28%	Incomplete - calculation is for Regional roads only. Data excludes traffic counts on local city roads and Provincial highways due to data compilation and accuracy challenges.
Fuel Sales	1,467,858	*41%*	Excludes commercial diesel fuel sales and assumes exogenous fuel consumption by external visitors is offset by local residents/businesses fuelling up while in other communities
Vehicle Registration	1,870,533	*47%*	Excludes emissions occurring within community boundaries by vehicles registered outside of the community

With regard to the relative differences between the three approaches used in this case study, the underestimated GHG figure from the VKT approach in Waterloo can be easily explained by the lack of city road data which collectively would make-up a large portion of community transportation activities. Potentially the fuel sales approach may yield a GHG value closer to that of the more complex vehicle registration approach if it were to include commercial diesel consumption as this was estimated in the latter methodology. However, both of these approaches have an uncertainty or confounding factor as indicated in the Gaps/Notes column in the table above, which consequently impairs the ability to identify one more complete or representative than the other.

There is no theoretical reason to accept or reject one method over another as all three are acceptable in a voluntary GHG program context in that they are transparent and defensible methodologies.[xiv] They differ in that each uses different data inputs, assumptions and processes to quantify emissions within the community. However, it is how the output information is utilized – i.e. the objective – by the local government that becomes the deciding factor on which methodology shall be used. For instance, local governments who want to influence the number of vehicles travelling through their community may simply increase parking costs, reduce road lanes is target areas and prioritise transit and bike lanes in downtown cores as examples. In such a case, the best method to measure the effectiveness of this change would likely be the VKT method where traffic counts are used. In contrast, the retail fuel methodology would be best suited to local governments who use outreach efforts to encourage modal switching behaviour changes (e.g. increased or new transit locations). Each method has its strengths and weaknesses as summarized in the table below. Strengths and weaknesses as summarized in Table 2, and discussed further below.

Table 2. Review of Methods and Key Criteria

Criteria	Vehicle Registration Method	Fuel Sales Method	Vehicle Kilometres Traveled (VKT)
Accuracy / Representative Nature	**Moderate to High** Comprehensive inputs are representative but accuracy is somewhat hampered by assumptions on fuel consumption	**Moderate to Low** Assumes exogenous fill-ups at local fuel stations are offset by locals fuelling up outside of community	**Low** Method is based on numerous assumptions and may not represent actual population (depending on number of locations selected)
Data Availability	**Low to Moderate** Many complex sources	**High** Data is easy to access and paired down to city scale	**Low to Moderate** AADT input data must be manually collected
Data Completeness	**High** Main dataset provides complete list of vehicles (yr. and class) registered within community	**Medium** Data excludes commercial fuel purchases, skewing diesel values	**Low** Virtually impossible to capture all intersections and traffic flow info.
Cost & Staff Effort	**High** (~$1000 + significant staff time or additional cost for consultant expertise)	**Low** (~$500) – nominal staff effort	**Moderate** no additional cost expenditure but significant staff time required)
Conversion Accuracy	**Medium** 3 stages removed from direct use of emission factor	**High** Direct use of fuel emission factor with consumption data	**Low** 4 stages removed from direct use of emission factor
Ease of Replication & Comparability to Prior Years	**Moderate** Very detailed with many data inputs	**High** Buy annual fuel data and apply emission factor	**Low** AADT[xv] data collect intermittently over several years
Usefulness in Monitoring Progress	**Moderate** Complexity of data inputs can make this very challenging	**Moderate – High** Has the potential to reflect impacts that reduce local fuel consumption	**Low** Only where traffic volume is reduced vs. fuel conservation and efficiency
Complimentary Policies	• Transportation demand management planning	• Increasing transit usage • Eco-driving	• Urban land planning (intensification)

Criteria	Vehicle Registration Method	Fuel Sales Method	Vehicle Kilometres Traveled (VKT)
	• Urban land planning (intensification) • Increasing transit usage • Eco-driving •	•	• Increasing transit usage • Transportation management policies

It should be noted that the three transportation methodologies reviewed, are all reasonable for use in voluntary GHG mitigation programs and defensible in that there is a well –established methodology for each. However, each utilizes different information and processes to quantify emissions within the community transportation sector. As such, each methodology has its own advantages and disadvantages for use by local governments during the development of GHG inventories as identified above. In addition, each has varying requirements for data collection and methodological assumptions. A brief synopsis of each method follows.

The vehicle registration methodology could be considered to have a high degree of accuracy, but it is complex and requires data from several inputs. This methodology may prove very difficult to replicate in the future due to potential changes to data collection processes. Numerous datasets has to be collected from various sources (specifically vehicle registration information and estimated distance traveled) each time the GHG inventory is completed. Many municipalities may have a difficult time accessing data depending on the availability for smaller and mid-size municipalities. Additionally, the data has to be paid for and requires significant expertise to analyze appropriately.

The retail fuel sales method is a more direct look at the quantity of fuel purchased within the municipalities as opposed to estimation based methods drawn from multiple sources. Although this is the simpler methodology, in terms of data collection and accuracy, it should be noted that it does not take fuel efficiency, or distance travelled into consideration. Furthermore, the data set is not complete, in terms of filling the gap in rural or commercial consumption data and has a cost as data must be purchased. Making estimations for the missing rural data is relatively simple and based on population statistics, all assumptions and estimates will affect the outcome of the data, and its ability to be compared annually and to other local governments. The main flaw of this approach is that it is highly sensitive on the amount of exogenous fuelling that occurs from vehicles registered outside of the community. The geographical proximity of the community with the GHG action plan in relation to other urban centres or popular destinations may influence this factor.

The VKT methodology uses AADT traffic counts and road length segments to calculate VKT. This data is generally available from a local governments transportation department (road segment lengths can be determined using GIS). Where data is not available, assumptions must be made to estimate VKT per kilometre of road, based on available data will affect the outcome of the data, and comparability between years. A key aspect of this approach is that it will require coordination of multiple local governments in order to capture data from all roads traveled within the Region. In addition, typically AADT information is collected intermittently over time at different intersections so that at in any given year, several intersection points will have outdated data. The AADT/VKT method will also not capture initiatives such as anti-idling and consumer adoption of electric vehicles if they don't directly impact traffic counts.

In general, from an isolated perspective, the Retail Fuel Sales method is the most straightforward and the least arduous methodology for establishing community transportation GHG emission calculations and monitoring. The Vehicle Registration methodology is a close second to the Retail Fuel Sales methodology in terms of rigour and thorough data coverage. The VKT methodology has a more specific role with transportation infrastructure management but is less useful in GHG emission reduction frameworks.

DISCUSSION

Community transportation GHG emissions planning will result in different approaches strategies and policies to each local government depending on their size, level of influence over roads and regional transit, willingness of elected councils to adopt by-laws such as penalties for excessive engine idling or preferential parking policies for hybrid and electric vehicles as well as staff expertise. Strategies for reducing emissions may be similar, but each local government will have its own actionable priorities and policies. For instance, a local government may prioritize transit policy, whilst another focuses on reducing urban sprawl; both may have a similar effect on transportation emissions. Local governments that track community data and launch such initiatives need to be able to monitor progress with respect to the policy implemented. Capturing the emission reductions can be difficult, time consuming and lead to challenges in assessment of absolute emission reductions if the wrong methodology to capture and quantify the emissions is used. In some cases, local governments have attempted to monitor implementation of policies based on their GHG reduction potential as individual actions. However, this form of specific measurement tends to exclude other influencing variables such as population growth, changes in the economy and potential advances in other local carbon-intensive activities. As such, every local government will need to first establish and understand the relationship between input and output data involved in evaluating, implementing and monitoring different initiatives. This will then allow for the identification of policy, objectives, indicators, prioritization of strategies, in order to select the appropriate monitoring program.

For example, if shifting peak road demand for a busy intersection or to decrease the need to expand a transportation corridor is the objective, examining traffic counts and alternate routes and modes of mobility (transit, bike paths) are factors to be considered. In order to evaluate these types of interventions, traffic count and vehicle registration data can be used to calculate potential changes in VKT and fuel consumption to help model their impact when implemented. Fuel sales, while not a variable or useful input dataset in this planning context, are specifically useful to measure the impact of implementing transportation planning policies after the fact within a GHG emissions inventory. In Waterloo Region, three different actions at the municipal level were evaluated with this approach. The impact of implementing their Regional Transportation Master Plan, a community-wide anti-idling by-law and providing charging stations to encourage the local use of 1000 plug-in electrical vehicles (i.e. as replacements to internal combustion engines) were evaluated by using vehicle registration data modelled with expected modal shifts and reduction in fuel consumption which would result in a decrease of 75,000, 3000 and 2950 Tonnes CO_2e by their target year. As all of these initiatives should in theory affect fuel consumption, future progress monitoring should indicate a change in the local emissions by examining the local retail fuel sales data in the future.

The planning process must recognize and appreciate the areas where local governments can exercise their influence. In the context of the planning, local governments have legislative powers to affect change in land use and development. In other areas, such as buildings and transportation they typically use other policy levers (e.g., incentives, education) to affect change. Understanding the objective and intent of potential actions will help local governments identify opportunities and constraints as well as what the applicable methodology should be. This can be addressed by developing the inventory in concert with preliminary brainstorming for the action plan to flush out the types of initiatives that the community is interested in and has capacity to implement.

If transportation initiatives are to contribute effectively to achieve GHG emission reduction targets set by a municipality, the action should affect the input data source used in the emissions inventory. Moreover, the types of actions selected should be of a magnitude to both offset any anticipated population growth but also reduce the carbon intensity of the way people, goods and services move around a community. There are also many synergies exist between GHG reductions and other transportation objectives. For example, decreasing congestion can lead to a significant drop in GHG emissions and the accompanying reduced speed limits tend to reduce the severity of crashes[xvi]. This inter-relationship between data inputs, objectives and outputs is illustrated below in Figure 1.

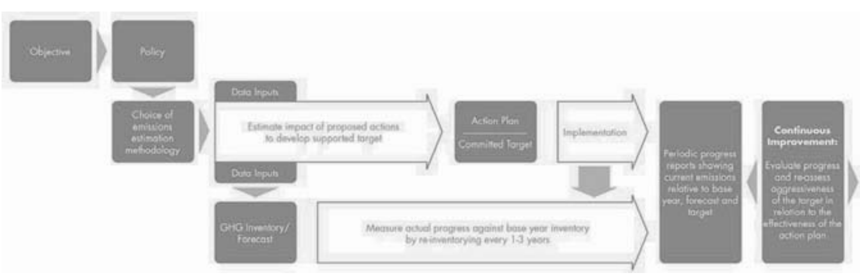

Figure 1. Inter-relationships of Transportation Inputs and Outputs

GHG reductions from external sources (i.e., those beyond the control of the municipality) also have an effect on GHG emissions within any given local government. These external sources may include, but are not limited to, new technologies (engines), low carbon fuels and increased fuel efficiency standards. Therefore, it is in the best interest of the municipality to focus on community transportation initiatives they can control and have the capacity to implement.

From the analysis of the pros and cons of using all three methodologies, Waterloo Region recognized that the baseline inventory and forecast needs to utilize locally representative emissions data and use a relatively simple and replicable methodology in order to measure progress in the future. Furthermore, recognizing that many communities' efforts in GHG mitigation are not reflected in the datasets used for progress reporting, Waterloo Region made the link between the choice of inventory methodology and data sources and type of actions in their plan that have the ability to demonstrate their impact. A prime example of this where community transportation emission estimates using traffic count data will not show the impact of idling reduction campaigns or promotion of electric vehicles, whereas use of fuel sales data and/or advanced transportation modeling can capture these changes over time.

CONCLUSION

Through a comparative analysis of three commonly used transportation emissions estimation methods, it was concluded that the retail fuel sales method is the least arduous methodology and reasonably accurate to replicate and suitable for monitoring progress. However, vehicle registration data combined with transportation modelling can be useful at the action planning and target setting stages to assess the potential for initiatives to achieve emission reductions. Availability of staff expertise, data and financial resources are also influential factors and should be key considerations to determining which of the transportation methodologies would be best suited. It can also be insightful to examine the interrelationship between the different stages of local GHG reduction frameworks and associated datasets when making these choices.

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Experimental Analysis of Single-Lane Roundabout Slip Lanes: Fuel Consumption and Emissions

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ABSTRACT

Vehicular fuel consumption and emissions performance (CO_2 and CO) are examined experimentally within single-lane roundabouts with a slip lane, under yield, stop, and free-flow exit control scenarios; these are compared to no slip lane using a gap acceptance-based performance experimental assessment SIDRA tool. For comparison to other types of traffic control, the same experimental roundabout is converted into a signal intersection and into all-way stop-controlled intersection. With a free-flow slip lane exit type, overall average total roundabout fuel consumption was reduced by 26%, CO_2 emissions were reduced 27%, and CO emissions were reduced 17%, compared to an all-way stop-controlled intersection. As expected, results indicate that a roundabout with a free-flow slip lane exit type significantly reduces total average fuel consumption and pollutant emissions within a roundabout, compared to all-way stop-controlled intersection.

Author keywords: Roundabout, slip lane, fuel consumption, pollutant emission, SIDRA.

INTRODUCTION

This paper examines vehicle fuel consumption and pollutant emissions improvements when a slip lane is installed at a roundabout. Though roundabouts are increasingly used in the U.S., research has yet to quantify slip lane contributions to their general effectiveness. A slip lane, a separate lane that relieves right-turning traffic flow, reduces approach delay by allowing right-turning movements to bypass the roundabout, thereby reducing vehicle conflicts, delays, and stops. Vehicle delays increase acceleration/deceleration cycles, stops, and time spent idling at the intersection. Operational performance of roundabouts, measured as roundabout capacity and delays, typically is based on one of three capacity methods: gap acceptance, empirical regression, or a hybrid of gap and empirical methods (TRB, 2000) and NCHRP Report 572 (NCHRP, 2007).

Hallmark et al. (2008) noted that roundabouts reduce vehicle delay and the number and duration of stops that would occur in traditional signalized or all-way stop-controlled intersections. Also, several previous studies show that implementation of roundabouts significantly reduces vehicle fuel consumption and pollutant emissions.

Mandavilli et al. (2003) studied and collected actual data before and after three stop-controlled intersections in Kansas were replaced by roundabouts. Using SIDRA (Signalized and Unsignalized Design and Research Aid, 2007), Mandeville and his team found a 45% reduction in carbon monoxide (CO), a 61% reduction in carbon dioxide (CO_2), a 51% reduction in nitrogen oxides (NO_x), and a 68% reduction in hydrocarbons (HC).

Hyden and Varhelyi (2000) evaluated speeds and emissions before and after installation of roundabouts in Sweden. They found at a previously unsignalized intersection that CO emissions increased by 6% and NO_x by 4%; at a previously signalized intersection, however, CO decreased by 29% and NO_x decreased by 21%.

Using SIDRA to quantify the impact of roundabouts on emissions and energy consumption, Ariniello and Przybyl (2010) studied several sustainable performance measures for 15 roundabouts in the City of Boulder, Colorado. They found that at high volume, roundabouts can reduce CO_2 emissions by up to 400 metric tons per year and energy consumption by up to 45,000 gallons of gasoline per year.

SIDRA software is commonly used to analyze traffic operations at roundabouts. In Australia, Akcelik and Besley (2004) used it with gap acceptance techniques to analyze roundabout capacity and performance, analysis based on empirical models to estimate gap-acceptance parameters. Akcelik et al. (2012) carried out a research to calibrate the vehicle parameters of fuel consumptions and emission models used in SIDRA. The fuel consumption and emission models use vehicle parameters, traffic and road parameters.

SIDRA includes such parameters as vehicle volumes and movement paths, yield and stop slip lane exit configurations, gap acceptance and follow-up headway attributes for selected movements, and roundabout geometry attributes (inscribed diameter, number of entry lanes, and average entry lane width). It uses a four-model elemental model for estimating fuel consumption and pollutant emissions (cruise, declaration, idling, and acceleration). SIDRA also has the capacity to output performance measures such as average intersection delay, 95% back of queue, total effective stops, stop rates, travel distance, travel time, travel speed, costs, fuel consumption, and pollutant emissions (carbon dioxide, hydrocarbons, carbon monoxide, and NO_x).

Neither vehicle fuel consumption nor pollutant emissions evaluations were found in the literature for roundabouts where slip lanes were installed. Nothing was found specifically focused on air quality related to roundabout slip lane performance. The purpose of this paper is to estimate vehicular fuel consumption and emissions performance within single-lane roundabouts with a slip lane, under yield, stop and free-flow exit control scenarios.

METHODOLOGY

Al-Ghandour et al. (2011*)* studied roundabout slip lane performance by conducting both experimental balanced (total traffic flow into and out of each roundabout approach is the same) and more realistic unbalanced flow scenarios (traffic flow into and out of different roundabout approaches is different) for a range of volume levels. SIDRA was used in this study to explore experimental traffic flows in a single-lane roundabout with a slip lane, compared to signal and all-way stop-controlled intersections. SIDRA automatically sets gap acceptance parameters for the roundabout and slip lane as a function of geometry, circulating flow rate, entry flow rate, and other factors; it limits other parameters such as critical gap headway (t_c) to range from 2 to 8 seconds, and follow-up headway (t_f) to range from 1 to 5 seconds.

A balanced experimental traffic percentage turning volume distribution (33%) was focused to demonstrate six scenarios S1—no slip lane; S2—yield sign; S3—stop sign; S4—free-flow lane; S5—signal intersection; and S6—all-way stop-controlled intersection (Figure 1). These scenarios were studied under the assumption that total traffic flow into and out of each intersection approach is the same. Scenarios S1 to S6 were initialized, analyzed, and then volumes were controlled through several iterations.

Slip lane right-turning traffic volume as the dominant turn ranged from 50 vehicles per hour to 500 vehicles per hour, in increments of 50—representing low, moderate, and high volumes.

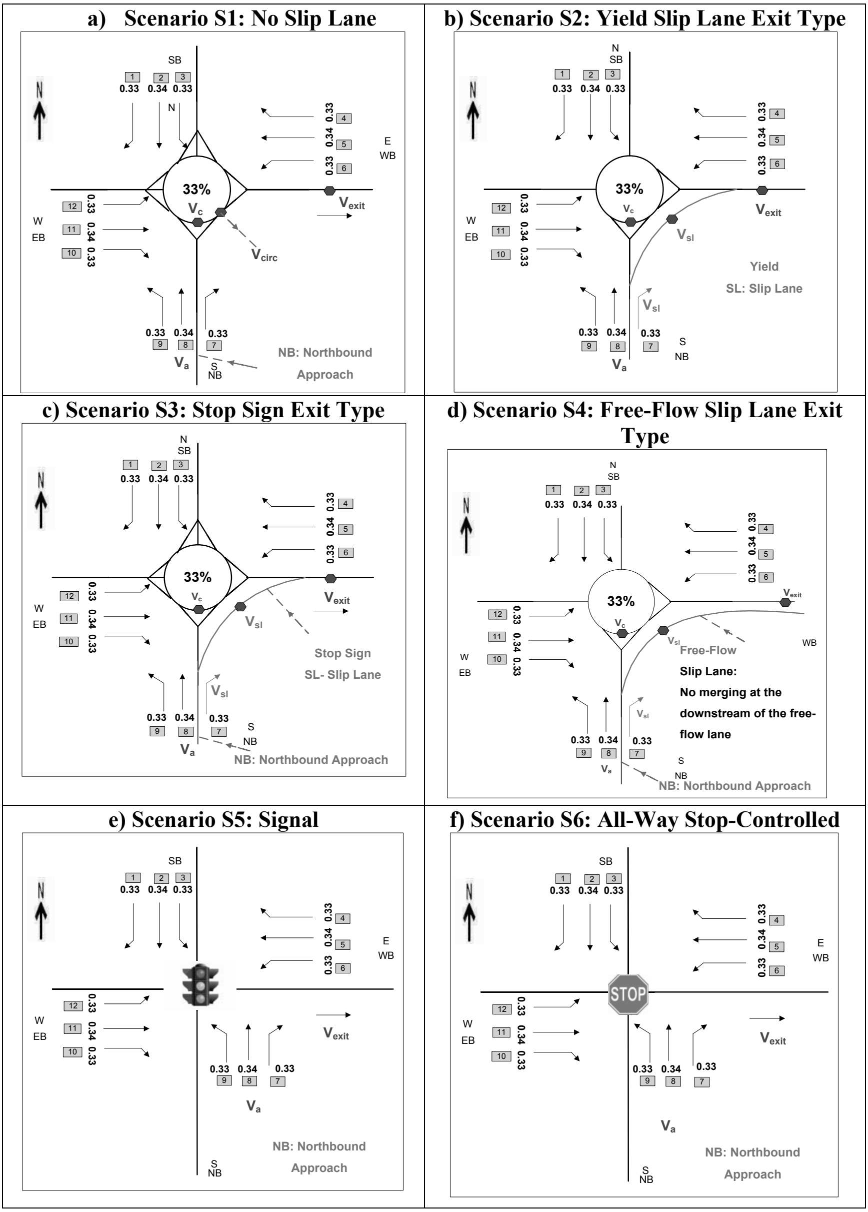
Three volume distributions were sampled: 50, 250, and 500 vehicles per hour (Table 1), and total approach volumes (V_a), conflicting volumes (V_c), and slip lane right-turn volumes (V_{sl}) for all scenarios (S1-S6) are summarized. Volumes for each roundabout approach (V_a), or intersection, are assumed to be the same as for each exit approach (V_{exit}). Fuel consumption, emissions (CO_2 and CO), and average delay (in seconds) for all vehicles entering the intersection approaches are used as the Measure of Effectiveness (MOE).

Table 1. Total Approach and Conflicting Volumes.

V_{sl}: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach	Volumes (Vehicle/hour)	S1-S6 (33%)
V_{sl} = 50 (Low)	V_a	150
	V_c	150
V_{sl} = 250 (Moderate)	V_a	757
	V_c	757
V_{sl} = 500 (High)	V_a	1,515
	V_c	1,515

V_a : Approach volumes. V_c: Conflicting circulating volumes.

V_{sl}: Slip lane volumes as dominant right turn, vehicles per hour.



V_a : Approach volumes. V_{exit}: Exit approach volumes. V_c: Conflicting circulating volumes. V_{sl}: Slip lane volumes as dominant right turn, vehicles per hour, for S1-S4. V_{cir}: Circulating volumes for S1-S4. Movement Turn No. 7 represents right turn, vehicles per hour, for S5-S6.

Figure 1. Traffic Percentage Distribution Flow Pattern (Scenarios S1-S6).

ANALYSIS AND RESULTS

As slip lane (right-turning) traffic volume (V_{sl}) increases, the conflicting circulating volumes (V_c), decrease; average delay, fuel consumption, and emissions also decrease, in a non-linear, or exponential, relationship. For roundabouts (S1-S4), the highest roundabout average delay (Figure 2), fuel consumption (Figure 3), and emissions (Figures 4 and 5) observed in Scenario S1 (no slip lane), was a result of the combined highest approach volumes (V_a), highest total roundabout volumes, and highest conflicting circulating flow (V_c) and also increase number of idling (stops). The lowest roundabout average delay, fuel consumption, and emissions observed in Scenario S4 (free-flow slip lane), was a result of the combined lowest approach volumes (V_a), lowest total roundabout volumes, lowest conflicting circulating flow (V_c), and number of stops.

If Scenario S4 (free-flow slip lane) is compared with both Scenario S5 (signal intersection) and Scenario S6 (all-way stop-controlled intersection) (Figures 2 to 5), Scenario S4 shows significant reduction of total average fuel consumption and pollutant emissions. Therefore, under different scenarios, slip lane performance is most effective under a higher right-turning traffic pattern distribution.

As more traffic is diverted outside the roundabout on the slip lane (right-turn movement), the slip lane reduces more roundabout conflicting circulating volumes. Therefore the average delay in the roundabout is reduced, thereby reducing vehicle conflicts, delays, and stops, and reducing vehicle fuel consumption and pollutant emissions.

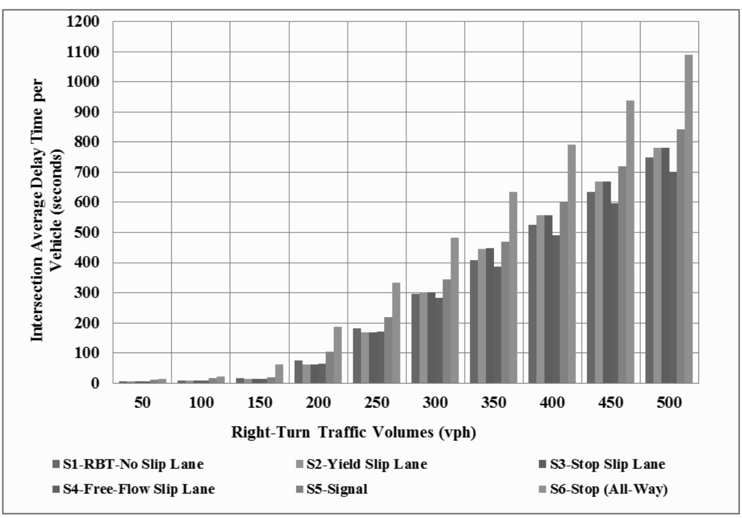


Figure 2. SIDRA: Roundabout (Intersection) Average Delay for Scenarios S1-S6.

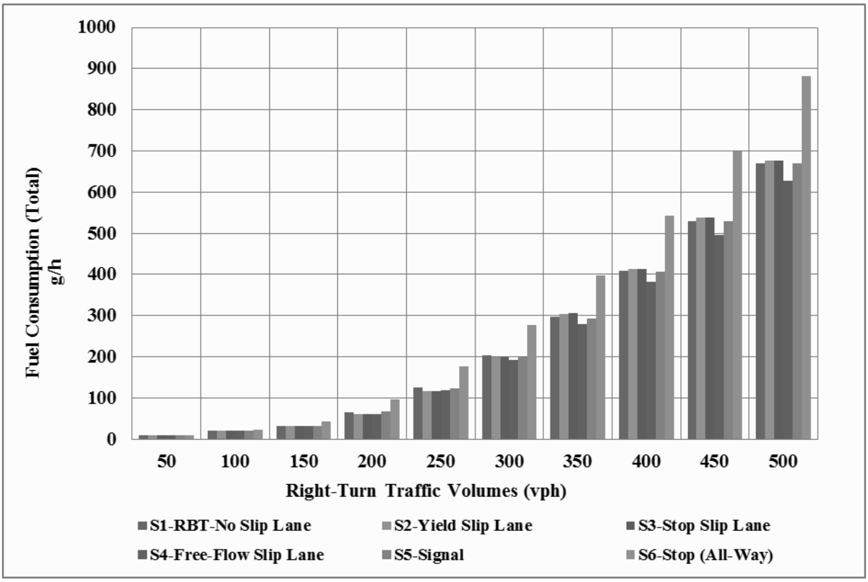


Figure 3. SIDRA: Roundabout (Intersection) Total Fuel Consumption for Scenarios S1-S6.

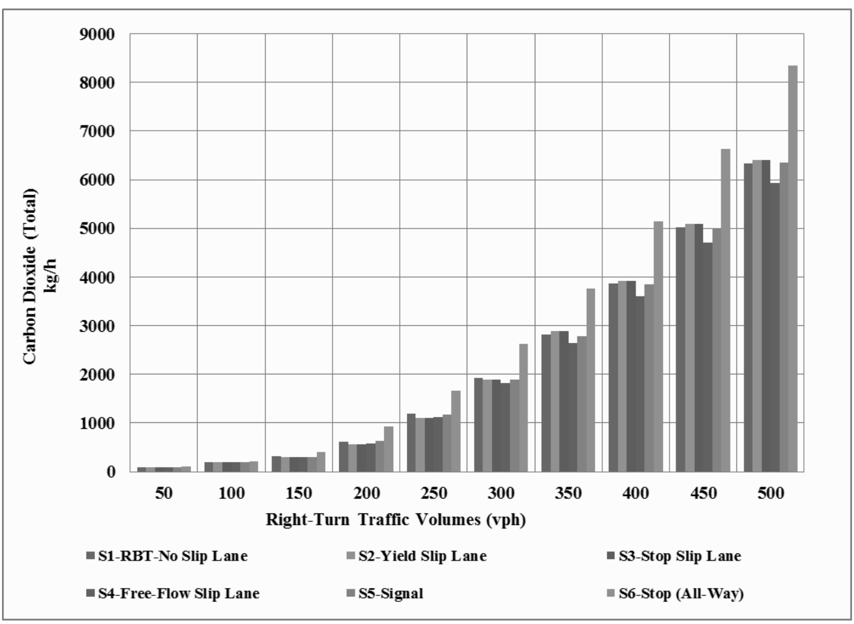


Figure 4. SIDRA: Roundabout (Intersection) Total Carbon Dioxide (CO_2) Emissions for Scenarios S1-S6.

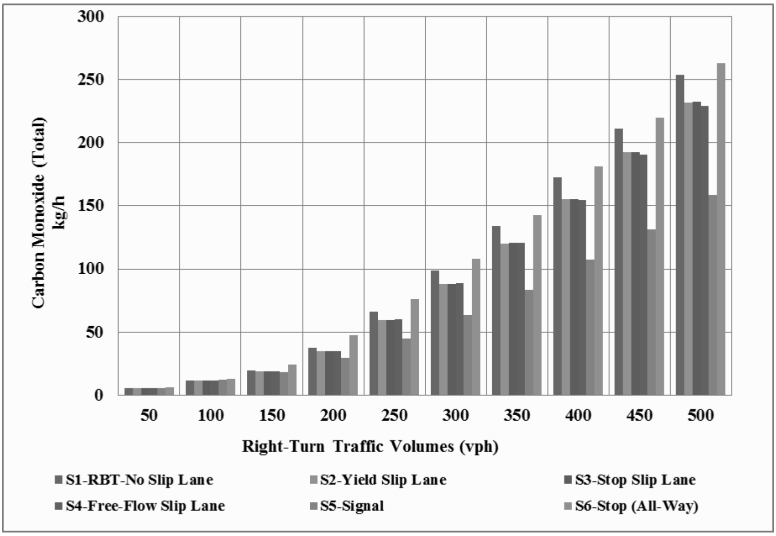


Figure 5. SIDRA: Roundabout (Intersection) Total Carbon Monoxide (CO) Emissions for Scenarios S1-S6.

Number of stops is found correlated to both fuel consumptions and emission. For example, with traffic volumes V_{sl} = 50 vehicles per hour, a roundabout with a free-flow slip lane exit type has less total effective stops (349 vehicles/hour), and less fuel consumptions and emission, than an all-way stop-controlled (850 vehicles/hour).

Impact of Slip Lane on Total Fuel Consumption

A sample of the results from SIDRA (Table 2) is compared, based on total fuel consumption between highest values from Scenario S6 (all-way stop-controlled intersection), as the before case, and lowest values from Scenario S4 (roundabout with a free-flow slip lane exit type), as the after case. Total fuel consumption is shown in Table 2 in gallons per hour for all vehicles. With high traffic volumes V_{sl} = 500 vehicles per hour, a roundabout with a free-flow slip lane exit type has less total fuel consumption (626.7 gal/hour) for all vehicles than an all-way stop-controlled intersection (881.9 gal/hour)—a 29% reduction (calculated as -28.94 % = ((626.7-881.9)/881.9)). Thus, reduction of total fuel consumption via the use of a free-flow slip lane is shown to be greater than in an all-way stop-controlled intersection.

Table 2. SIDRA Percent Change in Fuel Consumption – Scenarios (S4 and S6).

V_{sl}: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach	Total Fuel Consumptions (gal/hour)		Percent Change
	S6 (All-Way Stop-Controlled)	S4 (Free-Flow Slip Lane)	
V_{sl} = 50 (Low)	10.4	9.6	-7.96%
V_{sl} = 250 (Moderate)	176.3	118.3	-32.90%
V_{sl} = 500 (High)	881.9	626.7	-28.94%

Impact of Slip Lane on Total Emissions

With high traffic volumes V_{sl} = 500 vehicles per hour (Table 3), a roundabout with a free-flow slip lane exit type has less total CO_2 emission (5,935 kg/hour) for all vehicles than an all-way stop-controlled intersection (8,353 kg/hour)—a 29% reduction (calculated as -28.94 % = ((5,935-8,353)/ 8,353)) (Table 3). Similarly, with a free-flow slip lane, there is a 17% reduction of CO emission, compared to an all-way stop-controlled intersection. Thus, reduction of total CO_2 and CO emissions via the use of a free-flow slip lane is shown to be greater than in an all-way stop-controlled intersection.

Table 3. SIDRA Percent Change in Emissions – Scenarios (S4 and S6).

V_{sl}: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach	Total Carbon Dioxide (CO_2) (kg/hour)		Percent Change	Total Carbon Monoxide (CO) (kg/hour)		Percent Change
	S6 (All-Way Stop-Controlled)	S4 (Free-Flow Slip Lane)		S6 (All-Way Stop-Controlled)	S4 (Free-Flow Slip Lane)	
V_{sl} = 50 (Low)	98.60	90.80	-7.91%	6.28	5.34	-14.9%
V_{sl} = 250 (Moderate)	1,669.40	1,120.00	-32.90%	75.96	59.53	-21.04%
V_{sl} = 500 (High)	8,352.70	5,935.10	-28.94%	263.41	229.13	-13.01%

Statistical Validation

For each scenario, the standard deviation and standard error are recorded for roundabout (intersection) fuel consumption that tested statistically significant, using the 95% confidence interval (alpha 0.05). Using the standard error, it is possible to calculate the 95% confidence interval for the roundabout (intersection) total fuel consumption reduction that might be achieved by implementing the free-flow slip lane exit type. The 95% confidence interval is ±1.96 standard errors from the total fuel consumption reduction percentage of reduction. Therefore, reduction of total fuel consumption from implementing a free-flow slip lane exit type, compared to an all-way stop-controlled intersection, is estimated between -34% and -19% (Table 2). Reduction of total fuel consumption from implementing a yield-sign slip lane exit type is estimated between -32% and -16%. Another comparison of total fuel consumption is made between Scenario S5 (signal intersection) as the before case, and lowest values from Scenario S4 (roundabout with a free-flow slip lane exit type) as the after case. Reduction of total fuel consumption from implementing a free-flow slip lane exit type compared to a signal intersection is estimated between 3% and -12%.

The SIDRA results for the six scenarios are compared. A free-flow slip lane exit type with moderate traffic volumes (250 vehicles per hour) shows significant reduction in roundabout average delay (operational improvement), from 182.3 sec/vehicle (no slip lane) to 171.3 sec/vehicle: a 6% reduction in S4, and from 218.4 sec/vehicle (signal): a 22% reduction; and from 333.1 sec/veh (all-way stop): a 46% reduction, (Figure 2). Similar results were noticed for CO_2 and CO emissions. A free-flow slip lane exit type shows significant reduction of CO_2 from average total of 2,225 kg/h (signal) to 2,099 kg/h: a 6% reduction; from average total of 2,982 kg/h (all-way stop): a 27% reduction. Finally, for CO emissions, a free-flow slip lane exit type shows significant reduction of CO from average total of 108 kg/h (all-way stop) to 91 kg/h: a 17% reduction.

CONCLUSIONS

SIDRA was used in this study to explore experimental traffic flows in a single-lane roundabout with a slip lane, compared to signal and all-way stop-controlled intersections. Roundabouts with slip lanes are expected to reduce vehicle fuel consumption and emissions as a result of reduced delays and stops. Reasonable estimates are generated for overall CO_2 and CO emissions as well as fuel consumption.

As expected and statistically validated, results indicate that a roundabout with a free-flow slip lane exit type significantly reduces total roundabout (intersection) average fuel consumption and pollutant emissions values, compared to having no slip lane or a signal or stop sign control intersection. With a free-flow slip lane exit type, overall average roundabout fuel consumption was reduced 26% (the estimated 95% confidence interval of reduction estimated between -19% and -34%) compared to a all-way stop-controlled intersection, and was reduced 5% (the estimated 95% confidence interval of reduction estimated between -12% and 3%) compared to a signal intersection. Results are similar for carbon emissions: overall average CO_2 value was reduced from 2,982 kg/hour (all-way stop-controlled intersection) to 2,099 kg/hour (roundabout with a free-flow slip lane). A roundabout with and without slip lane shows a more significant improvement of fuel consumption and pollutant emissions values than a signal intersection or a stop sign control intersection. Hence the most effective roundabout performance in reducing delay, fuel consumption, and pollutant emissions generally is obtained from a free-flow slip lane.

RECOMMENDATIONS

SIDRA can be used to analyze a slip lane's contribution to improve roundabout capacity, delay, and to diminish fuel consumption and pollutant emissions. Additional analysis should be conducted for other variables: different unbalanced flow scenarios (traffic flow into and out of different roundabout approaches is different); heavy vehicles**,** different speeds, and other traffic controls such as a two-way stop sign of a major-minor intersection. To validate SIDRA sensitivity, future analysis should vary its default values for gap acceptance parameters and compare results to MOVES (Motor Vehicle Emission Simulator) from EPA (U.S. Environmental Protection Agency) models or a micro-simulation such as VISSIM, which will be able to estimate emissions based on vehicle mode. Hydrocarbons (HC) and nitrogen oxides (NO_x) emissions can be included in future studies.

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Geo-spatial and Statistical Methods to Model Intracity Truck Crashes

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ABSTRACT

Off-network characteristics such as land use, demographic, and socio-economic characteristics and on-network characteristics are indicators of development and growth patterns in a study area. These factors not only have an effect on truck trips generated or truck operations in an area but also influence mobility and safety offered by a transportation network. However, the role of these off- and on-network characteristics on intracity trucks crashes has not been studied in the past. The key objectives of this research are: 1) to investigate the relation between intracity truck crash occurrences and various independent variables (off- and on-network characteristics), and, 2) to develop macro-level intracity truck crash estimation models. A Geographic Information Systems (GIS) based methodology was adopted to identify intracity truck crash zones, capture spatial off-network characteristics data within 0.25-mile buffer for each selected zone and develop intracity truck crash estimation models. The working of the methodology is illustrated using 2008 data for the city of Charlotte, North Carolina. Truck crash occurrences seem to be significantly affected by land use characteristics such as institutional area, heavy commercial area and 0.25 to 0.5 acre residential area. Planning and building well balanced neighborhoods, and, implementing improved design strategies and safety treatments in residential areas will help promote safety and enhance quality of life in these areas.

KEYWORDS: Truck, Crash, GIS, Prediction, Land Use

INTRODUCTION

There has been a renewed interest in statistical ranking criteria to identify hot spots and develop crash estimation models to proactively enhance safety in recent years. These models can be used to make long-range transportation planning and land use planning related decisions. However, freight safety, specifically truck safety, was meagerly addressed. Trucks and long-combination vehicles (LCVs) that carry approximately 70% freight have significant potential in triggering crash occurrences. Studies show that an increase in truck volume tends to result in an increase in severe crashes (Huang et al., 2010). Interstate roadways often experience high percentage of truck trips. Despite this, only 24% of fatal truck crashes are observed on Interstate roadways (NHTSA 2006). Out of all, ~59% of fatal truck crashes occur on undivided highways that do not have controlled access and have signalized intersections. The abnormally high proportions of crashes on non-Interstate roads when compared to the proportion of truck volume using these roads needs research and better understanding of causal factors to plan, build or retrofit the existing transportation network.

There has been considerable research over the last three decades on crash prediction or estimation models (Abbess et al., 1981; Poch and Mannering, 1996; Hauer et al., 1998; Ivan et al., 2000; Lyon et al., 2003; Miaou and Lord, 2003; Oh et al, 2003; Pulugurtha and Sambhara, 2011; Pulugurtha and Nujjetty, 2012). While a few researchers (Vavilikolanu, 2008) have focused on intercity truck transportation and its effect on safety, not many authors have researched on intracity truck transportation and its effect on safety. The characteristics of intracity truck transportation and their impacts are different than intercity truck transportation. Network characteristics such as inadequate turning radius or low sight distance further aggravate the problem on intracity roads.

Mobility and safety on roads depend on developments and their growth patterns. The indicators of these factors are off-network characteristics such as land use, demographic, and socio-economic characteristics and on-network characteristics. However, research on truck crash estimation models relating crashes to demographic, socio-economic and land use characteristics are hardly found in the literature. Truck crash estimation models developed considering such characteristics would play a significant role in incorporating safety into the planning process and adopt a proactive approach to make road transportation network more effective and efficient for use. The findings from such a research will also help plan and build well balanced neighborhoods with adequate design features to accommodate different modes of transportation.

The key objectives of this research, therefore, are: 1) to investigate the relation between intracity truck crash occurrences and various independent variables (off- and on-network characteristics), and, 2) to develop macro-level truck crash estimation models.

METHODOLOGY

The proposed research methodology to achieve the above stated objectives includes the following steps:

1. Defining study area
2. Extracting off-network and collecting on-network characteristics
3. Developing statistical models
4. Validating the models

Defining Study Area

Study area needs to be selected in such a way that it represents various levels of road classes to avoid any possible discrepancies and biased results. The selection of a study area also depends on the availability of data such as truck crash data, land use characteristics (residential, commercial/retail, industrial, and institutional), demographic characteristics (population, household units, age, and gender), socio-economic (auto-ownership, population in labor force, household income and unemployment rate), and, on-network characteristics (the number of lanes, the number of driveways, the number of unsignalized intersections, the number of signalized intersections, the presence of a median, the number of horizontal curves, length and annual average daily traffic).

The study area was selected based on the availability of the above databases used in this research. The truck crash data was overlaid on the street network to identify intracity truck crash zones for modeling. These intracity zones are linear in nature and are defined as links connecting two major intersections (mostly, signalized). The on- and off-network characteristics of or along a selected intracity truck crash zone are similar. In total, 50 intracity truck crash zones were identified to extract data and develop models so as to yield statistically meaningful outcomes.

Extracting Off-network and Collecting On-network Characteristics

In this step, features available in GIS were used to extract off-network characteristics for each intracity truck crash zone. The spatial overlay and data processing approach adopted by Pulugurtha and Repaka (2008) and Pulugurtha and Sambhara (2011) to develop pedestrian activity and pedestrian crash estimation models for signalized intersections was used in this research. The extraction and computation of demographic, socio-economic and land use characteristics is briefly discussed next.

Demographic and Socio-economic Characteristics

To extract zone-specific demographic and socio-economic characteristics, planning variables data was overlaid on 0.25-mile buffers generated around each selected intracity truck crash zone. The demographic and socio-economic characteristics within the buffer around each selected intracity truck crash zone were extracted. The spatial attribute data pertaining to the demographic and socio-economic characteristics was processed, adjusted based on the area that falls within the respective buffer, and then stored in a database for modeling and analysis.

Land Use Characteristics

To extract specific land use characteristics and use them in intracity truck crash estimation modeling, land use coverage was overlaid on 0.25-mile buffers generated around each intracity truck crash zone. The area of each land use characteristic within the buffers around each selected intracity truck crash zone was extracted and appended to the database for modeling and analysis.

On-network Characteristics

Aerial photographs and field visits as well as network files maintained by local agencies were used to extract on-network characteristics such as the number of lanes, the number of driveways and the number of unsignalized intersections, the number of signalized intersections, the presence of a median, the number of horizontal curves, length and annual average daily traffic.

Develop Statistical Models

The database built from previous step was used for developing intracity truck crash estimation models that provide insights on the degree to which one or more independent variables potentially have a positive or negative effect on intracity truck crashes.

First, independent variables that are not correlated to each other were identified by testing multicollinearity between themselves. In general, two independent variables are said to be perfectly multicollinear if the Pearson Correlation Coefficient (strength of association or linear relationship) between the two independent variables is equal to 1 or -1. The higher the absolute value, the stronger is the relationship between the two independent variables. Highly correlated independent variables could produce significant overall P-values even when the variables do not have an effect on the dependent variable. Hence, it is recommended that the correlations among the (independent) variables considered for developing the models be in the range (-0.3, +0.3).

Miaou and Lum (1993) found that conventional linear regression models were not appropriate for modeling vehicle crash events on roadways. Since crashes are counts, generalized linear models (GLMs) based on Poisson, Negative Binomial (NB) or Gamma distribution may be more appropriate for modeling. Shankar et al. (1998) indicated that the NB model may be more appropriate as geometric and traffic variables are likely to have location-specific effects. The NB model assumes that unobserved crash heterogeneity across sites (intersections, road segments, etc.) is Gamma distributed (Mitra and Washington, 2007). Considering findings from past research, non-linear count models were therefore developed using the independent variables that are not correlated to each other.

The independent variables with a P-value greater than or equal to 0.05 were eliminated one after another (independent variables with highest P-value was eliminated first) and the analysis was repeated. This process was repeated until all the independent variables in the model had a P-value less than 0.05. This model was considered as the final model.

SPSS® (2008) was used to compute the Deviance and Akaike's Information Criterion (AIC) for each developed model and test the goodness of fit. In general, the crash estimation model developed is considered good if AIC value is low and the value of Deviance to Degrees of Freedom is equal or closer to one.

Validating the Models

Data for eight zones, not used in model development, were used to validate the generated truck crash estimation model. The values for the independent variables were substituted into the model equation developed and compared to the actual truck crash counts. The percent difference in values of observed and estimated values for the eight zones was then computed. In addition, the root mean square error, which measures the average of the square-root of the sum of the squares of the errors, was also computed and compared to validate the model.

ANALYSIS AND DISCUSSION

The city of Charlotte, NC was considered as the study area in this research. All data used in this research was obtained, for the year 2008, from the city of Charlotte Department of Transportation (CDoT). Figure 1 shows the spatial distribution of year 2008 truck crashes in Charlotte, NC.

As stated previously, demographic, socio-economic, land use and on-network characteristics for 50 randomly selected intracity truck crash zones were extracted to conduct statistical analysis and to develop intracity truck crash estimation models. The following independent variables were initially considered for analysis and model development.

Land use
- 0.25 to 0.5 acre residential
- 0.25 acre residential / apartments
- 0.5 to 2 acres residential
- > 2 acres residential
- Light commercial
- Heavy commercial
- Light industrial
- Heavy industrial
- Institutional (major cultural, educational, medical, governmental, religious and other institutions)

Demographic and socio-economic
- Population
- Population in family households
- Median age
- Median age males
- Median age females
- Auto-ownership
- Average household income
- Unemployment rate
- Population in labor force

On-network
- Number of lanes
- Number of driveways and unsignalized intersections
- Number of signalized intersections
- Presence of median
- Number of horizontal curvatures
- Zone length
- Average annual daily traffic (AADT)

Land use characteristics were expressed in square feet whereas demographic, socio-economic and on-network characteristics were expressed in numbers (without any units).

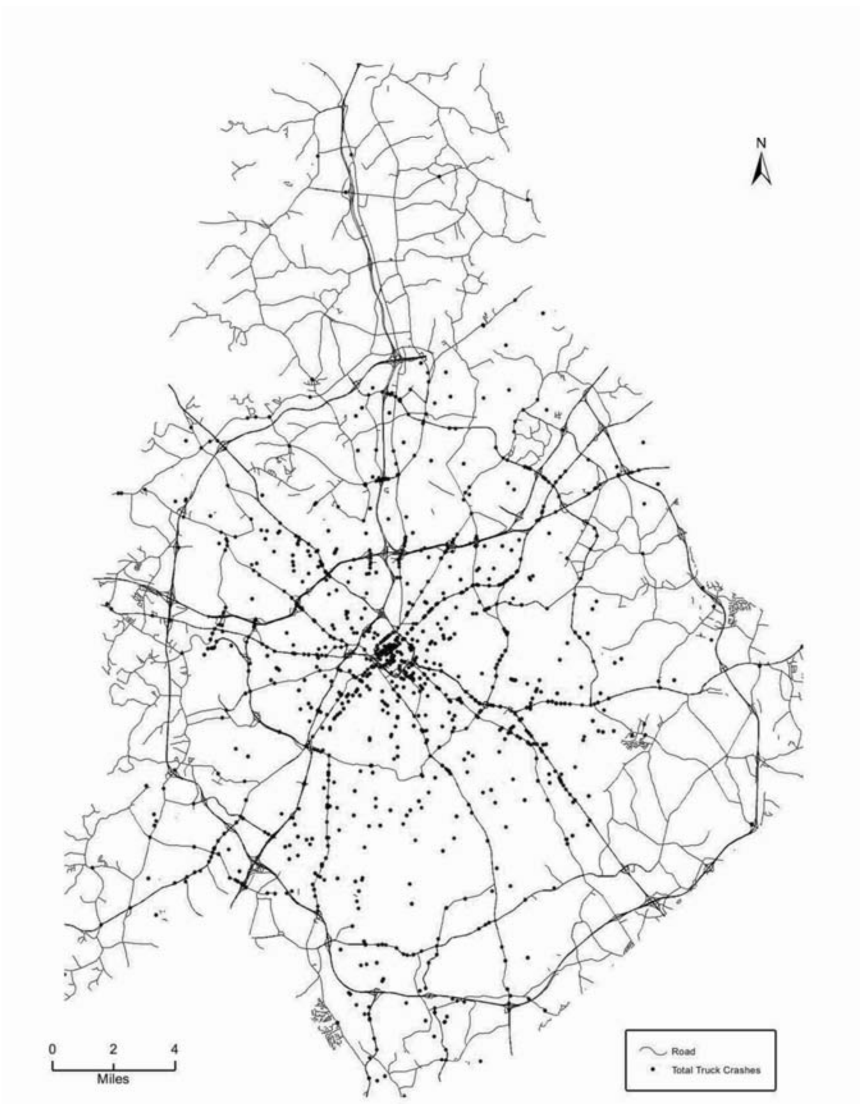

Figure 1. Spatial distribution of year 2008 truck crashes – Charlotte, NC.

A correlation matrix was first developed using SPSS® (2008) to evaluate the strength of correlation between the independent variables. Table 1 summarizes the correlation matrix developed using the generated database. The red colored numbers in the table denote the variables with correlation coefficients that are unacceptable based on criteria discussed in the "Methodology" section. Based on the computed Pearson correlation coefficients, the following variables were identified as not correlated to each other and were selected to develop intracity truck crash estimation models.

1. 0.25 to 0.5 acre residential
2. 0.25 acre residential / apartments
3. 0.5 to 2 acre residential
4. Light commercial
5. Heavy commercial
6. Institutional
7. # of lanes

The intracity truck crash estimation models were then developed using SPSS® (2008). A NB distribution based model was developed as data was observed to be over-dispersed (i.e., variance is much greater than the mean). Insignificant variables were eliminated one after another while developing the final model. The P-value for all the variables in the final model is therefore less than 0.05. The coefficients for independent variables in the final model developed using 0.25-mile buffer width dataset are shown in Table 2.

From Table 2, it can be observed that an increase in 0.25 to 0.5 acres residential area increases the number of intracity truck crashes while an increase in heavy commercial area or institutional area decreases the number of intracity truck crashes. The negative coefficient for heavy commercial and institutional area could be due to better geometric / design features provided to accommodate truck traffic along corridors with these types of land uses. In general, the relative effect (negative or positive) on truck crashes is highest due to institutional area followed by heavy commercial area and 0.25 to 0.5 acre residential area within a 0.25-mile buffer.

Table 1. Correlation matrix

Variable	R1	R2	R3	R4	HC	HI	I	LC	LI	POP	POPFAM	AGEMED	AGEMEDM	AGEMEDF	VPH	AHHI	LBF	UNEMR	Lanes	Drivewa	Signals	Median	Horiz	Zone	AADT
R1	1.00																								
R2	-0.06	1.00																							
R3	0.17	-0.11	1.00																						
R4	-0.18	-0.33	0.16	1.00																					
HC	-0.04	-0.03	-0.22	-0.22	1.00																				
HI	-0.06	0.14	0.17	-0.22	-0.35	1.00																			
I	-0.20	-0.25	-0.06	-0.04	-0.13	-0.45	1.00																		
LC	0.20	0.09	-0.14	0.06	-0.09	-0.10	-0.23	1.00																	
LI	0.31	-0.10	-0.35	-0.13	-0.18	-0.08	0.10	0.27	1.00																
POP	0.65	0.47	0.06	-0.12	0.09	-0.09	-0.29	0.44	-0.03	1.00															
POPFA	0.76	0.41	0.17	-0.04	-0.12	-0.05	-0.31	0.36	0.03	0.92	1.00														
AGEME	0.76	0.12	0.05	-0.38	0.18	-0.04	-0.08	0.24	0.25	0.65	0.60	1.00													
AGEME	0.74	0.12	0.06	-0.38	0.17	-0.04	-0.05	0.24	0.25	0.63	0.59	1.00	1.00												
AGEME	0.77	0.12	0.05	-0.38	0.20	-0.05	-0.12	0.24	0.24	0.66	0.61	1.00	0.99	1.00											
VPH	0.61	0.46	0.14	-0.04	-0.01	-0.13	-0.34	0.49	-0.08	0.91	0.86	0.53	0.52	0.54	1.00										
AHHI	0.60	0.09	0.31	-0.38	0.06	-0.04	-0.01	0.16	0.18	0.45	0.43	0.76	0.77	0.75	0.54	1.00									
LBF	0.30	-0.11	-0.17	-0.30	0.21	0.16	0.32	0.08	0.29	0.29	0.22	0.73	0.74	0.71	0.05	0.35	1.00								
UNEMR	0.56	0.50	0.00	-0.12	0.13	-0.12	-0.29	0.47	-0.06	0.98	0.85	0.59	0.57	0.60	0.92	0.41	0.25	1.00							
Lanes	0.20	0.20	0.10	-0.07	0.10	-0.07	-0.24	0.13	-0.02	0.35	0.34	0.31	0.31	0.31	0.23	0.13	0.20	0.33	1.00						
Driveway	0.56	-0.03	0.50	-0.15	-0.30	-0.19	-0.04	-0.09	-0.09	0.27	0.33	0.43	0.44	0.42	0.34	0.76	0.05	0.20	-0.09	1.00					
Signals	0.14	0.08	-0.05	0.16	0.33	0.21	-0.22	0.55	0.17	0.47	0.30	0.26	0.25	0.28	0.45	0.19	0.21	0.50	-0.02	-0.05	1.00				
Median	0.36	0.17	0.16	0.23	-0.34	0.07	-0.18	0.30	0.17	0.25	0.39	0.05	0.04	0.05	0.26	0.03	-0.13	0.20	0.28	0.13	0.11	1.00			
Horiz	0.03	-0.17	0.15	0.62	-0.39	0.19	-0.28	0.37	0.01	0.16	0.20	-0.12	-0.11	-0.12	0.25	-0.06	-0.15	0.18	-0.01	-0.02	0.33	0.24	1.00		
Zone	0.45	0.03	0.18	0.43	-0.10	0.24	-0.39	0.61	0.23	0.54	0.61	0.24	0.23	0.24	0.59	0.17	0.03	0.51	0.14	0.06	0.59	0.46	0.71	1.00	
AADT	0.05	-0.16	0.05	0.32	0.31	0.23	-0.31	0.29	0.22	0.19	0.14	-0.02	-0.02	0.00	0.16	-0.09	-0.04	0.20	0.26	-0.16	0.49	0.09	0.53	0.61	1.00

Note: R1 = 0.25 to 0.5 acre residential, R2 = 0.25 acre residential / apartments, R3 = 0.5 to 2 acres residential, R4 = >2 acres residential, HC = Heavy commercial, HI = Heavy industrial, I = Institutional, LC = Light commercial, LI = Light industrial, POP = Population, POPFAM = Population in family households, AGEMED = Median age, AGEMEDM = Median age males, AGEMEDF = Median age females, VPH = auto-ownership, AHHI = Average household income, UNEMR = Unemployment rate, LBF = Population in labor force, Lanes = # of lanes, Driveways = # of driveways, Signals = # of signalized intersections, Median = Presence of a median, Horiz Curv = # of horizontal curvatures, Zone Length = length of the zone; AADT = average annual daily traffic.

Table 2. Final model – Independent variables and coefficients

Independent Variables	Coefficient
Intercept (Constant Term)	3.639
0.25 to 0.5 acre residential area within 0.25-mile buffer	0.002
Heavy commercial area within 0.25-mile buffer	-0.005
Institutional area within 0.25-mile buffer	-0.025

The computed AIC for the final model is 187 while Deviance / Degrees of Freedom is 1.3. These parameters seem to be reasonable indicating the goodness of fit of the model developed.

Models were validated by substituting data for eight randomly selected truck crash zones that were not used for model development. The results from model validation indicate that the difference between the estimated number of intracity truck crashes and the actual number of intracity truck crash counts was observed to vary between ~-32 percent to ~158 percent for the final model (Table 3). The average percent difference is 37.8 while the computed root mean squared error is 24.25. These values, though, seem to be reasonable are not the best.

Table 3. Model Validation Results

ID	Actual # of truck crashes	0.25-mile	
		Est. # of truck crashes	% Diff.
1	2.0	2.1	5.9
2	3.2	4.4	39.1
3	2.3	1.6	-32.3
4	4.2	5.9	40.5
5	3.6	6.2	71.6
6	2.8	7.3	158.6
7	1.6	2.4	47.7
8	1.8	1.3	-28.8
Average			37.8
Root mean squared error			24.25

CONCLUSIONS

Demographic, socio-economic, land use and on-network characteristics were used as independent variables to research the role of these variables on intracity truck crashes and develop an intracity truck crash estimation model. Spatial data was extracted using 0.25-mile buffer width generated around each selected intracity truck crash zone. Based on the goodness of fit tests, the model obtained using off-network characteristics within a 0.25-mile buffer width was observed to be reasonable. However, the variation in percent difference between actual and estimated truck crash counts was found to be high in some cases. It is possible that using a different buffer width might help yield better results. The role of spatial extent in modeling intracity truck crashes thus warrants further investigation.

Truck crash occurrences seem to be significantly affected by land use characteristics such as institutional area, heavy commercial area and 0.25 to 0.5 acre residential area. Land use characteristics such as institutional area and heavy commercial seem to have a negative effect on truck crash occurrences, possibly due to better geometric / design features provided to accommodate truck traffic along corridors with these types of land uses. Therefore, planning and building well balanced neighborhoods (with an ideal mix of different land uses), and, implementing improved design strategies and safety treatments (example, adequate turning radius or sight distance) in residential areas will help promote safety (lower truck related crashes) and enhance quality of life in these areas.

The methodology proposed in this research is easy to adopt and can be applied universally to urban settings of any size and level. The results from such a process can be proactively used to estimate intracity truck crashes, incorporate them into planning process and enhance safety.

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Impacts of Network Connectivity on Multimodal Travel Metrics

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ABSTRACT

In recent years, the transportation planning sector has witnessed a steady growth in the design and implementation of policies and projects aimed at providing infrastructure not only for automobiles, but also for pedestrians and bicyclists. In the United States, multiple cities have implemented policies and design frameworks to encourage more pedestrian and bicyclist activity. Providing increased connectivity is commonly held to facilitate these modes of travel, but connectivity has a complex relationship with drivers' route choices. Since interactions with motor vehicles are a major factor in pedestrian or bicycle comfort levels, connectivity has a complex interaction with non-motorized modes as well. This paper presents a methodology for quantifying these interactions, paying particular attention to impacts on the bicycle and pedestrian modes in addition to vehicular modes. The use of active transportation indices (ATIs) play a central role in this analysis, linking shifts in vehicular volume to suitability for non-motorized travel. This methodology is tested on networks representing the southern part of the Austin, Texas metropolitan area, but the formulation is generic and readily transferable to other regions. Results of this application indicate that average path travel times between origins and destinations within the network and the link-congestion attributes like the volume-to-capacity ratio rise with reductions in connectivity and network-accessibility at both the South Austin regional (full-network) level and also at the local (intersection) levels where ATI indices are affected in addition to them. Additionally, improved vehicular networks have favorable effects on pedestrian and bicyclist activity, also shown in this study through the isolated attribute of traffic volumes.

INTRODUCTION AND BACKGROUND

Effective transportation networks must serve a variety of trips on a diverse set of modes. Considerable planning and research effort has been involved in identifying network structures and characteristics that maximize the ability of these networks to serve these needs. In practice, networks exhibit multiple topologies, including traditional grids, subdivisions with cul-de-sacs, and so forth. Connectivity is a common way to classify and compare these topologies. Figure 1 juxtaposes two network designs to show contrasts in the connectivity features for similarly sized land areas. While the straight line distances between the origin-destination pairs (A to B) are the same, the actual path distances are quite different for the two cases: 1.3 miles in the first case and 0.8 miles in the second. While only one-half mile, the difference between these two distances may be for many people the difference between an un-walkable and a walkable distance. This small but effective example reiterates the significant impact connectivity designs have on walking and bicycling behavior.

To date, several researchers have proposed both qualitatively and quantitative connectivity metrics (see Dill, 2004 for a review). However, as we show in later sections, the relationship between connectivity and travel conditions is not easy to quantify, even when only considering the driving mode. In some circumstances, improving connectivity also aids mobility, while in other circumstances providing increased connectivity actually increases travel times for all travelers. Therefore, we believe that a rigorous network assignment model is needed to accurately predict these impacts, especially in multimodal contexts – the complexity of the interactions renders engineering judgment alone insufficient. Furthermore, in recent years, the transportation planning sector has witnessed a steady growth in the design and implementation of policies and projects aimed at providing infrastructure not only for automobiles, but also for pedestrians and bicyclists. In the United States, multiple cities have implemented policies and design frameworks to encourage more pedestrian and bicyclist activity. Providing increased connectivity is commonly held to facilitate these modes of travel, but as discussed above and demonstrated quantitatively in the next sections, titled 'Motivation', connectivity has a complex relationship with drivers' route choices. Since interactions with motor vehicles are a major factor in pedestrian or bicycle comfort levels, connectivity has a complex interaction with non-motorized modes as well. This paper presents a methodology for quantifying these interactions, paying particular attention to impacts on the bicycle and pedestrian modes in addition to vehicular modes. Active transportation indices (ATIs) play a central role in this analysis, linking shifts in vehicular volume to suitability for non-motorized travel. This methodology is tested on networks representing the southern part of the Austin, Texas metropolitan area, but the formulation is generic and readily transferable to other regions.

Thus, the primary contributions of the paper are the following:

1. A small example demonstrating that the relationship between connectivity and mobility can be complex and requires a bona fide network assignment model.
2. Comparison of network topologies using such a methodology in real-world networks and comparing certain metrics that highlight the importance of good connectivity in networks.
3. Development of active travel indices incorporating these changes in vehicular traffic, quantifying impacts on non-motorized modes.

The remainder of the paper is organized as follows. Section 2 presents a small example of the complex relationship between connectivity and mobility. Section 3 discusses the experimental design, the construction of the scenarios, the modeling process, and the active transportation index. Section 4 describes the changes to 1) auto traffic on one Origin-Destination (O-D) pair, 2) changes to auto volumes on all of the links, and 3) the ATI on a small subset of links. Section 5 discusses results and Section 6 offers conclusions and points to future research directions.

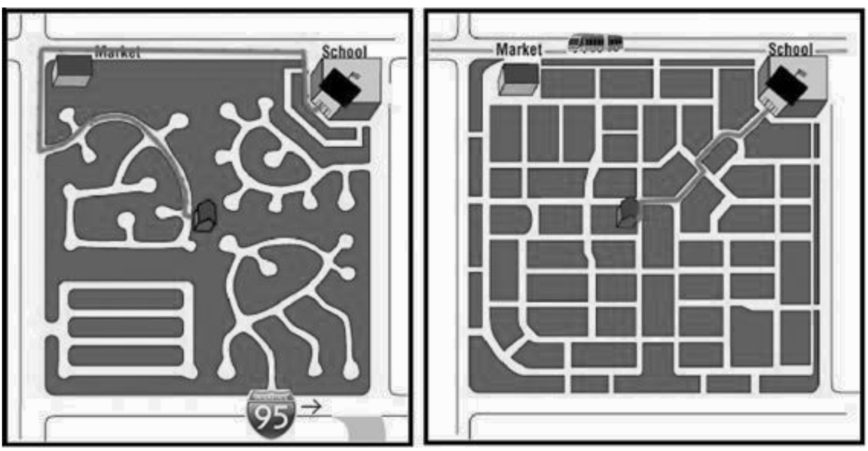


Figure 1. Connectivity features & significant differences in ease of travel and accessibility. (Source: streetsblog.org)

MOTIVATION: CONNECTIVITY AND VEHICLE MOBILITY

The impact of network connectivity on traffic and other modal flows can either increase or decrease mobility, depending on the network structure. Such systems can behave counter-intuitively, necessitating a formal methodology for evaluating connectivity-related policies. Figures 2 and 3 present a small example illustrating this phenomenon: starting with a "low-connectivity" network, adding some additional links decreases travel times; but continuing to add more links ultimately increases travel times for everybody in the network, even with signal timing adjusted for flow changes. (This example only considers the driving mode for clarity; the connection with bicycle and pedestrian flows is developed in the sections that follow.)

Figure 2a shows the initial network, with the speed limit and saturation flows of each roadway segment shown. The "short" links (1,3), (3,5), (4,2), and (4,6) are 0.5 miles long, and the "long" link (3,4) is 1 mile long. Thus, the un-delayed travel times on each link are as shown in Table 1. There are five Origin-Destination (O-D) node pairs, with a demand rate of 1000 vph between each: (1,2), (1,6), (3,4), (5,2), and (5,6). Circles denote traffic signals; all intersections in this example have a cycle length of 84 s. Nodes without circles have no conflicting flows and require no control. Since there is only one feasible path for each O-D pair, the roadway volumes must be as in Figure 3a. Uniform demand from links (1,3) and (5,3) suggests an equal division of the green time between these approaches. If there is no lost time, the ratio of green time to cycle length is $G/C = 0.5$ for both approaches, the capacity on each approach is $sG/C = 2000$ vph (where s is a link's saturation flow), and, using v to denote approach volume, the uniform signal delay is given by relation (1) for both approaches.

$$d = \frac{C}{2}\frac{\left(1-\frac{G}{C}\right)^2}{1-\frac{v}{s}} = \frac{C}{4} = 21 \text{ s} \tag{1}$$

Thus, the travel times for each O-D pair are as shown in the first column in Table 2. (For example, the path from 1 to 2 requires traversing the path [1,3,4,2], with link travel times of 60 s, 120 s, and 60 s, plus 21 s of signal delay for a total of 261 seconds).

Figure 2b shows the same network, but with two additional links designed to provide direct connectivity for two of the O-D pairs. The unlabeled links have the same characteristics as in Figure 2a. Assuming that all travelers take the fastest route in the network, the flows will then be as in Figure 3b. This changes the degree of saturation for the signalized intersection 3, and re-applying equation (1) shows that the signal delay has been reduced to $C/6 = 14$ s for each approach. (Despite this reduction in signal delay, it is still faster for travelers on O-D pairs (1,2) and (5,6) to take the direct links.) The second column in Table 2 shows how travel times have changed. Notice that this new network Pareto-dominates the first from a travel-time perspective: nobody is worse off, and some travelers are better off. In particular, O-D pairs (1,2) and (5,6) benefit from a direct link, while O-D pairs (1,6) and (5,2) benefit from lower signal delay along their route due to diversion from the former O-D pairs.

Figure 2c shows the same network with yet more connectivity in the form of a two-way street, perhaps with the intention of spreading out demand across multiple signals rather than concentrating it at one. Figure 3c shows the resulting flows after travelers adjust paths to minimize their own travel times. Notice that the optimal timing at each signal is still to allocate half the green time to the two competing approaches (at node 8, half the green time to eastbound traffic, and half to a northbound/southbound phase), based on equating degrees of saturation. Here, the signal delay on node 8 is $C/4 = 21$ s, while the signal delay at nodes 3, 7, and 9 is $C/7 = 12$ s, leading to the O-D travel times in the third column of Table 2. The reader may verify that the travel times on paths [1,7,8,9,6], [1,3,8,4,6], [5,3,8,4,2], and [5,9,8,7,2] are equal, validating the assumption that all of these paths are used in Figure 3c. Note that this change has led to a strict *increase* in the travel time for each O-D pair – more connectivity does not always help.

This example is clearly simplistic, but nevertheless shows that the relationship between network connectivity and overall mobility is not obvious, particularly when intersection control and route switching must be taken into account.

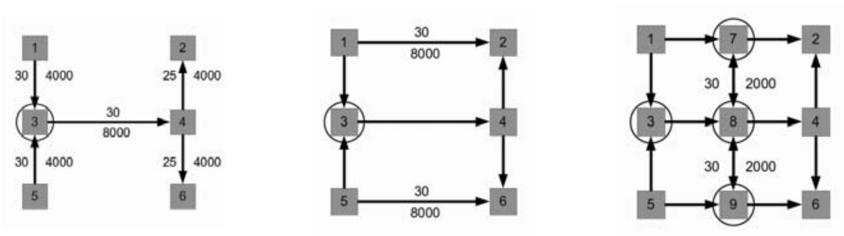
Table 1.Undelayed Travel Times on Each Link.

Link	Undelayed travel time (s)
(1,3)	60
(3,4)*	120
(4,2)	72
(4,3)	72
(5,3)	60
(1,2)**	120
(5,6)**	120
(1,7)***	60
(3,8)***	60
(5,9)***	60
(7,8)***	60
(7,9)***	60
(8,4)***	60
(8,7)***	60
(8,9)***	60
(9,6)***	60
(9,8)***	60

*only exists in networks (a) and (b); **only exists in network (b);
***only exists in network (c)

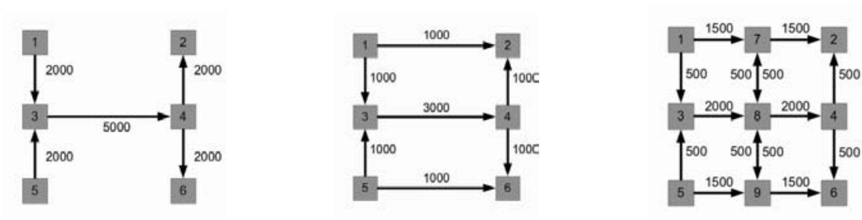
Table 2. Travel Times in Each Network, in Seconds.

O-D pair	Network (a)	Network (b)	Network (c)
(1,2)	261	120	132
(1,6)	261	254	285
(3,4)	120	120	141
(5,2)	261	254	285
(5,6)	261	120	132



(a) (b) (c)

Figure 2. Three networks demonstrating non-monotone relationship between connectivity and mobility. Figures indicate new links' speed limit (mph) and saturation flow (vph).



(a) (b) (c)

Figure 3. Equilibrium flows for all three networks, accounting for signal retiming and drivers changing routes to be on shortest paths.

EXPERIMENTAL DESIGN

This section describes the study area, the construction of the scenarios, the modeling process, and the active transportation index in the subsections that follow.

Study Area

The study area, approximately six miles south of downtown Austin, Texas, is highlighted in Figure 4. This network primarily contains suburban development types. The two scenarios evaluated in this section of the study include the network as is (poorly connected) and a version of the network assuming improvements have been made to improve the level of connectivity.244

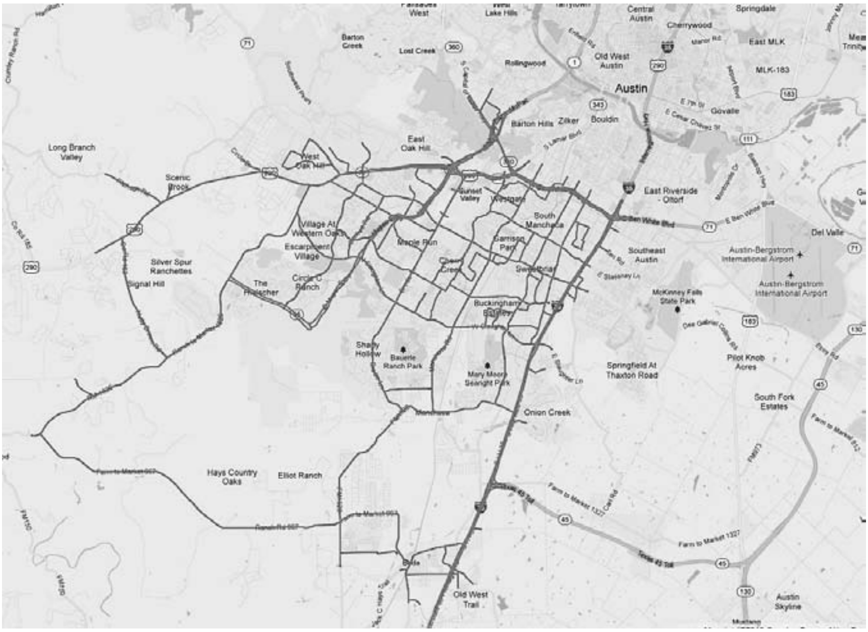


Figure 4. Study area with the network highlighted.

Scenario Construction

We construct two scenarios using the same basic network structure, one representing poor connectivity and the other representing improved connectivity. These scenarios are developed from the same study area by varying the construction of the traffic analysis zones (TAZ) and the centroid connectors used to load trips onto the network. The well-connected network assumes the centroid of each TAZ can access each roadway in the TAZ, with a centroid connector connecting each centroid to several different roadway links. The poorly connected network divides the single centroid in each zone into a number of smaller centroids, each associated with only one connector, effectively requiring a certain portion of the centroid's demand to use that particular connector.

This modified network is more poorly connected than the original network in the sense that the vehicles movements are more constrained, with only one choice to enter the roadway network. By contrast, in the original network, drivers had several choices and could use any of the centroid connectors. So, while the inherent network structure for this study network has been kept the same, we create scenarios to test the impacts different connectivity levels have on the motorized traffic and mobility in general.

Figures 5 and 6 illustrate this modification. The shaded centroid (labeled 100513) illustrates one such example of a centroid that was initially connected by three connectors, and subsequently is broken up into a constituent three separate centroids, each having one cul-de-sac-like connector. The total demand on the original centroid-connectors is then equally split over the newly created centroid-connectors.

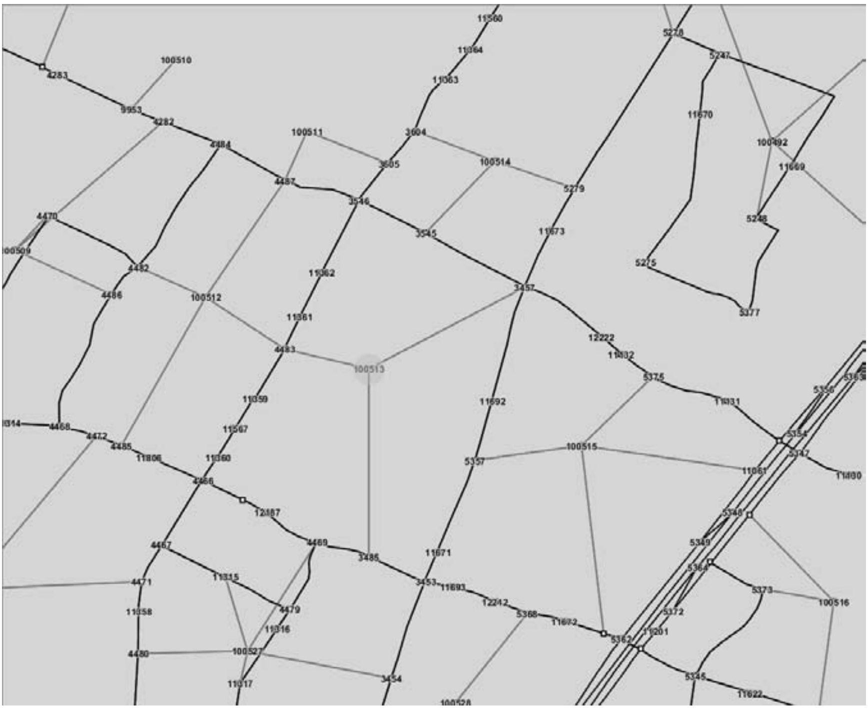


Figure 5. Well-connected network.

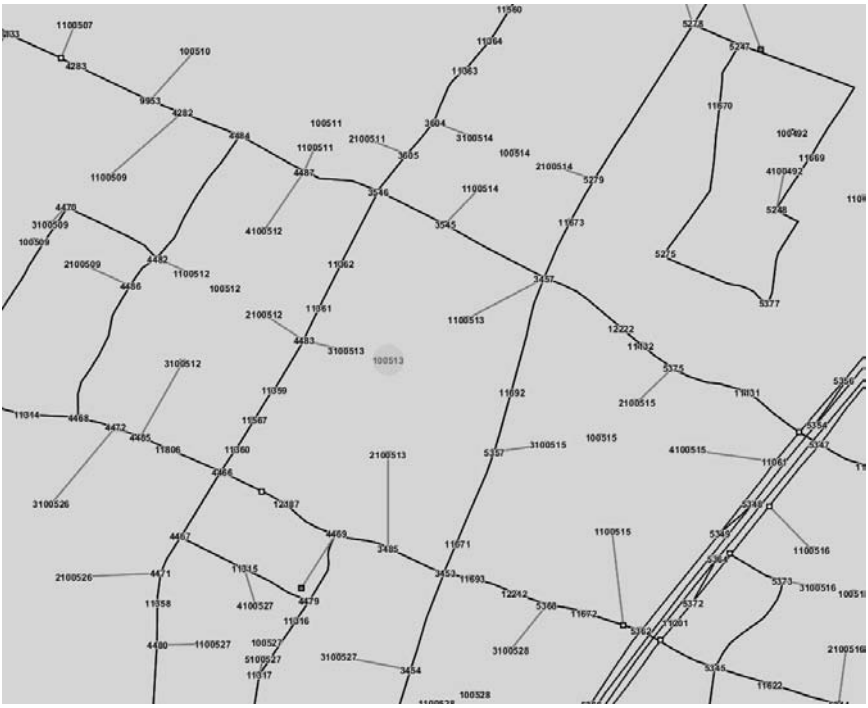


Figure 6. Poorly connected network. Note that the original centroid is retained for illustrative purposes, but is no longer connected to the network, and not used as an origin or destination.

Dynamic Traffic Assignment Modeling

In this analysis, we used dynamic traffic assignment (DTA) to predict how roadway volumes and route choice are related to connectivity. DTA is a methodology that predicts the travel times and congestion level for a given set of route choices, under the assumption that drivers choose routes to minimize travel times. Since route choice depends on travel time, and travel time depends on route choices, DTA is an iterative methodology which converges to a consistent "equilibrium" solution in which no driver can reduce their travel time by switching to any other path. As the name suggests, *dynamic* traffic assignment can capture route choices and congestion patterns varying over time, as opposed to static traffic assignment models which implicitly assume steady-state conditions. The traffic modeling framework VISTA (2) was used for this analysis.

Active Transportation Index

The active transportation index (ATI) connects pedestrian and bicyclist perceptions about infrastructure quality and surrounding land uses to travel time and distance, and quantifies the tradeoffs between all related attributes. The attributes included in measuring the ATI for pedestrians and bicyclists were determined based on the recurring attributes throughout prior research studies and analysis. Although the ATI is not all encompassing, the authors believe it adequately represents the attributes of highest importance for pedestrians and bicyclists when making transportation trips related to commuting or errands.

With the attributes determined for each street segment and intersection, weights were assigned to each characteristic. The weights were assigned based on prior work and expert opinions gathered from various studies (Kasemsuppakorn and Karimi 2009, Stinson and Bhat 2003, Sener, Eluru and Bhat 2009). The Pedestrian Environmental Quality Index (PEQI) and Bicycle Environmental Quality Index (BEQI) from the San Francisco Department of Public Health were very valuable tools in determining appropriate weights for each attribute. From the PEQI and BEQI, many attribute weights were translated directly, however, not every attribute considered for the ATI is included in either the PEQI or BEQI ("Bicycle Environmental Quality Index (BEQI) (2009)", "The Pedestrian Environmental Quality Index (PEQI)" (2008)). For the differences or gaps in attribute weights, the authors relied on comparative ranking of comparable attributes, assigning similar weight ranges to attributes of similar importance. These attributes, and the characteristics related to each attribute, along with the corresponding weight are shown in Table 3. For this study, the ATI is broken into ranges that represent the "friendliness" of a given link based on the sum of all weights for that link. The values for each range, shown in Table 4, were defined based on the author's research in prior studies, examining different threshold values for each attribute. Using experiential background and descriptions of various road segments with different attribute combinations, five ranges were defined as excellent, very good, good, poor, and very poor. These range levels present a reasonable scale to characterize the perceived usability of a given segment based on its infrastructure.

Table 3. ATI Street Segment Attributes and Characteristics with Assigned Weights.

Attribute	Characteristic	Weight
Number of Lanes	Pedestrian/Bicycle Only Street	12
	1 Lane	9
	2 Lanes	6
	3 Lanes	3
	4+ Lanes	0
Posted Speed Limit	Under 25 mph	10
	25 mph or None Posted	5
	Over 25 mph	0
Bicycle Lanes/Sharrows	Two Directions	10
	One Direction	5
	None	0

Attribute	**Characteristic**	**Weight**
Width of Bike Lane	> 6 ft	15
	5 - 6 ft	10
	< 5 ft	5
	None	0
Width of Sidewalk	Greater Than 8 Feet	15
	4.5 - 8 Feet	10
	Less Than 4.5 Feet	5
	No sidewalk	0
Pavement Type/Condition	Smooth Surface	15
	Mild Obstructions (cracks)	10
	Medium Obstructions (raised cracks, raised parallel pavement)	5
	Large Obstructions (pot holes, bumps)	0
Bicycle/Pedestrian Signs/Postings/Markings	3+ countermeasures	11
	2 countermeasures	7
	1 countermeasure	4
	None	0
Traffic Volume	Less than 1,000 vehicles/day (vpd)	15
	1,000-6,000 vpd	11
	6,001-12,000 vpd	4
	More than 12,000 vpd	0
Street Lights/Shade Trees	Yes	5
	No	0
Adjacent Land Use	Residential	3
	Commercial/Retail	2
	Business/Industrial	1
	Construction	-2
	Abandoned/Empty	-5

Table 4. Ranges of ATI Scores for Street Segments.

	Street Segment ATI
Max Possible Points	111
Min Possible Points	-5
Excellent	≥95
Very Good	80-94
Good	66-79
Poor	46-65
Very Poor	≤45

RESULTS AND ANALYSIS

This section describes the results of applying this analysis to the South Austin area network, described in Figures 5 and 6. We describe impacts of connectivity variations in networks on vehicular path travel times at the full- network level as well as local levels, and impacts on the ATI at the intersection level. The two networks selected for this analysis have been created as variants of the same network described in Figure 4, which represents the region approximately six miles south of downtown Austin, described in detail in the earlier sections. The primary points of difference in the two network connectivity scenarios was discussed in the subsequent section 'Experiment Design' and the subsections there-in and the results of the dynamic traffic assignment (DTA) model and implications of the same will be discussed in the sections that follow.

Impacts at the Regional (Full-Network) Level

At the full network level, we look at the total system travel time (TSTT), which is the sum total of travel times of all the vehicles entering and leaving the network at their respective origins and destinations, based on the travel demand for the region. The DTA model was run for the three hour evening peak period (PM Peak – 4 PM to 7 PM). The following Table 5 gives the total travel time comparisons for the full networks.

Table 5. Total System Travel Time (TSTT).

Network (South Austin, TX)	TSTT (hours)
Well Connected Network	36326
Poorly Connected Network	55647

Note that we see a considerable increase in the TSTT, by a factor of about 1.5 in transitioning from a sufficiently well connected network to a relatively poor-connected network. Taking this analysis a step further, we compute the travel times between all the O-D pairs in the network and observe some stark contrasts among the two networks based on their travel time distributions. These travel times are averaged over all possible paths between any given O-D pair, and computed at the second hour of the PM peak duration, since the simulation begins on an empty network initially and the first hour mostly includes the warm-up period of the simulation. The following figures illustrate the distribution of average travel times between all O-D pairs in the network across the two scenarios, well connected and poorly connected.

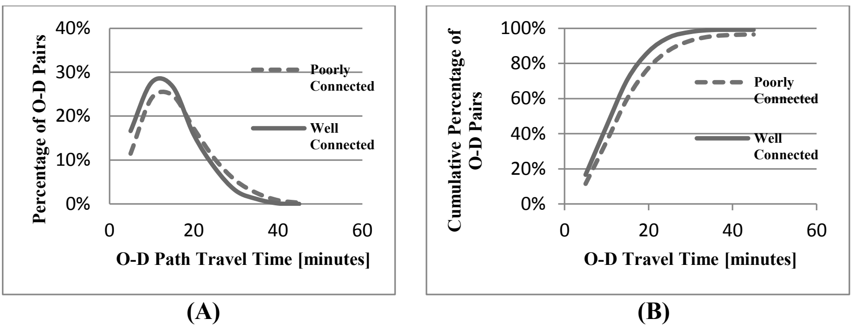


Figure 7. O-D path travel time distribution for the 5-6 PM peak period.

The curves illustrate the distribution of average path travel times across all the O-D pairs for both the scenarios considered. We observe from the curves in Figure 7(A) that at higher values of travel times, we have a much higher percentage of O-D pairs corresponding to those values in the poorly connected network than in the well-connected one, also indicated from the rightward shift in the curve for the poorly-connected network. Figure 7(B) illustrates the cumulative distribution function of the O-D travel time, and from them we observe that we get a higher value of travel time for the poorly connected network over the entire range of cumulative percentages of O-D pairs. Thus, we notice a stochastic dominance of the poorly connected network over the well-connected one in the travel time component across all percentiles of available O-D pairs. Figure 8 denotes the volume to capacity ratio of all the links in the network, a commonly used metric to model link congestion and some interesting trends are observed in that as well.

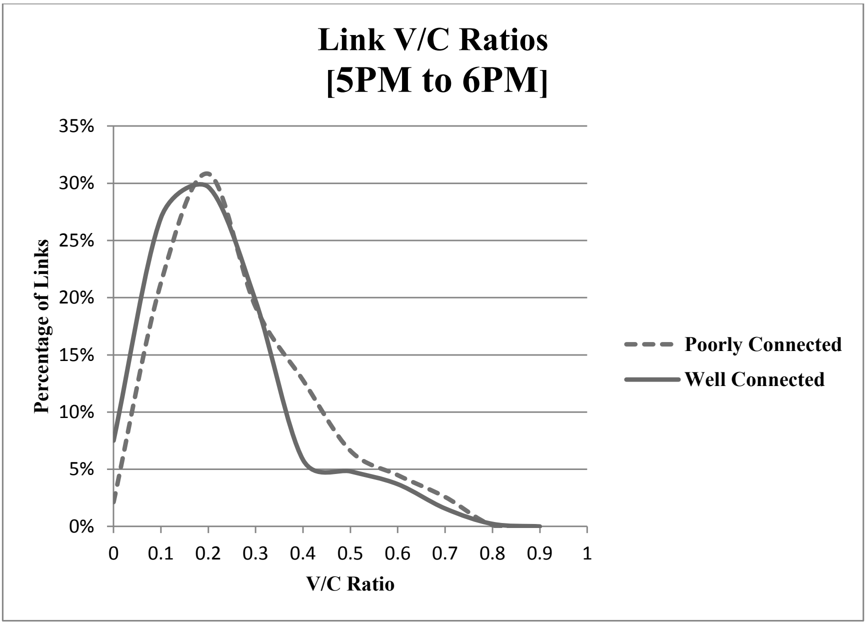


Figure 8. Volume-to-capacity ratios on the links in the two scenarios.

It can be noticed from the graphs that the poorly connected network does have a much higher percentage of links at higher values of V/C ratio than the well-connected network. The V/C ratio has been the standard metric to represent congestion in traffic engineering practice, as described in the Highway Capacity Manual (HCM, 2000). In these computations, congestion is typically measured on a scale relating traffic volume typically in the peak hour to the capacity of the facility, and hence the usage of peak hour traffic volumes in the graphs.

Impacts at Local (Links and Intersection) Level

In this subsection, in order to capture the local effects of connectivity features of a network and to set the base for subsequent ATI analysis, we compare travel conditions between two representative O-D pairs in the two networks. Figures 9, 10 and 11 below show the region and the O-D pairs, which includes several major arterials and a busy intersection. In particular, the intersection of Brodie Lane and Slaughter Lane was chosen and the links were identified as street segments traveling south on Brodie Lane, traveling west on Slaughter Lane, traveling north on Brodie Lane, and traveling east on Slaughter Lane. The following figure shows the intersection in detail (the red color dot is the intersection).

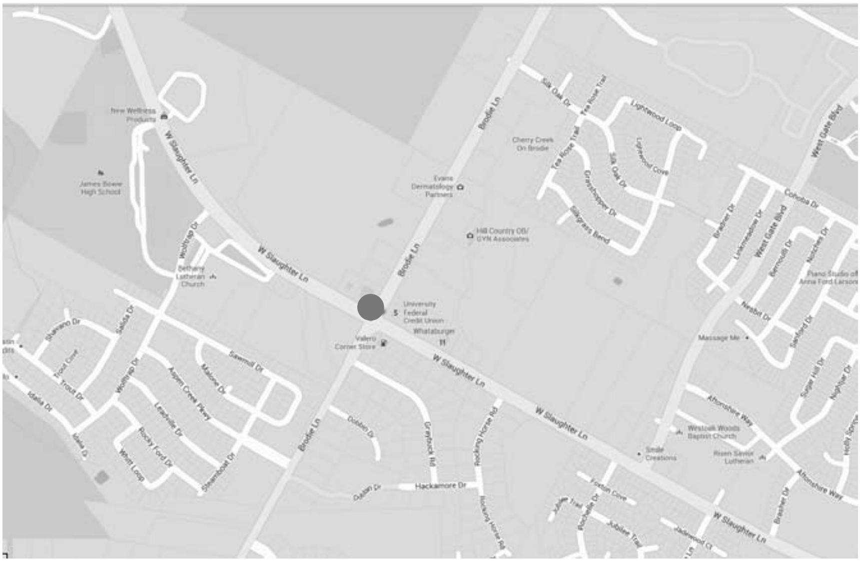


Figure 9. Application at local level (intersection at Brodie Ln. and Slaughter Ln.).

O-D pairs that use this intersection have been chosen and travel time and distance metrics have been compared across the networks with varying levels of connectivity. The following figures illustrate the O-D pairs.

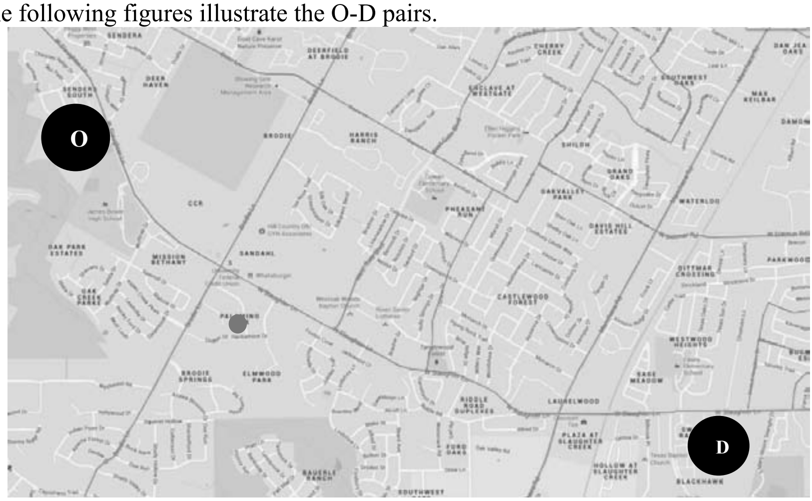


Figure 10. O-D pair 1.

Figure 11. O-D pair 2.

Table 6 shows the difference in path lengths and travel times between these pairs within the two network scenarios.

Table 6. Variations in the Metrics across All Possible Paths in Two Networks.

Parameter	Well Connected Network	Poorly Connected Network
O-D Pair 1		
Path Length (miles)	3.00	5.70
Path Travel Time (minutes)	6.10	13.58
O-D Pair 2		
Path Length (miles)	2.82	4.00
Path Travel Time (minutes)	5.01	11.33

The average travel time between the O-D pairs show considerable differences, mainly because of a bottleneck created when vehicles were only able to access one arterial when departing from the origin. The average path length also shows an increase because we modify the centroid connectors in such a way that the vehicle movement is more restrictive, and there are only a few limited places where drivers originating from a particular location can enter the main network, as opposed to the well-connected scenario where they have the liberty to choose the locations to enter the network based on their final destinations, and this may lead to them taking a much longer path than before.

Thus, it can be seen that network connectivity variations can have an impact on the driving patterns and vehicular and motorized travel in general as a whole. When vehicles are forced to use only one roadway to enter and egress the network, as opposed to choosing the roadway that will make their travel time the shortest, unnecessary delay is added to the network.

ATI Calculations

Since gathering the data needed for the ATI can be time intensive, for the purposes of this paper we looked at 1) the ATI on four links at one intersection and 2) the change in travel volume on all of the links in the network. The goal of this study is to examine how changing the network connectivity impacts the ATI. The node was identified as the intersection of Brodie Lane and Slaughter Lane and the links were identified as street segments traveling south on Brodie Lane, traveling west on Slaughter Lane, traveling north on Brodie Lane, and traveling east on Slaughter Lane. The node was chosen because it is located in a typical area that would draw pedestrians and bicyclists for many transportation trips related to work or errands, including a pharmacy, a church, a school, several restaurants and other shops. Each link ATI was calculated in the 0.5 mile direction away from the intersection, rather than crossing through the intersection. The half-mile distance was chosen as a typically accepted walking distance. Additionally, this was the extent to which the area was captured in Google Earth, which was used to gather certain segment characteristics, including presence of bicycle lanes and sidewalks, signs, postings and markings, and adjacent land use, among others.

Assigning a weight value respective to each link characteristic for the four links studied resulted in the ATI values shown in Table 7. When the connectivity was improved for vehicular traffic, the same data points were analyzed for each link. All link infrastructure characteristics remained the exact same in the before and after networks, except for link volumes. Interestingly, the volumes on two links were reduced, while the volumes on the other two links increased, shown in Table 8. With this information, the only differences in the ATI for the before and after networks was reflected in the change of volume. However, because of the range of volume characteristics being large, no changes were made in the ranges of ATI scoring, even with the volume of traveling north on Brodie Lane being about one-third on the well-connected network compared to the poorly connected network. This change is also shown in the ATI scores for each link in Table 7. This is a simple scenario, and in a true network change, the authors would expect infrastructure changes to take place, whether it is in posted speed limit, presence or width of bike lanes or sidewalks, or other infrastructure attributes.

Table 7. ATI Scores for Each Link before and after Network Connectivity Improvements.

Street Segment	ATI Well Connected	ATI Poorly Connected
South on Brodie Lane	40	40
West on Slaughter Lane	41	41
North on Brodie Lane	58	47
East on Slaughter Lane	46	46

Table 8. Daily Vehicle Volumes on Each Link before and after Network Connectivity Was Improved for Vehicular Traffic.

Street Segment	Volume Well Connected	Volume Poorly Connected
South on Brodie Lane	6600	6020
West on Slaughter Lane	10160	10270
North on Brodie Lane	5360	17200
East on Slaughter Lane	8740	8490

Street segments for traveling south on Brodie Lane and west on Slaughter Lane were categorized as very poor (from Table 4), both in the poorly connected and the well-connected networks. The street segment for traveling east on Slaughter was poor in both the poorly connected and well-connected networks. Similarly, the street segment for traveling north on Brodie Lane was at the low end of the poor range in the poorly connected network, but with the effect of the volume on the ATI score in the well-connected network, it moved up to the top of the poor range.

Throughout many earlier studies conducted, the impact of traffic volume is regarded as highly important for both pedestrians and bicyclists, shown through this shift in the ATI range of friendliness on the street segment for traveling north on Brodie Lane. In this case, improving the network for vehicular traffic has a positive effect on the numerical ATI range, although not in the category. Translating this result into experience would mean less perceived danger or risk by pedestrians or bicyclists, with potentially more using this link to travel for transportation purposes of work commuting or running errands in the well-connected network than in the poorly connected network to improve vehicular connectivity.

Link Volume Changes

The entire study network has 2440 links. Running analysis on the volume on each link, we know if the ATI improved or worsened by subtracting the volume on the well-connected network from the link volume on the poorly connected network. Although this does not allow us to see to what degree the ATI changes for each individual link, whether it moves from very poor to excellent or excellent to very poor, or even stays within the same range for small changes, we can get a sense of the overall impact on this network. Of the 2440 links in this network, 1,462 saw a decrease in traffic volume and thus, an improved ATI. For 911 links, the traffic volume increased, worsening the ATI, and sixty-seven links remained unchanged. Overall, there is a 60% improvement in the traffic volume for this network, supporting the hypothesis that improving the vehicular network connectivity also improves the network for pedestrian and bicyclist activity. While these overall network results are contradictory to the specific intersection of Brodie Lane and Slaughter Lane, we did see slight improvements in traveling south on Brodie Lane and east on Slaughter Lane, although they did not improve enough to move ranges.

The VISTA DTA software produced volume data for the peak three-hour period in units of vehicles per hour. Using the assumption of the 5:00 to 6:00 PM peak hour carrying one-tenth of the traffic per day, the change in volume per day was calculated to address the impact on the ATIs. As shown in Figure 11, the distribution of traffic volume differences is skewed right of zero, which corresponds to the 60% of links seeing an improvement in traffic volume on the well-connected network relative to the poorly connected network. The statistics of this distribution state zero as the mode. The link with the greatest ATI improvement had a decrease in traffic volume of 13,690 vehicles per day in the well-connected network. The link with the worst ATI decline had an increase in traffic volume of 42,120 vehicles per day in the well-connected network.

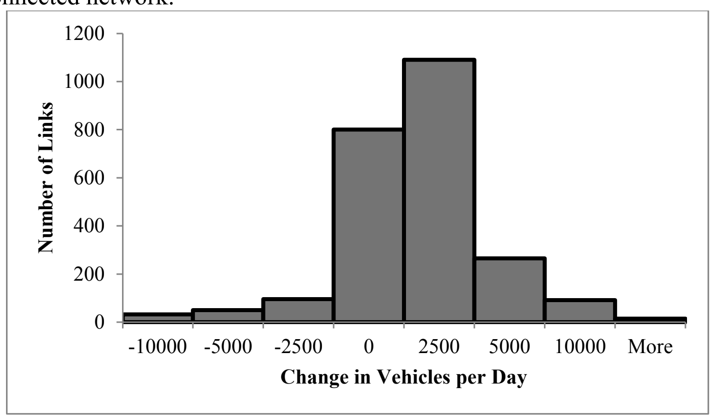


Figure 11. Distribution of daily vehicular traffic volume changes in moving from well-connected to poorly connected network connectivity during the evening peak hour.

DISCUSSION

Our initial hypothesis was that improving vehicular network connectivity would also improve pedestrian and bicyclist activity, as measured by the ATI. The results show that this hypothesis does not apply universally: in applying the ATI to one specific intersection area of four links, results were mixed. In analyzing the impact of volume change, two of the links saw slightly higher volumes, one saw a decline in volume, and one saw a more drastic decrease, yet none of the changes were enough to shift any segment into a new ATI category ranking. For traveling north on

Brodie Lane, the well-connected vehicular network traffic volume was nearly one-third, which caused the numerical ATI range to improve, though not the category, and had a positive impact and favorable effect on pedestrian and bicyclist activity.

However, the hypothesis was better-supported when considering volume changes on the network as a whole. Looking at the poorly connected network compared to the well-connected, improved vehicular network, sixty percent of links included in the overall network saw a decrease in traffic volume when the vehicular network connectivity was improved, and thus an improved ATI for pedestrian and bicyclist activity. Note that this study was specifically designed to isolate the impact of connectivity alone: no other attributes of the network were adjusted (number of lanes, presence of sidewalks or bicycle paths, etc.). All other attributes being equal, comparing the traffic volume for the poorly connected network to the well-connected network shows specifically how the improvements in vehicular network connectivity impact pedestrian and bicyclist activity through the ATI. This measure could be further developed to understand for how many links the improvements in traffic volume caused a positive change in the ATI range category and to what degree, rather than just looking at overall improvements.

CONCLUSIONS AND FUTURE SCOPE OF WORK

This paper analyzes the impacts of improving vehicular network connectivity on pedestrian and bicyclist activity through the measurement tool of the active transportation index (ATI). This study contributes to existing research in multiple ways. First, it seeks to measure the impact of network connectivity on vehicular traffic, using dynamic traffic assignment. Second, building on these vehicular impacts, we use the ATI to measure how pedestrians and bicyclists are also impacted by network connectivity changes. While earlier studies have measured an area for hindrances or impedances to gauge an ease for pedestrian or bicyclist activity, this study is the first to practically measure both combined in one tool, specifically incorporating the impacts of vehicle travel. This methodology was demonstrated in a network representing a suburban region south of Austin, Texas, changing centroid connector structure to create networks of different connectivity with a common structure, enabling a direct comparison.

Several insights were obtained from this analysis. First, if no new links are created or no changes are made to the physical infrastructure of the existing lengths (adding lanes, changing direction of traffic, adding or removing sidewalks or bicycle lanes, etc.), the only difference to be captured is the change in automobile traffic volume along the segment. Knowing this, assessments using the ATI to measure impacts from changing a network can be done very easily with quick results. Secondly, this research spotlights the need for planning network connectivity, both from the beginning and for making changes or improvements, in a multimodal reference frame, rather than focusing on one mode. The mindset of including and planning for multimodal travel is growing and receiving more attention in the planning and policy arenas and the ATI can be leveraged as a tool to better understand these relationships and tradeoffs. Similarly, the ATI can be used to help plan for better pedestrian and bicycle facilities, operating congruently with regular automobile traffic. The attributes included and characteristics measured are common to any region or city, thus allowing the use of the ATI to be transferrable and relevant in areas outside of the study region of Austin, Texas.

Further work should be done to include assessing more segments and intersections for impacts from improving vehicular network connectivity on pedestrian and bicyclist activity. While the segments used in this research are considered good “typical” segments of attractions and destination points for pedestrians and bicyclists, gathering more data points would garner further support in stating that improving vehicular network connectivity has a positive or negative impact on pedestrian and bicyclist activity. Additionally, as discussed in Section 4, the method of applying the ATI onto street segments and intersections will result in a more universal interpretation of impacts by relating the attributes of the physical and built environment to a perceived distance length, either positive or negative, onto the actual length of each segment. Additional future work aims to improve the utility of the ATI by replacing the range of weight points and categories of Excellent, Very Good, Good, Poor and Very Poor. When regression analysis is complete, the authors hope to determine the correlations between attributes as they all relate to travel time.

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Load-Based Life-Cycle Greenhouse Gas Emissions Calculator for Transit Buses; An Atlanta, GA Case Study

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ABSTRACT

Using the Public Transit Greenhouse Gas (GHG) Emissions Management Calculator (hereafter the Calculator), this paper presents a case study of transit bus GHG emissions using Atlanta, GA data. The Calculator, developed by Georgia Tech researchers, is the first load-based life-cycle emissions model for transit buses. The modal modeling approach of the Calculator estimates emissions as an indirect function of engine load, which in turn is a function of transit services parameters such as driving cycle (idling and speed-acceleration profile), road grade, and passenger loading. Direct emissions are calculated based on the scaled tractive power (STP) operating mode bins employed in the MOtor Vehicle Emissions Simulator (MOVES) model, and life-cycle emissions are calculated using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. The case study compares life-cycle greenhouse gas emissions of five vehicle technologies, namely, conventional compression ignition, parallel hybrid electric, series hybrid electric, battery electric and fuel-cell electric, in combination with three fuel types, namely, conventional diesel, compressed natural gas (CNG), and 20% biodiesel. The comparisons are carried out for two public transit route types, e.g. an urban transit route vs. an express bus route. The Atlanta case study showcases the practice-ready capabilities of the GHG emissions calculator in assessing the differences in technology and fuel performances under different operating conditions. The results illustrate that the decision as to which bus technology-fuel combination produces the least greenhouse gas emissions is a function of location and route characteristics. The Calculator will support transit agencies in evaluating bus technologies for GHG emissions within the context of local conditions.

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INTRODUCTION

With increasing concern over climate change, the amount of greenhouse gas (GHG) emissions has become an important criterion as transit agencies plan for new vehicle purchases. To this end, Weigel (2010) developed the original GHG Emissions Management Calculator. The original Calculator employs national average emission rates for different vehicle types. The emission rates are designed to represent emissions under what could be considered average, or typical operating conditions. Such single-point emission rates are generally derived from laboratory or field testing under representative operating conditions. For example, emissions are often collected in the laboratory on engine or chassis dynamometers under varying load conditions designed to represent a duty cycle. Use of single-point average emission rates is very useful in comparative technology performance assessments and development of national average emission inventories. However, the original modeling approach does not provide the flexibility of assessing the differences in technology performance across routes. Average emission rate models are not useful for such purposes.

In 2012, the Federal Transit Administration (FTA) commissioned the update of the Calculator. The purpose of the update was two-fold: 1) to include more vehicle and fuel options such as battery electric vehicles, and 2) to properly compare the performance of different vehicle technologies under different operating conditions. For the model to be useful to policy analysts that are trying to decide which technology is more efficient for a given set of transit services parameters, users need to be able to differentiate between the performance of various technologies in the field, i.e. on specific routes or generalized route types, under a variety of operating conditions such as number of stops, passenger loading, and road grade.

CALCULATOR OVERVIEW

The updated GHG Emissions Management Calculator is the first interactive GHG calculator equipped with the capability to estimate emissions as a function of engine-load, using a load surrogate known as Scaled Tractive Power (STP). This same STP modeling approach is employed in the US Environmental Protection Agency (EPA) emission rate model known as the MOtor Vehicle Emissions Simulator (MOVES). MOVES is the current federally approved emission rate model for use in regional and microscale air quality impact analyses for regulatory purposes. MOVES emission rates are employed in the Calculator and resulting emissions are based upon the user-supplied vehicle operating parameters that affect fuel consumption and emissions. For life-cycle emissions estimation, the Calculator uses a combination of load-based emissions estimated from MOVES for direct emissions during vehicle operations, and upstream fuel-cycle emissions estimated from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

Inputs

The Calculator allows users the flexibility to specify customized geographical, meteorological and operational parameters. Figure 1 is a screenshot that provides an overview of key inputs for the Calculator, listed as follows:

- City and state, which mainly impact power generation mix in life-cycle emissions estimates for electricity.
- Terrain roughness, tied in to considerations of road grade in the estimation of direct emissions. The Calculator provides a default terrain roughness value based on the city and state, but it also allows users to override the default value.
- Meteorological settings, which play an important role in load-based emissions estimates. Users can choose to model either a winter or a summer scenario. Within each seasonal scenario, users are prompted to choose the severity of the local climate, an index that represents a temperature and humidity combination within the Calculator.
- Duty cycle, which depicts the speed-acceleration profile and the frequency of stops. The Calculator includes 14 built-in duty cycles that are representative of routes that traverse different areas ranging from high-density urban cores to suburbs. Alternatively, users can supply their own duty cycles, typically collected using a GPS device.
- Passenger loading, which affects the weight of the vehicle and therefore, engine load.
- Propulsion and fuel options. Currently, users can choose from conventional spark ignition/compression ignition (SI/CI), hybrid electric, battery electric and fuel cell electric vehicles. The fuel options for SI/CI and hybrid electric buses include conventional diesel, gasoline, compressed natural gas, as well as 2%, 5%, 10% and 20% biodiesel.

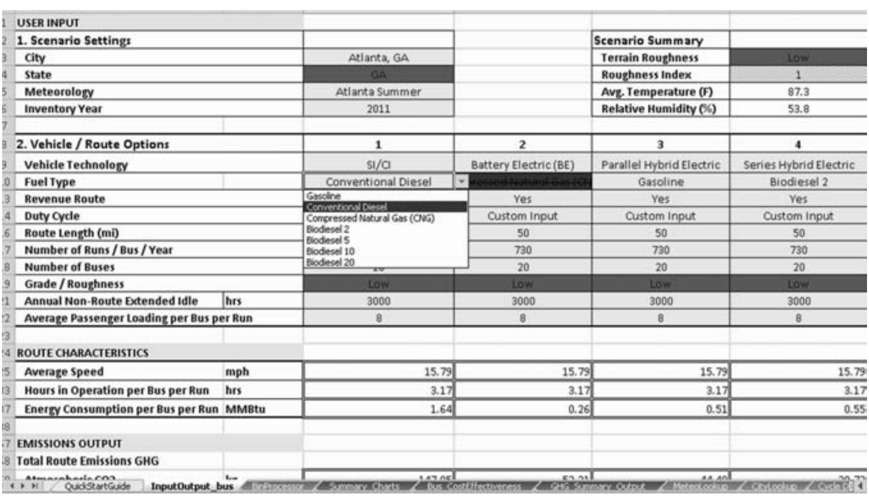

Figure 1 Example Screenshot of Calculator Inputs

Outputs

The calculator has been designed to provide comprehensive and relevant outputs for transit agencies and researchers. The objective was to provide transit decision makers with relevant and straightforward information and researchers with detailed technical results, both final and intermediate. All emissions and energy consumption are to be expressed in per year, per vehicle-mile, and per passenger-mile basis. The results from the Calculator are displayed as pre-defined tables and charts. Figure 2 showcases some output charts the Calculator produces.

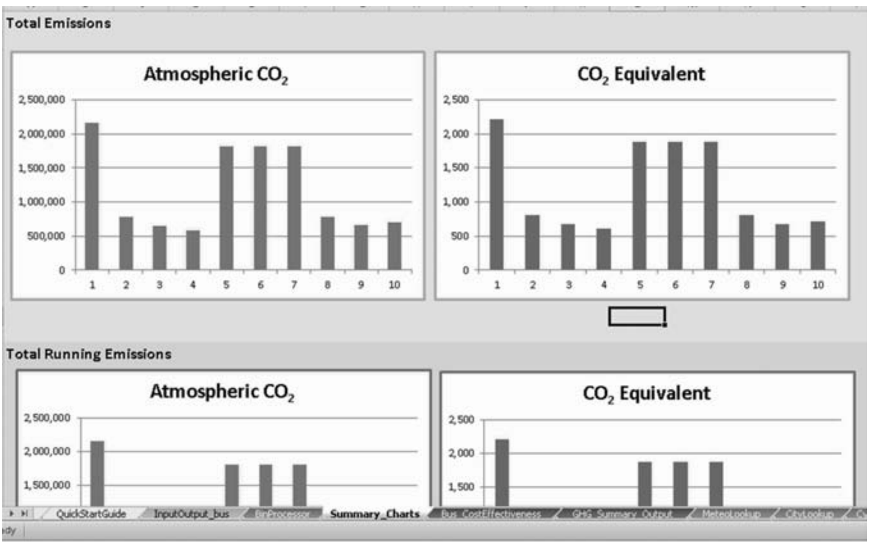

Figure 2 Example Screenshot of Calculator Outputs Showing Comparisons of Emissions across Technology/Fuel Options

DATA DESCRIPTION

The paper applies the Calculator to two empirical bus routes in Atlanta, GA to evaluate GHG and criteria pollutant emissions from various vehicle technologies. Figure 3 depicts the geographical extent of the two routes. The urban route, shown in blue, is based on a GPS trace collected on a Metropolitan Atlanta Rapid Transit Authority (MARTA) bus traversing an urbanized area featuring Emory University and the Center for Disease Control (CDC). The express route, shown in green, is based on a GPS trace collected on a Georgia Regional Transportation Authority (GRTA) Xpress bus, starting in the outer-suburbs and ending in Midtown Atlanta, with a majority of the mileage accumulated along Interstate 85. The authors chose these two routes for the case study because of the drastically different speed-acceleration profiles, and therefore, vehicle operating modes, between the urban transit route and the express route. The following sections provide detailed information regarding the data as well as emission results from the respective routes.

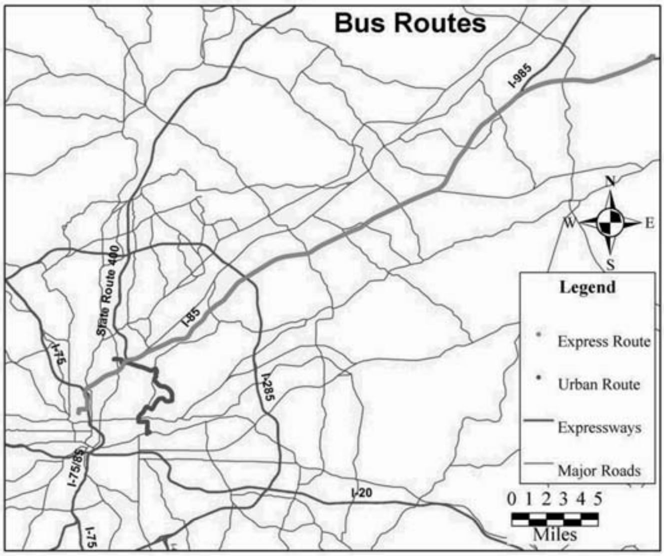

Figure 3 Example Bus Routes for Case Study

Urban Transit Route

The urban transit route starts in the Lindberg MARTA Station and ends in the Avondale MARTA Station along urban arterials. The area that the route goes through features a mixture of low- to medium-density residential (densely spaced single family residences and medium-rise apartments), low- to medium- density commercial areas, and major employers such Emory University and the CDC. The duration of the route is 1,966 seconds, or just over half an hour, traversing a total distance of 8.61 miles. The average speed is 15.8 miles per hour (mph) with a maximum speed of 36.8 mph. The maximum acceleration observed on the route is 3.46 mph per second (mphps) and the maximum deceleration rate is 5.77 mphps. As shown in Figure 4, the urban transit route features frequent stops with about 20% of the total duration spent in idling mode.

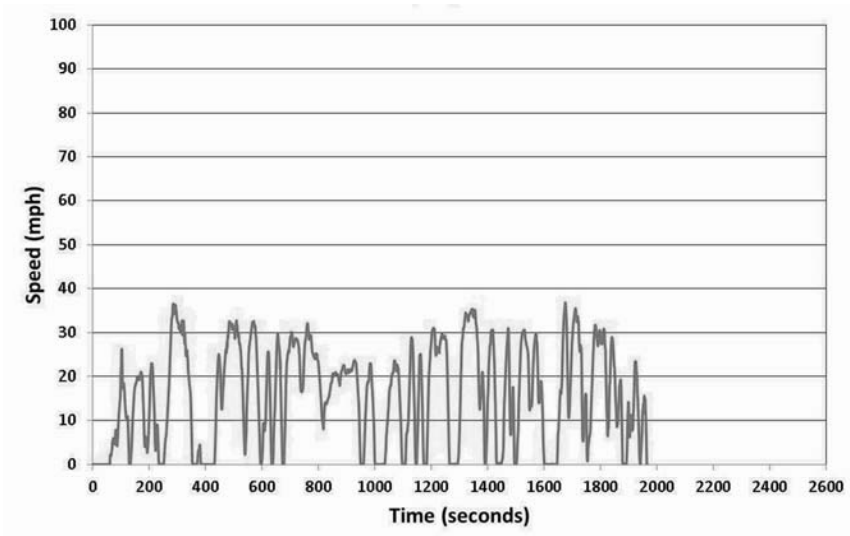

Figure 4 Time-Speed Trace of the MARTA Urban Transit Route

Express Bus Route

The express bus route starts in the Hamilton Mill park-n-ride and ends in Midtown Atlanta, collected on a GRTA Xpress bus using a GPS logger. A major portion of this route is on the freeway. The total duration of the route is 2,187 seconds, or about 36 minutes. The total distance is 36.8 miles, with an average speed of 60.6 mph and a maximum speed of 88.0 mph. The accelerations and decelerations are steeper compared to those observed on the urban transit route. The maximum acceleration of the express bus route is 6.5 mphps and the maximum deceleration is 7.4 mphps. The express bus route features very little idle activities—less than 1% of the total duration can be classified as idling. Figure 5 shows the time-speed trace of the express bus route, depicting the high-speed operations observed on this route.

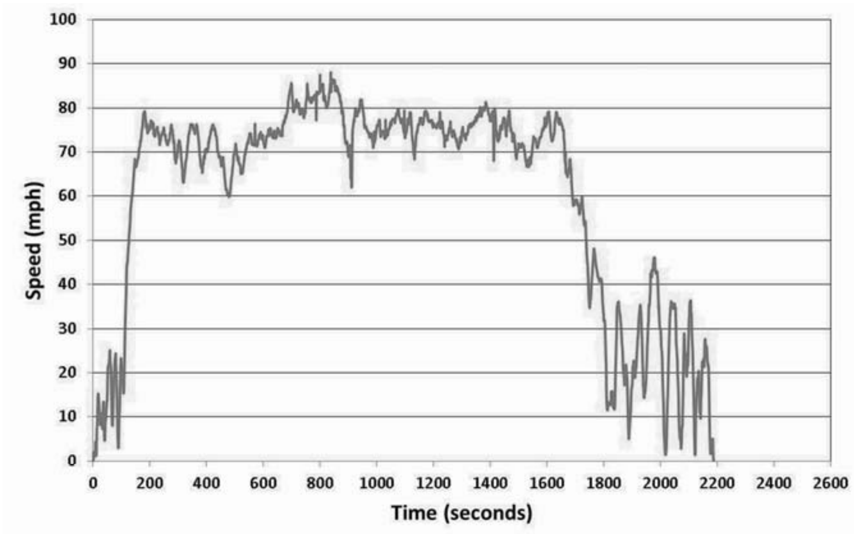

Figure 5 Time-Speed Trace of the GRTA Xpress Bus Route

Because battery-operated electric vehicles cannot sustain high-speed operations, the GRTA Xpress bus cycle is physically impossible for electric vehicles to achieve. To provide a sensible comparison, the authors modified the GRTA Xpress Bus cycle according to the physical speed constraints of electric vehicles. Specifically, the maximum speed was capped at 60 mph, a hypothetical top speed that may still be too high for electric vehicles to sustain, but reasonably reflects freeway operations. The detailed modification methodology is described below.

First a total of 1550 speed values were reduced to 60mph to limit top operating speeds. To keep the original cycle distance after the speed reduction, the additional distance needed was calculated.

=original cycle distance – cycle distance after limiting top speed to 60pmh
=36.79mi - 30.49mi = 6.30mi

Additional time (sec) needed traveling at 60mph, or .0167 miles per second (mps) to cover needed distance was calculated.

= 6.30mi/.0167mps ≈ 378sec

The 378 needed speed values at 60mph were inserted into the cycle trace at the freeway portion. The resulting time-speed trace of the modified GRTA Xpress Bus Cycle is depicted in Figure 6. After the modification, the total distance stays 36.8 miles, but the total duration increases from 2,187 seconds to 2,565 seconds. The average speed is 51.63 mph and with a maximum speed of 60 mph. The maximum acceleration of the modified express bus route is 5.03 mphps and the maximum deceleration is 5.22 mphps. The modified GRTA Xpress Cycle will be used in the case study for emissions comparisons.

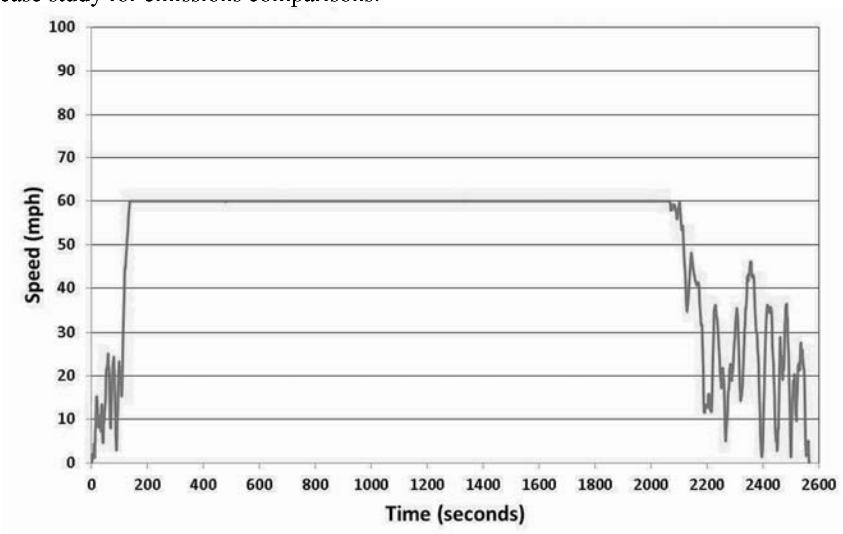

Figure 6 Modified GRTA Xpress Cycle for Electric Vehicle Options

RESULTS AND DISCUSSIONS

The Calculator processed the two time-speed traces and produced total emissions on the routes. Table 1 shows the emissions results normalized into per-mile emission rates for easy comparison. The Calculator is capable of producing more technology-fuel combinations than what is shown in Table 1, but due to space limitations, only the most relevant technology-fuel combinations are shown, namely, SI/CI in combination with diesel, compressed natural gas (CNG), 20% biodiesel (B20), parallel and series hybrid electric (HE) buses in combination with diesel and B20, battery electric (BE) buses, and fuel-cell electric (FCE) buses. The SI/CI-diesel combination is considered as the baseline scenario in the case study. As far as emission results, Table 1 shows the four major GHG's, namely, carbon dioxide (CO_2), methane (CH_4), Nitrous Oxide (N_2O), and elemental carbon (C), along with CO_2 equivalent (CO_2e), calculated based on the global warming potential (GWP) of each of these gases (US EPA, 2012). The Calculator also provides emissions from criteria pollutants including carbon monoxide (CO), volatile organic compounds (VOC), oxides of nitrogen (NOx), particulate matter ($PM_{2.5}$ and PM_{10}), and sulfur dioxide (SO2). For a concise discussion, the paper will pay most attention to CO_2e.

For the urban transit route, the CI-diesel combination emits 3.39 kilograms of CO_2e per mile including life-cycle emissions associated with fuel production and transportation. Within all CI options, B20 produces the least life-cycle CO_2e

emissions, amounting to 2.87 kg/mi, a 15% reduction compared to the baseline scenario. The SI/CI-CNG combination produces slightly more CO_2e compared to the B20 option, at 2.93 kg/mi, a 14% reduction compared to the baseline scenario. Hybrid electric buses, both parallel and series, produce less CO_2e compared to SI/CI buses, regardless of fuel. Given the same fuel option, either diesel or B20, parallel hybrids and series hybrids produce comparable amount of CO_2e, although series hybrids show a slight advantage in this case. HE buses that run on diesel fuel produce about 21% less CO_2e compared to the SI/CI-diesel buses. HE buses that run on B20 would provide an additional 11% reduction in CO_2e emissions compared to CI-diesel buses, amounting to 32% total reduction. BE buses seem to be even more advantageous in terms of GHG savings compared to HE buses, even though the power generation mix in Georgia is largely fossil-based. The CO_2e emission rate for BE buses on the urban transit route is 2.16 kg/mi, amounting to a 36% reduction compared to the baseline scenario. Interestingly, the life-cycle CO2e emissions for FCE buses are rather large. Producing CO_2e at a rate of approximately 2.88 kg/mi, FCE buses perform just slightly better than the SI/CI-CNG option in terms of GHG savings, and worse than all other alternative propulsion-fuel combinations within the scope of this paper.

On the modified express bus route, the baseline SI/CI-diesel combination emits 3.12 kg of CO_2e per mile. Contrary to the case in the urban transit route, within all SI/CI options, CNG performs better than B20 with regard to CO_2e savings on the modified express route. CNG buses produce 2.28 kg CO2e per mile, 27% less than the baseline scenario, whereas buses that run on B20 only produce 11% less CO_2e than their diesel counterparts. Due to the dominance of high-speed cruising observed on the express bus route, the hybrid technologies provide less GHG savings compared to the reductions in the case of the urban transit route. The parallel hybrid buses that run on diesel emit 3.03 kg CO_2e per mile, only a 3% decrease from the baseline SI/CI-diesel combination. The parallel hybrid buses that run on B20 emit 13% less CO_2e than the SI/CI-diesel buses, but only 2% less than SI/CI buses that also run on B20. Similarly, series HE buses offer lackluster CO_2e emissions reductions compared to their SI/CI equivalents. In both fuel options of diesel and B20, parallel HE buses perform worse than SI/CI-CNG buses with regard to GHG savings. The CO_2e savings that FCE buses deliver on the modified express bus are comparable to HE buses that run on B20. At an emission rate of 2.67 kg/mi, FCE buses reduce life-cycle CO_2e emissions by less than 14%, compared to the baseline scenario. If BE buses can sustain the 60-mph top speed for more than 15 minutes, as required for the modified express bus cycle, BE buses would offer impressive CO_2e savings at 2.01 kg/mi. Even though the effect of energy savings due to regenerative braking is not as pronounced under freeway operating conditions as opposed to local travel conditions, BE buses still require less energy to operate because electric motors and batteries are more energy efficient than SI/CI engines.

Table 1 Bus Emission Rate Results

MARTA Urban Bus Cycle										
Technology		SI/CI	SI/CI	Parallel	Series	BE	SI/CI	Parallel	Series	FCE
Fuel		Diesel	CNG	Diesel	Diesel	Electricity	B20	B20	B20	Hydrogen
CO_2	kg/mi	3.305	2.702	2.617	2.605	2.152	2.769	2.256	2.219	2.458
CH_4	g/mi	4.026	9.325	2.707	2.897	0.032	3.591	2.414	2.584	19.848
N_2O	g/mi	0.014	0.101	0.009	0.009	0.034	0.088	0.059	0.063	0.012
C	g/mi	0.001	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000
CO_2e	kg/mi	3.394	2.930	2.677	2.669	2.163	2.873	2.326	2.293	2.879
CO	g/mi	2.014	23.175	1.423	1.462	1.895	2.049	1.445	1.487	0.638
VOC	g/mi	0.410	0.251	0.277	0.298	0.040	0.655	0.443	0.474	0.279
NO_x	g/mi	5.084	7.120	3.671	3.723	1.596	5.165	3.726	3.781	1.803
$PM_{2.5}$	g/mi	0.181	0.118	0.127	0.133	0.107	0.202	0.141	0.148	0.485
PM_{10}	g/mi	0.296	0.347	0.204	0.215	0.196	0.357	0.246	0.259	0.960
SO_2	g/mi	0.988	1.132	0.669	0.713	7.200	1.070	0.724	0.772	1.840
GRTA Express Bus Cycle, Modified for Electric Vehicle Options										
CO_2	kg/mi	3.059	2.129	2.979	2.918	2.002	2.691	2.633	2.559	2.286
CH_4	g/mi	2.748	6.394	2.579	2.677	0.030	2.450	2.300	2.387	18.459
N_2O	g/mi	0.008	0.045	0.008	0.008	0.032	0.059	0.056	0.058	0.011
C	g/mi	0.001	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000
CO_2e	kg/mi	3.119	2.278	3.036	2.977	2.012	2.761	2.700	2.628	2.677
CO	g/mi	0.692	12.995	0.657	0.676	1.763	0.735	0.697	0.717	0.593
VOC	g/mi	0.281	0.173	0.265	0.272	0.037	0.450	0.424	0.437	0.259
NO_x	g/mi	2.372	5.782	2.266	2.283	1.484	2.422	2.313	2.332	1.677
$PM_{2.5}$	g/mi	0.120	0.084	0.113	0.115	0.100	0.135	0.127	0.130	0.451
PM_{10}	g/mi	0.198	0.241	0.187	0.192	0.183	0.241	0.227	0.233	0.893
SO_2	g/mi	0.684	0.778	0.643	0.666	6.696	0.740	0.696	0.721	1.711

CONCLUSIONS

The case study results show that the optimal propulsion/fuel type for GHG savings is highly dependent upon the route characteristics. For example, for the conventional SI/CI technology, B20 and CNG emit comparable amount of CO2e on the urban transit route, but CNG appears to be provide more GHG savings than B20 on the modified express bus route. When it comes to propulsion technologies, hybrid buses show around 30% GHG reduction compared to the SI/CI counterparts on the urban transit route featuring stop-and-go operations, but the reduction is much smaller on the modified express bus route. The GHG savings of battery electric buses are impressive for both the MARTA urban route and the modified GRTA Xpress route, but the limitation lies within the capability of BE buses to sustain high-speed operations. GHG savings from BE buses also rely heavily on the power generation mix. A large portion of Georgia's electricity is generated from fossil-based plants. In states where more renewable energy sources are used in power generation, BE buses will show even higher GHG savings. Similarly, emissions from FCE buses vary considerably from location to location, depending on the source of hydrogen. However, given the numerous possibilities of hydrogen production and transportation, the precise estimation of fuel-cycle FCE bus emissions remains a challenge. The results from the Calculator illustrate that bus technology-fuel combination purchase decisions impact greenhouse gas emissions as a function of location and route characteristics, and that using a national average fuel consumption value is not adequate to support locally optimized decisions.

The Calculator serves as a starting point in assisting transit agencies with location- and route-sensitive decision-making with regard to climate change mitigation when planning for new fleet purchases. Further research is needed to calibrate and validate model results. Still under development, the Calculator will continue to evolve and improve with the availability of field test data and user feedback.

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Life Cycle Greenhouse Gas Analysis of Foam Stabilizing Base

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ABSTRACT

Foam stabilized base (FSB) is a cold asphalt recycled mix, which uses 100% reclaimed asphalt pavement (RAP) or a combination of RAP and crushed concrete pavement with 2 to 2.5% of foamed asphalt binder. The production process involves injecting 1 to 2% water into hot asphalt binder in a patented foaming chamber to develop foams which is 10 to 15 times the original volume of the asphalt cement. In additional to its cost advantage, foam stabilized base is more environmental friendly than traditional bitumen stabilizers due to a reduction in natural resources, energy consumption during production and construction, and emissions of greenhouse gases (GHG). The application of FSB could help asset owners to meet their sustainability objectives and comply with relative regulatory requirements. This paper presents a life cycle analysis (LCA) of GHG emissions from FSB production and construction. The analysis assesses the environmental impacts of FSB compared to other alternative designs over the entire life cycle of pavement assets including site preparation, raw material extraction and transportation, installation and construction, operations and maintenance, and asset demolition. Based on the analysis of a set of design alternatives and project cases, it is shown that FSB could reduce GHG emissions by up to 69.5% from project construction. This presentation is useful to 1) understand the FSB material, pavement design and construction , 2) designers and contractors who want to benchmark their design and construction options, 3) state and local agencies that are increasingly mandated to improve their environmental friendly engineering practices, and 4) researchers who identify ways of improving construction designs and processes that reduce long-term GHG emissions.

INTRODUCTION

The asphalt pavement is one segment of construction and infrastructure industries to build national asphalt highways, streets, airport runways, parking lots, and sports areas. Asphalt paving industry by far is the most extensively used materials of paving roads and highways worldwide. In US, it is estimated that more than 92% of the total of 4 million kilometers of paved roads and highways are surfaced with asphalt; in Europe, more than 90% of the total 5.2 million kilometers; In Canada, about 90% of 415,000 kilometers (Mangum, 2006). Such an extensive usage of asphalt leads the asphalt industry to the national power drivers for infrastructure development and domestic economic growth engine. In 2007 alone, US produced 500-550 million

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metric tons of asphalts in roughly 4,000 asphalt production sites, worth in excess of 30 billion USD and support more than 300,000 employments across the construction industry.

The massive production and construction of asphalt materials pose concerns to the environment. EPA identified the annual criteria pollutants of 56,000-74,000 lb/yr for a typical asphalt production plant, including sulfur dioxide (SO_2), nitrogen oxide (NOx), carbon monoxide (CO), and volatile organic compounds (VOC), and volatile Hazardous air pollutants (HAPs) organic compounds. In recent years, the carbon emissions (or GHG emissions) quickly grows as special attentions and under public regulation. EPA (2011) reports that asphalt accounts for 4.3 percent of the total non-combustion CO_2 emissions in petroleum system and emits over 300 million tons of CO_2e in 2010 for the total of asphalt and road oil together[i]. At a project level, Amlan (2011) studied Michigan HMA pavement practices and found that annual 511.27 metric ton CO_2 e/year were generated from a life cycle phase of a road. National Asphalt Pavement Association (NAPA) estimated a typical HMA production plant generates around 15.2 kg CO_2/ton duration regular production process.

With changes in construction materials cost, stricter environmental regulations, and availability of novel green technologies, the asphalt pavement industry is seeking various technologies in pavement while reassessing the environmental benefits of potential choices. The total emissions of asphalt industry have also been decreased by 97 percent from 1970 to 1999, while the production of asphalt pavement materials increased by 250 percent. So far, several mainstream technologies can help the asphalt industry achieve greener performance, including reuse/recycling of reclaimed asphalt pavement (RAP), lowering the temperature of asphalt production (e.g. warm-mix and cold-mix), and porous pavement to promote water infiltration and storm-water management. For instance, FHWA and the U.S. EPA estimated that more than 90 million tons of asphalt pavements were reclaimed every year, making asphalt the most frequently recycled material. New Jersey DOT reported doubling the use of RAPs from 600,000 tons to 135,000 tons in 2001-2006. Using RAPs to replace virgin aggregates results in significant environmental benefits, reducing GHG emissions by 20.2% per ton in asphalt production, with 53.26 kg CO_2e/ton of 70% RAP compared to 66.73 kg CO_2e/ton in the virgin asphalt. Warm mix asphalt, as another alternative low-emission technology, allows for asphalt production and operation at a lower temperature ranging from 212-280 F than conventional hot mix technologies of 320 F. The warm mix technologies claimed a board adoption within 40 US states since it was first public demonstrated in 2004. Producing warm mix can reduce total life-cycle greenhouse gas emissions by an average of 5 percent. Combine warm mix with RAPs usage yields even greater benefits. Warm mix with 25 percent RAPs pavement could potentially offset asphalt pavement life-cycle greenhouse gas emissions by 15 to 20 percent. Awareness of asphalt environmental concerns has also being raised by industry-supported efforts such as GreenRoad rating system which incorporate asphalt recycling design as credits in rating road environmental stewardship.

FSB PRODUCTION SYSTEM

Foamed stabilized base (FSB) is a roadway recycling process in which the entire pavement and some of the underlying material is pulverized and treated with a foamed asphalt additive to produce an improved, stabilized base. FSB is also known as Foamed asphalt base stabilization, cold formed asphalt, or formed asphalt, and quickly becomes a popular cold recycling and reclamation method to minimize environmental impact of asphalt paving operations. The foamed asphalt fact was first found by Professor Ladis Csanyi at Iowa State University in 1956. In 1968, Moblie Oil of Australia modified the process to use cold water instead of steam, making foamed asphalt economical and more acceptable for the industry use. The US lagged adoption for this technology for many years since it was first used in Europe and South Africa.

In cold recycling production, the air and water are injected into the bitumen to produce foamed bitumen which is ideally suited for mixing with cold and wet construction materials (see Figure 1). Formed bitumen is also a highly economical binding agent because the quantities that need to be added into the production are very small. Foamed asphalt is non-continuously bound materials which perform like granular materials with retained inter-particle friction but increased cohesion and stiffness.

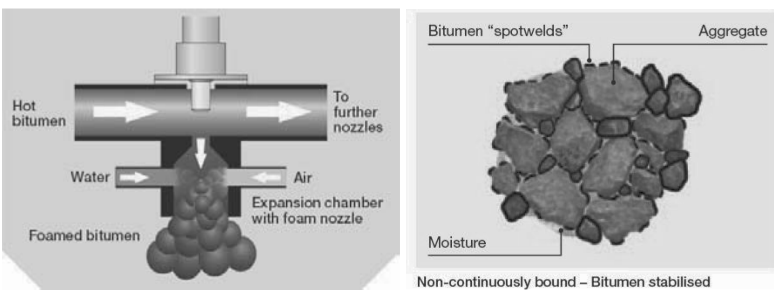

Figure 1 Foamed stablized based process illustration and final product (Figure from Whirgen)

The cold recycling can be achieved by two typical processes: cold "in-place" recycling and cold "in-plant" recycling. "In-place" uses mobile recycling machines to complete a series of recycling production and installation processes; while "in-plant" transports milled materials from an existing jobsite to a central plant where it is processed through a mixing machine. Typically, the "in-place" is more environmental conservative due to little transportation requirement for milled materials. Generally, the "in-place" recycling uses 100 percent of RAPs generated from the existing pavement, with a treatment depths ranging from 2-4 inches. In some cases, the treatment depths can range from 4-12 inches, where the underlying base or sub-base material is also been milled and mixed to produce a uniform base material. These cases are widely acknowledged as Full Depth Reclamation. Comparing with "in-place" method, "in-plant" is in possession of three benefits: control and selection of the input materials to meet certain standards, opportunities to improve the quality of the mix, and stockpiling capabilities to release the inter-dependency of the mixing and placing processes. The decision of selecting appropriate cold recycling method should be carefully made based on the most available project information. Over a half of agencies consider pavement condition, particularly distress survey, as one of the most important factors in the selection of cold recycling method. Geometry, climate, and surface treatment are other selection criteria in deciding to adopt cold recycling method.

FSB yields many benefits for its recycling material process. First, FSB reduces production cost since it requires less binder and water than conventional asphalt production, and also cuts the need to acquire and transportation of virgin materials. Second, FSB cuts energy demand and emits fewer emissions. The reuse of existing pavement materials saves materials' embedded energy and avoids transportation with fuel and emission consumption. Energy and emission are also conserved due to only the bitumen needs to be heated in the FSB production process. A survey shows that cold in-place recycling can reduce GHG emission by between 50%-85%. Third, FSB conserves the environment and benefits for the occupational health. Cold recycling keeps a lower temperature at production and installment process, limiting the polluting evaporation from construction process to the environment and creates a safer occupational environment for asphalt workers. Fourth, FSB enables a flexible schedule for the construction process. Conventional HMA needs to locate an asphalt plant within a close distance to the job site in order to maintain specific temperature requirements during asphalt installment. In comparison, FSB can be worked at a regular temperature and weather condition, being more flexible and constructible than conventional pavement process.

The current practices of FSB are widely adopted across the US. A total of 34 states with experiences with in-place cold recycling method are identified in a recent survey, where states are equally applying cold recycling to surfacing, repaving and remixing processes. However, there is no standardized guideline for recycling specification although 19 states already have their own requirements for cold recycling projects. In general, FSB follows a mix design principle with requirement for both tensile strength and tensile strength ratio, indicated in the AASHTO T 283. The structure properties of FSB are largely determined by its stiffness and permanent deformation. The majority of state agencies uses either Marshall or Superpave standards as their mix design methods for cold recycling, however 20-42 percent of the states has not developed mix designs for recycling project yet.

However, the environmental performance of cold recycling technologies has not been thoroughly studied so far. The detail of emissions generated from a life-cycle production is still unknown given such a new production process and mix design options. This paper aims to propose a holistic evaluation method to calculate FSB emissions during its life-cycle phases.

SYSTEM BOUNDARY

Figure 2 shows the major processes included in the cold central plant recycling (CCPR) system. The system was analyzed over five consecutive months (March 2012 to July 2012). The Life-cycle Analysis (LCA) starts with the production of raw materials on supplier sites and ends with the delivery of the pavement product to the customers; it includes all activities at supplier sites, FSB production plant and paving job sites. The life cycle elements covered in the system boundary include production materials, energy, manufacturing equipment/vehicles, operation of plant office, transport and storage of input materials (PAS 2050). GHG emissions arising from the production of capital goods are excluded from the assessment.

- Functional unit

The functional unit for the entire CCPR system is 1 kg of FSB pavement, which can be used to compare with 1 kg of FSB pavement from CIR and FDR system. Structure coefficient is introduced into the definition of functional unit when comparing FSB with other pavement alternatives (e.g. HMA).

- System description

Foamed asphalt is produced in Global Resource Recyclers (GRR) facility located in Forestville, MD, which is the first central processing plant in the USA to produce foamed asphalt. The making of foamed asphalt begins with the crushing of recycled asphalt pavement (RAP), thus diverting waste from land-fills and eliminating the need to quarry and transport virgin aggregate. Once the crushed pavement is sized, the unbeated RAP is then blended with hot asphalt cement, water and a small amount of Portland cement in a cold mixing process. Compared to the production of traditional "hot mix" asphalt, the foamed asphalt facility is expected to significantly reduce the GHG emissions due to 1) eliminating the use of energy stocks to heat aggregates, 2) eliminating the need to quarry and transport virgin aggregates, and 3) reducing the bitumen content by 60% over HMA.

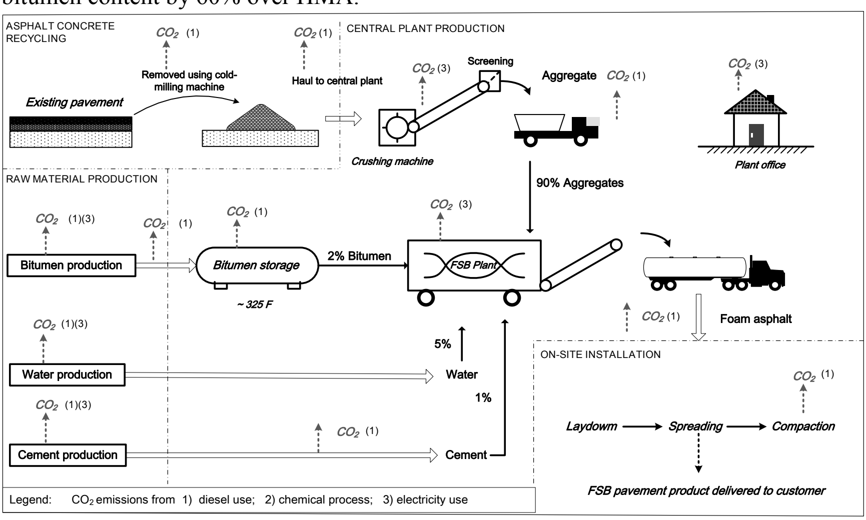

Fig.2 schematic of FSB pavement life cycle showing major system processes and emissions sources.

Double-lined arrows signify included transportation; dashed-line arrows signify the separation of activities in different locations.

Foamed asphalt can be used as a substitute of HMA in all patching and rehabilitation projects. To date it has realized the substitute function in replacing base course for a portion of parking lot projects – roughly 4" base course and 2" overlay. It resists cracking due to freeze thaw cycles and has been shown to last longer than a traditional asphalt base mix.

LIFECYCLE ASSESSMENT MODEL AND DATA COLLECTION

A model was created to calculate the GHG emissions associated with the production of 1 kg of FSB pavement. The assessment model was constructed referring the Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services, issued under the Publicly Available Specification (PAS). Global warming potentials were characterized with the IPCC 2007 methodology using a 100 year time horizon (25 and 298 for CH4 and NO_2, respectively) (Synthesis Report, 2007).

- Raw material acquisition, processing and transport

FSB is manufactured using 100% recycled asphalt pavement (RAP/rubble or milled pavement) in combination with a small amount of hot bitumen oil; that when blended together with potable water (foaming water ~2% and compaction water 1~2%) and 1% Portland cement. The GHG emissions from material manufacture and transportation include 1) embodied GHG emissions of construction materials, which are primarily due to their stoichiometric relationships based on the chemical compositions and energy consumption for manufacture process before transportation to construction sites, and 2) GHG emissions from fuel consumption for transporting materials to construction sites (Yan, et al., 2010). A large portion of the model data was collected onsite at GRR plant. These primary data include amount of RAP, bitumen oil, water and Portland cement over the analysis period. Transportation distances for the shipment of input materials were collected from GRR records. Life cycle GHG emissions from manufacturing raw materials, recycling pavement and material supplies were calculated using database available through the EIO-LCA model (CMUGDI. 2008).For materials that the sector classification cannot exactly match (e.g., aggregates), the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) was used. The details on the emission input parameters, equations and outputs are presented in the Supporting Information.

- Construction equipment operation

The approach to estimating emissions from equipment operation is based on theNONROAD2008 model from the EPA, which applies to the cold-milling machine, backhoe, bobcat/loader, sweeper/broom, excavator, air compressor, tractor, sterling, paver, roller and truck for the patching projects, as well as crushing machine and backhoes for the central plant (U.S.EPA, 2005). The GHG emissions from the operations are estimated from the hours of use, the number of pieces on site, and equipment-specific parameters such as the emission factor, the horsepower and the load factor. The NONROAD2008 built-in database provides the emission factors for 25 basic categories of equipment, but it does not distinguish the difference between various engine makers within the same type of equipment.[5] To address this problem, we gathered the engine emission information from the EPA off-road engine

[5] From the statistics analysis of the EPA engine certification database, the emission factors of the equipment with different engine makers may vary by as much as 30%, e.g., on average, a roller with a Deutz engine emits approximately 1063gCO_2e/hp/hr while a roller with a Cummins engine emits approximately 824gCO_2e/hp/hr.

certification database (U.S. EPA, 2012) and further stratified equipment types by engine maker and horsepower rating. The emission factor for FSB production plant is not available in the EPA off-road engine certification database. FSB production plant was estimated to consume 35 liter of diesel per hour of operation using Wirtgen Cold Recycling Manual. The associated GHG emissions are 96.9 kg CO_2e per hour of operation. The emission control technology is not considered, although it is increasingly used for some categories of off-road equipment, especially equipment operated in urban areas. Different activity modes (i.e., idling, moving, or using an attachment) may produce different amounts of air pollutant emissions, but it is simplified and incorporated into the calculation equation as an average impact factor (Lewis, et al., 2009). The details on the emission input parameters, equations and outputs are presented in the Supporting Information (IPCC, 2006b; U.S. EPA, 2010).

- Electricity provision for office operation and material storage

Electricity related GHG emissions were modeled using U.S. national average grid from EIO-LCA model. The price of electricity was assumed at 0.0986$/kWh. The operation of office was assumed to consume 20% of the whole plant electricity, the rest of which primarily resulted from the production of PCC - the other product in GRR plant irrelevant to FSB production. The electricity consumption of office operation was allocated to the production of FSB and PCC in proportion to the total output of each product. Bitumen storage tank was estimated to consume 12kW of electricity per hour of operation. Since it only operates one hour per month, bitumen storage tank only accounted for approximately 1.5% of the electricity use of office operation. Electricity consumption and emission factors for office operation and material storage are reported in Table S3 of the Supporting Information.

RESULTS AND DISCUSSION

Figure 3 shows the distribution of GHG emissions across the life cycle. The total global warming potential is 87.95 kg CO_2 equiv/ ton FSB pavement for the monitoring period. Material related activities are responsible for 28.9% of the total, with bitumen being the largest single contributor. Other contributions to GHG emissions across the life cycle come from GRR plant, 24.0%; and paving job site, 47.0%.

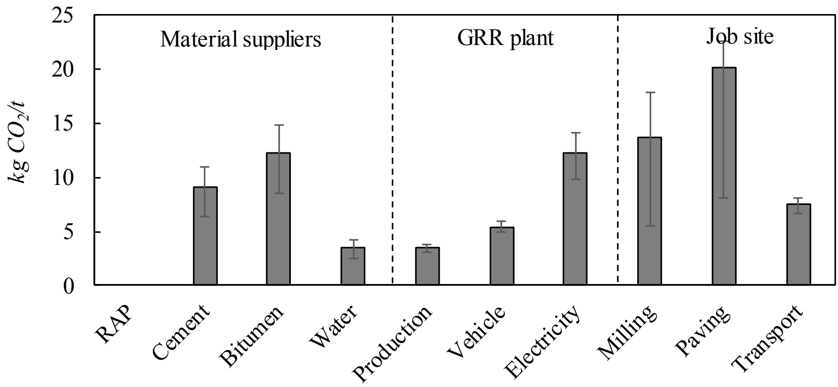

Fig.3. distribution of GHG emissions across the FSB pavement life cycle on a functional unit basis

- Emission uncertainties

Cement, bitumen and installation activities on the job site are major contributors to global warming potentials. In the FSB pavement life cycle considered here, GHGs from the production and transportation of cement and bitumen account for 24.4% of total system emissions. GHGs from equipment operation during installation activities account for an additional 47.3% of total system emissions. Our study relies on emissions estimates based on IPCC Tie 2 methodologies (IPCC, 2006) complied at monthly time steps. Whereas the consumption of cement and bitumen are based directly on GRR records and are therefore highly accurate, methods are also based on emission factors that, according to ICE database, have significant uncertainties. Emission factors for cement and bitumen production have reported uncertainties of ±30%. Reported uncertainties for equipment operation efficiency are -60% to +30%. Propagating uncertainties in cement and bitumen gives a GHG emission from material supply range of 23.94 to 36.82 kg CO_2 equiv per ton FSB (base-case value = 30.38 kg CO_2 equiv per ton FSB). Combined with the uncertainty in equipment operation, this gives an uncertainty range for total system GHG emissions of 55.48 to 109.13 kg CO_2 equiv per ton FSB (base-case value = 87.39 kg CO_2 equiv per ton FSB).

- Abatement analysis

Quantification of emissions reduction as compared to HMA must be made with caution: differences in system boundaries, pavement types, material structural performance, and other methodological nuances can have strong influences on the final results. It is with these cautions that we offer comparisons LCA for CCPR and CIR against HMA. The HMA pavement data are based on reporting from a hot asphalt production plant located in Maryland, International Construction Materials (ICM), and also literature-reported LCAs. NAPA reported that the proportion of RAP in HMA production ranges 5% to 30% and the range of GHG values for in-plant production is 17.32 to 16.85 kgCO_2 equiv/ton HMA. Our study lies on the high side of RAP proportion and low side of the plant GHG value for the conservative comparison. Figure 4 compares the life cycle GHG emissions from FSB and HMA base rehabilitation. FSB prevents approximately 19.1% of the GHGs compared to HMA pavement. Prevented emissions are directly related to the impact of the materials used, as measured from their production phase, typically accounting for 37.3% of the total emission from HMA. The strength coefficient of foamed asphalt is slightly less than hot mix such that approximately 10% thicker lift of GreenMix must be used to achieve the same performance standard as hot mix. With the strength performance considered, emission reduction over HMA should be 12.0 kgCO_2 equiv per ton pavement, which accounts for 11.0% of the emissions from HMA life cycle.

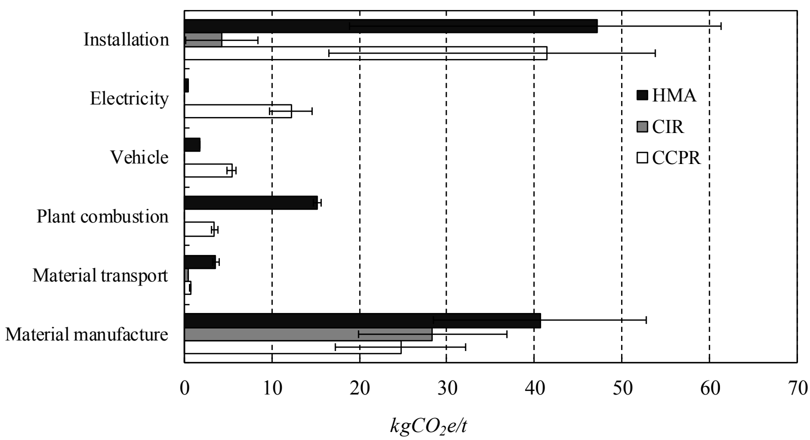

Fig.4. GHG Emission comparison amongst CIR, CCPR, and HMA base rehabilitation

CONCLUSION

This study uses life cycle analysis to calculate GHG emissions of FSB asphalt in both CIR and CCPR processes and compares their emissions with HMA production and placement. The main conclusions include:

- In the cradle to gate lifecycle analysis, CCPR emits an average 87.95 kg CO_2e/ton FSB pavement, CIR emits 33.15 kg CO_2e/ton, and HMA emits 108.76 kg CO_2 e/ton asphalt. Compared to HMA, the emissions reductions of CCPR and CIR are 19.1% and 69.5%, respectively. If the differences of structural performance are included, the emissions from CCPR and CIR are 11.1% and 66.4% lower than from HMA.
- CCPR generates an average emissions intensity of 87.95 kg CO_2e/ton FSB pavement, which can be broken down into three process: 22.4% emissions from materials, 30.3% from plant production, and 47.3% from job site construction; or into three emission sources: fuel consumption (58%), material embodied emissions (28%), and electricity usage (14%). The saved emissions of CCPR vs. HMA are primarily from fewer material embodied emissions due to higher use of RAP and less bitumen.
- CIR has average emissions intensity of 33.15 kg CO_2e/ton FSB pavement, where majority of emissions (87%) from materials suppliers and 13% from

construction and installation. Since RAP is 100% recycled and processed at the job site in CIR, no emission is associated with.

- Variances exist in calculated results due to the uncertainty of production techniques, mix design, data collection, and construction activities. After calibrating most uncertainties, emissions intensity for CCPR, CIR, and HMA range from 55.5-109.1 kg CO_2e/ton, 28.8-44.2 kg CO_2e/ton, and 67.4-136.0 kg CO_2e/ton, respectively.

This study provides a quantitative assessment methodology for emissions reductions due to FSB production and placement. This methodology is available for asphalt companies to quantify and verify carbon emission reductions. The calculated results also offer a project-wide carbon accounting basis for paving companies who wish to enter a carbon registry or claim carbon credits from FSB in order to enhance their competitive. The research can also help the paving industry appreciate the environmental benefits and co-benefits associated with FSB in future visions of industrial sustainable development.

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Estimation of Comparative Life Cycle Costs and Greenhouse Gas Emissions of Residential Brownfield and Greenfield Developments

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1. Abstract

This paper describes an approach to estimate life cycle costs and greenhouse gas emissions for residential brownfield and greenfield developments. The approach has been implemented in a spreadsheet estimation model that can be used to estimate the comparative life cycle costs and greenhouse gas emissions of major elements of residential brownfield redevelopments. The spreadsheet is available for download at http://www.cmu.edu/steinbrenner/brownfields/index.html. The estimation model includes default values and ranges based on a sample of US residential brownfield and greenfield developments and other literature sources. Model users can enter information about their own developments and compare life cycle costs and emissions with the sample for individual characteristics. Five major characteristics are included for the life cycle assessment of brownfields compared to greenfields, including brownfield remediation, residential building construction, infrastructure costs, residential building utilities and maintenance, and resident travel. Based upon the sample of brownfield and greenfield developments included, the brownfield developments tend to have lower average overall impacts due to lower travel costs associated with infill development closer to city centers despite costs associated with remediation. These averages show that a brownfield development can save each person $150 annually, compared with a greenfield development. Greenhouse gas emissions savings are an average of $1,200 kg$CO_{2e}$ per year per person. However, design decisions with respect to building type and density have large effects on overall development impacts for either brownfields or greenfields.

2. Introduction

Brownfields are properties with the presence or suspected presence of hazardous contaminants (EPA 2009). As a result, brownfield development generally incurs initial costs for environmental remediation. Despite this cost, brownfield development is being encouraged to improve overall metropolitan environmental quality and to reduce pressure for development of green spaces (Wernstedt 2006, Greenburg 2002). Brownfield development may also aid in the reduction of greenhouse gas (GHG) and other pollution emissions (Mashayekh 2012a).

While there are various federal, state and local programs and incentives in place to encourage brownfield redevelopment, there is little literature on the actual life cycle economic, environmental, and social impacts of such development (Nagengast 2011). This paper is intended to present an approach to estimate the overall life cycle costs and GHG emissions resulting from residential brownfield developments relative to traditional (greenfield) developments.

For this paper, we focus on the major categories of expenditure and GHG emissions that might differ between brownfield and greenfield developments. These categories are:

1- Remediation
2- Building Construction
3- Infrastructure
4- Utilities and Maintenance
5- Travel

Brownfield developments might have significantly lower infrastructure cost due to their compact nature and pre-existing infrastructure, such as roadways and pipelines, but may require significant capital for remediation before redevelopment begins (Burchell 2005, Leinberger 2009, Altshuler 1993). There may be other systematic differences between developments associated with income levels, diets, government expenditures, demographics or other factors, but these are not included within our scope of analysis.

We developed a spreadsheet tool which includes default and ranges of values for five different impact categories based upon a sample of brownfield and greenfield sites and other data from the literature. The tool is available for download on at http://www.cmu.edu/steinbrenner/brownfields/index.html . This tool is intended to be useful as a screening and benchmarking tool for developers and urban planners considering a new development. We encourage those using the tool to input the data that are specific to their projects and developments. In cases where data is not available for a specific project, the default data or ranges specified in the model may be used.

3. Data

A set of brownfield (BF) and greenfield (GF) development sites were identified in Nagengast (2011) and further refined by Mashayekh (2012b). This set of developments is used to develop default values of development characteristics and impacts as well as a range of characteristics and impacts. Users of the spreadsheet are encouraged to add their own development characteristics or customize the spreadsheet by adding additional criteria.

Our development sample includes pairs of two relatively large (more than 100 dwelling units within each development) residential brownfield and two greenfield developments with similar characteristics and building dates (developments completed within the last twenty years) in Baltimore, Chicago, Minneapolis, and Pittsburgh.. In Tables 1 and 2, we show data on the distance to center city, development density and walkability (measured on a scale of zero to one hundred depending on the number of amenities within 1.6 km of the site (Hoehner 2005)). On average, brownfield developments are 6 times closer to the center city, have 5 times more households per acre and have double the walkability index compared with greenfield developments. Table 1 lists data on brownfields and Table 2 presents data on greenfields. Site selection was not controlled for biases. We do acknowledge that the socio-economic characteristics of many of the infill and/or brownfield developments' residents are different than the general population. While lack of data on demographics of the brownfield/greenfield developments' residents might be viewed as a caveat in this study, the travel models used and the data generated from these models had many of the behavioral factors incorporated in them.

In addition to the comparison between brownfield and actual greenfield developments, brownfields were also compared to fast growing metropolitan neighborhoods in Table 2. These alternative greenfield locations were identified based on the fastest growing (by population) census tracts from 2000 to 2009 in each metropolitan area. Table 2 shows that brownfield redevelopments are ten times closer to city centers and have much higher development densities and walkability indexes compared with the fastest growing areas. The fastest growing census tract in each metropolitan area was even more remote from the center city than the identified greenfield developments, reflecting the continuing sprawling development of these metropolitan areas.

Comparisons of development density and of long term impacts can be done on the basis of household impacts or per capita. In this paper, we summarize impacts on a per capita basis, but we provide average household size for those wishing to normalize on a per household basis. The average household size for brownfields is 2.4 people/households (Table 1), whereas greenfields have a household size of 2.6 people/household (Table 2) (Census 2010).

Metropolitan Area	Brownfield Distance to Center City (km)		Brownfield Development Density (Household/acre)		Brownfield Walkability Index	
	BF1	BF 2	BF 1	BF 2	BF 1	BF 2
Pittsburgh, PA	9	10	6	27	45	82
Baltimore, MD	5	2	14	18	78	94
Minneapolis, MN	4	1	6	58	66	92
Chicago, IL	8	14	11	11	75	78
Average	6.6		18.9		76.2	

Table 1: Distance to Center City, Development Density and Walkability in Brownfield Redevelopment Neighborhoods (Sources: Google Maps (2011) for Distance to Center City, Google Maps and Specific Information from Developers and Planning Organizations for Density and Hoehner 2005, for walkability).

Metropolitan Area	Greenfield Distance to City Center (km)			Greenfield Development Density (household/acre)			Greenfield Walkabilty Index		
	GF 1	GF 2	FG	GF 1	GF 2	FG	GF 1	GF 2	FG
Pittsburgh, PA	44	22	53	1	2	0.2	6	43	91
Baltimore, MD	29	38	56	3	2	0.1	43	55	26
Minneapolis, MN	29	14	54	3	11	0.2	74	65	0
Chicago, IL	56	39	93	0.6	3	0.2	29	57	0
Average	33.8			3.2			46.5		

Table 2: Distance to Center City, Development Density and Walkability in Greenfields and the Fastest Growing (FG) Census Tracts (Sources: Google Maps for Distance to Center City, Google Maps and Specific Information from Developers and Planning Organizations for Density and Hoehner 2005, for walkability).

Data on BF and GF development characteristics has been compiled from a variety of sources (Nagengast 2011, Mashayekh 2012b). Whenever possible, we obtained publicly available data in which the developments occurred, such as US Census data by tract and origin-destination trips by zone from regional planning agencies. Case study interviews with individuals knowledgeable about particular developments were also used to augment these public data sets. For some items, regional or national averages were used for characteristics such as construction costs, energy use and maintenance. Impact measures are calculated or come from published data, such as the Texas Transportation Institute congestion reports (TTI 2009) and the economic input-output life cycle assessment model (CMUGDI 2011).

3.1 Basic Information on Developments

Basic information is intended to provide general characteristics concerning different BF and GF developments (Table 3). Since impacts are estimated as averages per capita in this research, this basic information provides a means to scale up individual impact estimates to entire developments. In assessing a new proposed development, the sample range can indicate whether or not the new development conforms to our sample. Our sample (“Sample” column in Table 3) is consisted of sixteen BF and GF sites in four cities of Pittsburgh, Minneapolis, Baltimore and Chicago.

Characteristic	Default (Median) Value	Sample Range
Size (acres)	35	3-145
Distance to city center	6.4	1-14
Number of Households	325	59-900
Household Size	2.4	1-6
Development Density	21	5-66

Table 3: Basic Information for Residential Brownfield and Greenfield Developments Based upon the Sample of Brownfield and Greenfield Developments in four cities of Pittsburgh, Minneapolis, Baltimore and Chicago

3.2 Remediation

A typical brownfield development requires varying degrees of remediation and cleanup. Brownfield remediation costs vary depending upon:

- extent and type of contamination present;
- brownfield size; and,
- proposed end use and desired level of remediation.

Among the least expensive remediation processes is to cap the brownfield site with new soil and use bioremediation. Mashayekh (2012b) assembled a set of eight remediation cost estimates from literature. The range of estimates is more than an order of magnitude, from \$ 22,000/acre to \$ 580,000/acre, adjusted to 2010 dollars. Even within the city of Chicago, a range of \$ 25,000/acre. To \$530,000/acre is reported for remediation strategies (Chicago 2003).

In practice, the highest remediation costs can be avoided by not redeveloping sites with these high costs. Selecting lower cost remediation sites allows more land redevelopment for the same fixed budget. In the eight remediation studies assembled by Mashayekh (2012b), only three included remediation costs in excess of \$ 100,000/acre. Following Mashayekh (2012b), we use an average point estimate of \$190,000/acre, with a 90% range of \$ 24,000 to \$ 550,000/acre for remediation costs. These costs have been adjusted in Table 4 to reflect 2012 figures based on the Bureau of Labor Statistics inflation rates (BLS 2012).[1]

[1] The wide range of remediation cost illustrated in Table 4 results in a significant amount of uncertainty in the cost-benefit analysis of BF and GF developments. In other words, costs and cost savings associated with BF and GF developments are significantly sensitive to remediation cost of the developments. Therefore, it is important that those who wish to use the model presented in this paper and the associated spreadsheet, use remediation costs specific to their projects to conduct a more accurate comparison.

	Default (Median) Value	Range
$ per acre	237,000	30,000-685,000
mt[2] CO_2e per acre	605	76-1,750
$ per capita	10,970	1,390-31,710
mt CO_2e per capita	28	3.5-81

Table 4: Median and Ranges of Costs and Emissions for BF Site Remediation (Adjusted 2012 Costs)

The Economic-Input-Output Life Cycle Assessment (EIOLCA) tool (www.eiolca.net) was used to estimate greenhouse gas emissions based upon these remediation costs (Hendrickson 2005). The EIOLCA tool uses economic activity from US sectors to estimate energy and GHG emissions. Using the EIOLCA "other nonresidential construction" sector to represent remediation activity, $237,000 would represent roughly 605 mt CO_2 equivalent GHG emissions (CMUGDI 2011). Using the range of remediation costs illustrated in Table 4, 76 to 1,750 mt CO_2 equivalent GHG emissions is estimated. These values are based on the average impact per dollar amount assumed in the EIOLCA model and do not include any uncertainty within the EIOLCA model.

3.3 Building Construction

The costs and emissions from building construction can vary significantly among developments due to design decisions on the part of developers or other owners and the underlying costs of building components. Of course, the exact same buildings could be built on a brownfield and greenfield development. For example, a residential development in the Pittsburgh region (Peter's Township) is built partly on a brownfield and partly on greenfields; the two portions of the development have essentially the same types of buildings. In this analysis, we use identical default values for BF and GF construction in the spreadsheet calculation tool since the building construction decision is not inherent in brownfield characteristics, whereas remediation costs are. While default costs are the assumed to be the same, the main different between BF and GF developments within this context comes from the density of each development. In practice, our sample of brownfield and greenfield developments suggests that residences (and households) are smaller for brownfield developments and there is a higher proportion of multi-family housing.

Table 5 shows the average estimates of costs and emissions for developments. Costs are taken from RS Means (2012) while emissions come from the economic input-output life cycle assessment tool (CMUGDI 2012) using the "Residential permanent site single- and multi- family structures" sector. The average costs estimates were based on average construction quality for a 186 sq. meter, two story, detached single family home with an unfinished basement. Low costs were calculated from an economy construction of an interior 93 sq. meter, 2 story row house with no basement, while high costs were luxury construction of a two story, 334 sq. meter, detached single family home with a finished basement.

[2] mt: Metric ton

	Default (Average) Value	**Range**
Size (sq.m.)	186	93-334
Cost per unit area ($/sq.m.)	1130	1120-1600
Total Costs ($)	210,000	100,000- 540,000
Greenhouse Gas Emissions (mt CO_2e)	139	66-360
Cost per capita ($/person)	87,500	41,700-225,000
Emissions per capita (mt CO_2e/person)	58	28-150

Table 5: Default and Range of Building Construction Costs and Greenhouse Gas Emissions

3.4 Development Infrastructure

As with building construction, the costs and emissions associated with development infrastructure can be expected to vary considerably due to different component standards, terrain effects and scale economies. For this analysis, infrastructure includes local water distribution, sewage, storm water pipes and roadways. Private infrastructure for electricity and telecommunications could also be required. More generally, infrastructure costs might also include expansions to regional water treatment plants or roadway networks. Payments for utilities such as power and natural gas include the capital costs of providing these services and are estimated in Section 3.5.

The literature on development infrastructure tends to focus upon effects of different lot sizes and the financial implications of different densities (Speir 2002, Najafi 2006, Mohamed 2009). Our estimates of median and ranges of infrastructure costs are taken from Najafi et. al. (2006) in Table 6. They used a sample of sixteen residential developments in Michigan and estimated the required physical infrastructure investments. Najafi et al. used RS Means cost figures to convert physical infrastructure into cost estimates (as done above for building costs). Subsequently, they analyzed variations with density and fiscal implications, but we simply use their estimates of costs directly and convert them into GHG emissions (Table 6). The EIOLCA model was used to convert the GHG emissions impact of the infrastructure costs (CMUGDI 2011; Hendrickson 2005).

	Road	Sewer	Water	Total
Length (ft/lot)	56 (35-116)	63 (42-164)	60 (27-164)	N/A
Capital Cost ($/lot)	3,200 (2,000-6,700)	2,100 (1,400-5,600)	3,000 (1,400-8,400)	8,300 (4,800-20,700)
Greenhouse Gas Emissions (mt CO /lot)	5.7 (3.6-12)	3.7 (2.5-10)	5.3 (2.5-15)	14.7 (8.5-37)

Table 6: Typical Capital and Operating Costs for Residential Developments modified from Najafi et al. (2006) for 2012 dollars

3.5 Building Utility & Maintenance

Building utility consumption and costs partially stem from housing construction design decisions made by developers and owners as well as household technology, demographic and socio-economic factors. In theory, the same housing could be placed in either type of development once remediation was completed. However, as shown in Table 3, development densities are higher and average household size lower in our sample of brownfield developments, resulting in variations in utility expenditures.

Other research comparing urban to suburban developments have found differences in utilities. Kaza (2010) found a small savings in residential energy use with greater density except for a 25% reduction per household moving to multi-family (+5) apartments from single family detached housing. In a Toronto housing study of different development densities, Norman. (2006) found that low-density suburban development had significantly larger GHG emissions than high density, multi-family, multi-story (+5) apartment buildings. Of course, numerous other factors may influence GHG emissions, such as micro-climate variations, energy efficiency building features, income, appliances and heating, lighting, ventilation, and air conditioning choices (NRC 2010). However, the fraction of multi-family dwelling in a development is likely to be a systematic difference between developments.

Since utility expenditures for the select brownfield and greenfield locations were not available, two public datasets were analyzed instead. Both the Residential Energy Consumption Survey and Consumer Expenditure Survey (CES) list annual household utility information. For this research, the Consumer Expenditure Survey (CES 2009) data was used. This CES dataset was chosen because it was more current at the time the research was conducted also provided values for water costs and household maintenance. The CES separates urban respondent's data into "Central City" and "Other Urban." We assume the former is a proxy for brownfields and the latter for greenfields.

Examining the CES data, greenfield developments have higher utility and maintenance costs compared to brownfields. On average, greenfield households spent 16% more on utility bills (electricity, natural gas and water) and 25% more on household maintenance than residences in brownfields annually (Table 7). The total difference including utilities and maintenance between developments is 19% as seen in Table 7.

	Central City (Brownfield) Cost ($)	**Other Urban (Greenfield) Cost ($)**	**Percent Change from BF to GF (%)**
Electricity	1,249	1,555	20
Natural Gas	498	555	10
Water	486	533	9
Total Utilities	2,233	2,643	16
Maintenance	977	1306	25
Total Annual Housing Costs	3,210	3,949	19

Table 7: Average Annual Household Utility and Maintenance Expenditures adjusted to 2012 dollars ($/household/year) (CES 2009)

3.6 Residential Travel

Nagengast (2011) using 2000 decennial census data and Mashayekh (2012b) using travel demand models examined the effect of residential brownfield developments on travel activity and travel costs. Both studies concluded that residential brownfield developments result in significant reductions in vehicle kilometers traveled (VKT) as well as the reductions in consequential greenhouse gas emissions.

Focusing on commute trips with census data and using the EIOLCA model, Nagengast (2011) reports that brownfield developments analyzed in the study are nearer to downtown, have residents that use public transportation more frequently for commuting, have similar average travel times to work and lower energy and greenhouse gas emissions for commuting. On average, the greenfield development commuters consume one-third more energy annually. Similar results are found for GHG emissions from commuting trips compared with brownfield developments.

Utilizing air pollution valuation data and travel demand models for various counties, Mashayekh (2012b) reports an average 52% reduction in brownfield developments' VKT compared with greenfield developments. Also on average, brownfield developments result in a time and fuel cost reduction of 60% and an external environmental cost saving of 66%. These external environmental costs are based on public health effects of conventional air pollution emissions. Reductions of VKT and its consequential greenhouse gas emissions are mainly due to the close downtown location of brownfield developments and fewer trips taken by the residents of these developments.

In a study done in the City of Toronto, Canada by Norman et. al. (2006), annual greenhouse gas emissions associated with automotive transportation is reported as

5,180 kg CO_2 eq./person/year for low density developments and 1,420 kg CO_2 eq./person per year for very high density inner-city developments. Low density developments were single detached dwellings with 19 houses/hectare while high density had apartments with more than five stories at 150 units/hectare (Norman 2006). While these CO_2eq figures are higher than the average GHG shown in Table 8, the difference can partially be attributed to the household size (person/household) used in each of the studies. Household size in Norman (2006) was assumed to be 3 persons per household.

Key transportation metrics are quantified in Table 8 to better outline the commuting variations between developments. One metric is the number of annual home-based work trips by automobile. The difference between BF and GF types of developments is 71 vehicle trips. One possible reason for the reduction of automobile trips is the use of public transit for brownfield commuters. Nagengast (2011) identified that 18% of brownfield residents use public transit. Using the same modal share percentage and allocated to the 71 vehicle trips, results in about 11 trips per person annually transferred to mass transit systems. The impact on the annual environment costs resulted from public transit usage will be insignificant.

Transportation Metric	Type of	BF	GF
Average Annual VKT (km/person/year)	HBW	1,007	2,484
	HBNW	1,840	2,979
Average Distance (km/trip)	HBW	11	18
	HBNW	7	10
Average Annual # of Trips (#/person/year)	HBW	94	165
	HBNW	269	304
Average Annual Cost of Time ($/person/year)	All Types	658	1,269
Average Annual Cost of Fuel ($/person/year)	All Types	179	346
Average GHG Emissions for Travel (kg/person/year) CO2	All Types	337	648
Average Annual Environmental Costs ($/person)	All Types	114	329

Table 8: Summary comparison of travel measures between brownfields and Greenfields (HBW: home based work, HBNW: home based non-work); Source: Mashayekh (2012b) (All costs are adjusted to 2012 costs)

3.7 Summary of Default Value Results

Table 9 shows an annual summary of the assumed default values for typical brownfield and greenfield residential developments which is used in the comparison spreadsheet. These default values represent the average within a range of values described in the above sections. In these summaries, capital costs for remediation and construction are converted into annual amounts assuming a 30 year planning horizon and a 5% discount factor. Remediation GHG emissions are simply divided equally among the thirty years. Remediation costs are assumed to be $ 237,000/acre with 12 households per acre and 2.4 individuals per household, all Mashayekh (2012b) rates adjusted to 2012 rates. Building energy savings are based on the 5% estimate developed above. Travel costs, costs of time and emissions come from Table 8.

While brownfield developments have costs for remediation and housing construction per capita, their inner city location results in savings in travel costs. Brownfield and greenfield sites can be compared using the 'impact comparison' columns in Table 9. These impact comparison columns are calculated by subtracting brownfield values from greenfield values. Therefore, a positive number indicates a lower cost or GHG value for brownfields compared with greenfields. A negative number indicates greenfields have lower cost or GHG value than brownfields. . Overall, the brownfield development is estimated to have 1% lower annual costs ($152/year), but 5% higher greenhouse gas emissions ($1,195 kg$CO_{2e}$ per person) compared to greenfield developments (Table 9). Greenhouse gas emissions have similar findings. Of course, these results are subject to considerable variation, especially with regard to building and remediation design decisions.

Categories	Brownfield Developments[1]		Greenfield Developments[2]		Impact Comparison[3]	
	Cost	GHG Emissions	Cost	GHG Emissions	Cost	GHG Emissions
	$/person/year	$kgCO_2e$/person/year	$/person/year	$kgCO_2e$/person/year	$/person/year	$kgCO_2e$/person/year
Remediation	692	1,766	0	0	-692	-1,766
Construction					0	0
Infrastructure	67	44	289	122	209	229
Housing	5,692	3,984	5,254	3,678	-438	-289
Building Utility	930	4,040	1,017	4,463	86	423
Electricity	520	2,594	598	2,981	78	387
Natural Gas	208	1,086	213	1,118	5	32
Water	203	360	205	365	2	5
Maintenance	407	285	502	352	95	66
Residential Travel – Fuel	179	337	346	648	167	311
Residential Travel - External Environmental Cost	114	--	329	--	215	--
Travel Time	658	--	1,269	--	611	--
Total	8,740	10,229	8,891	9,262	152	-1,195

[1] ***same Table IV as found on "Tab 2: Brownfield Impact" in the spreadsheet downloadable at*** http://www.cmu.edu/steinbrenner/brownfields/index.html.

[2] ***same Table IV as found on "Tab 3: Greenfield Impact" in the spreadsheet downloadable at*** http://www.cmu.edu/steinbrenner/brownfields/index.html.

[3] ***Differences in cost and GHG emissions between greenfield and brownfield developments. A positive number indicates a lower cost or GHG value for brownfields compared with greenfields. A negative number indicates greenfields have lower cost or GHG values than brownfields.***

Table 9: Summary of average cost and greenhouse gas emission by impact category between brownfield and greenfield developments.

4. Scenario Analysis

To illustrate the range of outcomes possible, Table 10 below shows the comparison of best and worst development scenarios. The best development scenario refers to the lower bound value in a specific category while the worst scenario refers to the higher bound. Within our estimated data ranges, it is possible to have brownfield developments, which have higher costs and emissions per capita than greenfield developments. Having brownfield developments with lower costs and emissions is also both possible and more likely based upon our default values.

Results of this section show that in the worst case scenario brownfield developments not only do not save but costs in extra annual $9,259 per person and extra annual $100,160 kg$CO_2$e of GHG emissions per person. In the best case scenario, brownfield developments generate $9,509 per person per year, which translates to $37,392 Kg$CO_2$e of GHG per person per year.

Category	**Brownfield Best Scenario Minus Greenfield Worst Scenario**		**Brownfield Worst Scenario Minus Greenfield Best Scenario**	
	Cost ($/person/year)	**GHG (kgCO_2e/person/year)**	**Cost ($/person/year)**	**GHG (kgCO_2e/person/year)**
Remediation	-174	-444	-2,026	-5,171
Utilities	5,924	100,227	-6,418	-32,599
Maintenance	95	67	95	67
Travel Fuel Cost	306	311	-41	311
Travel External Cost	845		-360	
Travel Time Cost	2,262		-759	
Total	9,259	100,160	-9,509	-37,392

Table 10: Comparison of Best and Worst Scenarios for Brownfield and Greenfield Developments for Data Ranges

5. Conclusions

Overall, we conclude that brownfield developments are more likely to have slightly lower costs and emissions per resident than comparable greenfield developments based on average values presented in this research. Despite incurring significant remediation costs, brownfields tend to be closer to center cities than greenfields which results in lower overall travel costs per resident.

Our estimates presented in this paper and in the supplemental spreadsheet, are subject to considerable variability among developments in terms of costs and GHG emissions. Regarding life cycle costs, the largest categories in our default expenditures are housing construction, building utilities and travel time. Building design decisions could significantly influence the overall life cycle costs. For cost savings, the factors with greatest sensitivity are the value of travel time, the cost of remediation and the external environmental costs of pollution emissions. In terms of

GHG emissions, the largest differences between brownfield and greenfield estimates are travel fuel combustion emissions, building utility emissions, and building construction emissions. The final estimates are sensitive to the assumed amounts of remediation, travel, utility use and construction estimates.

Design decisions with respect to building construction, location, building utilities and development density can significantly influence the overall costs and impacts of both brownfield and greenfield developments. If these factors are not carefully considered, remediation cost of brownfield developments could offset savings from housing or travel. Design decisions with respect to buildings or infrastructure could make brownfield developments more expensive than greenfields. For example, targeting high income development could lead to more expensive buildings and more concentrated travel in brownfields. Therefore, we encourage the use of site-specific data in making comparisons between brownfield and greenfield developments. We realize that cost may not be the only deciding factor between different development types, however the spreadsheet tool is useful as a site selection tool and to decide on the type of the development.

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EVALUATING THE PROGRESS OF CLIMATE CHANGE ADAPTATION PRACTICES ACROSS TRANSPORTATION PLANNING AGENCIES: A CASE STUDY ON THE MID-ATLANTIC

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ABSTRACT

In order to prepare and protect societies, economies, and the environment from the potential impacts of climate change, adaptation is required. Specifically, transportation organizations throughout the country including state Department of Transportation agencies and Metropolitan Planning Organizations (MPOs) should not only be reducing climate change impacts through mitigation but also supporting adaptation practices. This paper evaluates agencies' behavior in terms of their integration of adaptation practices with the transportation planning process. Eighteen MPOs within the Mid-Atlantic region are surveyed based on a series of questions to assess the agency's progress in adaptation such as vulnerability assessments, infrastructure design/construction, as well as practices that support mitigation. The results are used to compare progress across jurisdictions as well as identify areas for improvement. By providing guidance and methods for integrating adaptation practices, agencies can begin to protect and prepare transportation networks and facilities for the potential impacts of climate change.

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INTRODUCTION

As scientific evidence on climate change continues to support the relationship between anthropogenic activities and global warming, greenhouse gas concentrations continue to rise. While mitigation efforts are essential to slowing the threat of climate change, adaptation practices to build resilience and protection from impacts should be accelerated (Pew Center on Global Climate Change, 2009). In order to prepare and protect societies, economies, and the environment, adaptation is required.

Specifically, transportation organizations throughout the United States including state Department of Transportation (DOT) agencies and Metropolitan Planning Organizations (MPOs) need to alter their existing planning, design, and construction methods with regards to avoiding potential climate change impact. In order to begin integrating adaptation into the transportation planning process, tools are needed. One such tool is the Climate Change Adaptation Tool for Transportation (CCATT) (Oswald et al., 2012). Methods within CCATT encourage agencies to evaluate their level of progress toward implementing specific adaptation activities including those that support mitigation. For example, agencies can support the implementation of renewable energy based infrastructure (adaptation) in order to support alternative fuel vehicles (mitigation). This paper evaluates agencies' behavior in terms of their integration of adaptation practices within the transportation planning process.

Objectives

The objective is to provide data for which agencies can benchmark adaptation and mitigation activities, or track progress over time. Eighteen Mid-Atlantic MPOs are surveyed. The surveys use a series of questions to assess the agency's progress toward implementing adaptation practices such as vulnerability assessments, infrastructure design/construction, as well as practices that support mitigation. In addition to identifying their level of progress, the agencies are asked to assess the importance placed on implementing adaptation activities based on the following categories: (1) Infrastructure Service Changes and Improvements, (2) Data and Information, (3) Planning and Evaluation, and (4) Coordination and Cooperation. The results are used to compare progress across jurisdictions as well as identify areas for improvement. Ideally, by providing guidance and methods for integrating adaptation practices, agencies will be encouraged to protect and prepare their jurisdiction for the potential impacts of climate change.

Research Methodology

To assess current progress of adaptation practices in a consistent fashion throughout transportation agencies, the following methodology is used:

1. Review literature on regional climate change impacts, adaptation practices, and existing efforts.
2. Develop survey and distribute to participating MPOs throughout a geographical region (the Mid-Atlantic).
3. Analyze survey results based on key trends and identify specific areas of improvement.

4. Draw conclusions as well as make recommendations for how this can be applied to other regions throughout the country.

This methodology is based on an original pilot study which focuses on five MPOs in order to determine the applicability of the survey. Details regarding the pilot study are available in Oswald and McNeil (in press). The pilot study demonstrated that the survey mechanism was applicable and relevant to the region, and then the survey was then applied to the entire Mid-Atlantic region.

BACKGROUND

Scientific data suggests that current mitigation efforts such as setting emission limits will not be timely enough to avoid all potential impacts associated with climate change (Pew Center on Global Climate Change, 2009). Climate change impacts such as variability in temperature, precipitation, and sea level rise could lead to significant impacts on transportation facilities and systems (FHWA, 2011). In order to protect and prepare society, adaptation, or "adjustment of natural or human systems in response to past, current, or anticipated climate impacts" is necessary (IPCC, 2007).

The adaptation needs required to address climate change impacts, similar to climate change phenomena, are not homogeneous throughout societies, organizations, systems or regions. There are many factors that influence climate change impacts including geography, economy, social norms, and political structures. Therefore, understanding the impacts including temperature variability, precipitation variability, sea level rise, and increases in extreme weather events, specific to each region, is essential. These regions include the Northeast and the Mid-Atlantic, Pacific Northwest, Southeast, Midwest, West, Great Plains, and Alaska and the US Affiliated Islands (CIER, 2007). Identifying the adaptation needs of the Northeast and Mid-Atlantic is different than the West and therefore, comparing agencies within each region is ideal.

Infrastructure Adaptation

The impacts associated with climate change can have a direct effect on transportation infrastructure. Variations in temperature and precipitation can lead to coastal flooding, heat waves, land inundation, and loss of wetlands. These impacts can pose threat to transportation infrastructure through erosion of road beds, inundated roadways and transit networks, loss of emergency evacuation routes, loss of sediment around bridge abutments and piers as well as reduced bridge clearance (WILMAPCO, 2011). As a result, planners and engineers can integrate adaptation into the transportation planning process in order to protect existing as well as proposed facilities from climate change impacts. Recognized infrastructure adaptation practices include the following (WILMAPCO, 2011):

- Elevating facilities
- Relocating road sections and rail inland
- Restricting development within coastal areas
- Constructing seawalls, levees or dikes
- Using eco-engineering (natural ecosystems) through forests and wetlands to reduce flooding and erosion

In addition, adaptation practices can support mitigation through specific land use strategies. For example, adapting the existing layout or land use structure of a community can then reduce the need for vehicular travel and can promote pedestrian, cycling and transit mobility. In addition, adapting existing refueling stations to include alternative fuel options, can then promote the use of alternative fuel vehicles and ultimately reduce greenhouse gas emissions. Identifying vulnerabilities and then implementing adaptation strategies to improve the network can reduce potential impacts as a result of climate change.

Agency Adaptation

In addition to infrastructure adaptation, agency adaptation is also necessary and can enhance and facilitate the ability to implement infrastructure-based practices. Agencies many times face both real and perceived barriers associated with addressing climate change phenomena. Real barriers can include a lack of available resources, cultural rigidity, short term planning horizon, limited budget, and a lack of supportive policies. Perceived barriers include belief that there is no critical risk, a lack of examples or models, and the mismatch between planning horizons and climate projections (UK Climate Impacts Programme, 2009). In 2008, only eight states were directly addressing adaptation (Pew Center on Global Climate Change, 2008). As of 2012, 24 states have either completed an adaptation plan or are in progress (C2ES, 2012). In comparison, 32 states have addressed mitigation through the completion of a Climate Action Plan (U.S. EPA, 2012). Therefore, over the last few years an effort to integrate both mitigation and adaptation into the planning process has emerged as agencies are trying to overcome the barriers to adaptation.

Current Efforts

Transportation adaptation planning has developed over the last few years and specific tools, models and frameworks are being established in order to assist agencies in the process. An Adaptive Systems Management approach was developed by Meyer et al. (2010) and a Risk Assessment Model was created and used in pilot studies overseen by the Federal Highway Administration (FHWA, 2010). The model includes three steps: (1) develop inventory of assets, (2) gather climate information, and (3) assess the risk to assets and the system as a whole based on climate change projections. In addition, Oswald et al., (2012) developed a Climate Change Adaptation tool for Transportation, a tool that assists agencies in inventorying vulnerable infrastructure.

In addition to the development of models and tools, practical applications and regional studies are in progress. For example, The Gulf Coast Study (U.S. DOT, 2011) was completed focusing on the process of identifying regional climate change impacts and developing risk assessment tools for use by transportation planners. A similar study was implemented in Florida where the DOT funded the development of a method to determine vulnerabilities specific to sea level rise on their infrastructure network (Berry, 2012). In terms of adaptation to support mitigation, MPOs in California are addressing land use and transportation strategies through pedestrian and cycling programs, parking management, transit programs, and shared ride initiatives (Deakin, 2011). At the national level, both the FHWA (2012) and Federal Transit Administration (FTA, 2011) are implementing pilot projects where specific agencies aim to identify vulnerabilities through methods that can then be used as examples for future adaptation programs throughout the country.

These current efforts serve as motivation and examples for how agencies throughout the country can begin to adapt. Since the typical long range transportation planning timeframe is every four years, short term plans to implement adaptation efforts are required. However, within a four year timeframe, adjustments and revisions in the climate change projections occur as well as network changes. Therefore, adaptation planning is iterative however; evaluating the existing state of the practice can help identify current progress. Walker et al. (2011) completed a study that evaluated the state of the practice of transportation adaptation planning in the Pacific Northwest and Alaska. Similarly, this study focuses on the Mid-Atlantic and specifically MPO efforts to integrate climate change adaptation practices into their long range transportation planning process.

SURVEY METHOD

In order to assess the current efforts of MPOs within the Mid-Atlantic region, the regional impacts associated with this area were identified. There are three potential climate change impacts for the Mid-Atlantic region: increases in very hot days and heat waves, rising sea levels, and an increase in intense precipitation events (CIER, 2007). Therefore, by surveying MPOs within the same region, comparisons can be made in reference to these three impact areas.

All MPOs within the Mid-Atlantic were included in the “Request to participate” and eighteen responded favorably. Therefore, this survey targets eighteen jurisdictions as a sample of the Mid-Atlantic region MPOs. Although this study focuses on just the Mid-Atlantic, a similar study can be applied to agencies throughout other regions.

The survey was created electronically using Google Forms (Google, 2013). This survey tool was selected because it provides an easy way to access the information in “real time” where submissions are updated automatically on a user spreadsheet. The survey link was distributed via email and the respondents asked to complete the survey within two weeks. Participants were asked to represent the views/actions of their agency, rather than their personal views. For some MPOs, a group of employees completed the survey in order to increase the accuracy of their responses. The survey includes six sections as follows:

1. Background Information
2. Addressing Adaptive Capacity
3. Category #1- Infrastructure Service Changes and Improvements
4. Category #2- Data and Information
5. Category #3- Planning and Evaluation
6. Category #4-Coordination and Cooperation

Similar to the pilot study (Oswald and McNeil, in press), section 1, Background Information, includes questions regarding agency name, jurisdiction, and planning time horizon. Section 2, Addressing Adaptive Capacity, includes a list of barriers from the UK Climate Impacts Programme (2009) for respondents to identify those that pertain to their agency. For Sections 3-6, 39 adaptation practices (based on the four categories) are listed and the agency was asked their progress with regards to that practice. Table 1 shows the list of 39 practices based on the four categories.

For evaluating the agency's degree of progress, the following scale was used on the survey: (1) No Knowledge, (2) Awareness, (3) Actively Exploring, (4) Integrated into Existing Plans, and (5) Supporting Implementation. If an agency selected the last three options, "Actively Exploring", "Integrate into Existing Plans" or "Supporting Implementation," they were asked to provide examples or a description of how they are supporting that practice. For each practice, a short description of the components and activities related to that practice was provided as supplementary text to the question in order to provide context/examples for the agency if they are unfamiliar with the practice. The list of adaptation practices, as well as those in support of mitigation, were drawn from the following two sources: *TRB Special Report 290* (TRB Committee on Climate Change and Transportation, 2008) and the *Transportation's Role in Reducing Greenhouse Gas Emissions* (U.S. DOT, 2010).

In addition to the individual practices and progress level, the agencies were asked to compare each of the four categories based on their importance and priority with respect to responding to climate change. Responses were based on the following scale: (1) No Importance, (2) Slight Importance, (3) Moderate Importance, (4) Strong Importance, and (5) Extreme Importance. These responses were based on the practices that were defined for each of the categories; however, much of the interpretation of these categories is based on the existing progress of the agency within each category.

The final question on the survey, "Additional Practices" was an open-ended question that encourages the agency to provide any other adaptation practices they are currently implementing that may not be in the survey. This allows for the recognition that the survey is flexible and iterative since agencies may have innovative or location-specific practices that are not included in the survey.

Table 1. List of Adaptation Practices by Category

Category	#	Practice
#1- Infrastructure, Service Changes and Improvements	1	Alternative Fuel Infrastructure
	2	Fuel Efficient Vehicles Usage
	3	Alternative Energy and Energy Efficiency
	4	Urban Revitalization
	5	HOV Lanes
	6	Toll Facilities
	7	ITS Programs
	8	Park and Ride Locations
	9	Transit Stops
	10	Bicycle and Pedestrian Facilities
	11	Regional Transit Network
#2- Data and Information	12	Vehicle Miles Traveled
	13	Real-Time Traffic Information
	14	Congestion Index
#3-Planning and Evaluation	15	Congestion Management
	16	Travel Demand Modeling
	17	Peak Hour Congestion Pricing
	18	Vehicle Miles Traveled Fees

	19	Enhanced Urban Community Centers
	20 21	Rural Areas and Floodplains Intracounty Transit Ridership
	22	Regional Rail Ridership
	23	School Pedestrian Facilities
	24	Bus Rapid Transit Systems
	25	Walkable Community Plans
	26	Complete Streets
	27	Modal Shifts
	28	Sea Level Rise Analysis
	29	Storm Surge Analysis
#4-Coordination and Cooperation	30	Compact Development
	31	Telecommuting
	32	HOV Parking
	33	Employer Provided Transport
	34	Bicycle Accommodation
	35	Compressed Work Hours
	36	Parking Pricing Strategies
	37	Rideshare Programs
	38	Urban Growth
	39	Park and Ride Facilities

SURVEY RESULTS

Once the surveys were submitted, data analysis was completed. Information was tabulated for each question and displayed graphically based on categories. Specific similarities in barriers and constraints across agencies were identified through both "yes/no" as well as open-ended response questions. For each agency, specific characteristics such as population size were taken into account when comparing level of progress. Figure 1 displays the results of the adaptive capacity question which identifies specific agency barriers. The y-axis indicates the number of agencies (out of 18) that believe the barrier exists within their agency.

As shown, the limited budget, lack of available resources and lack of supportive policies and standards were present for over 50% of the total agencies surveyed. These are primary areas where effort can be made to alleviate these barriers which are preventing agencies from adapting.

The remainder of the survey included questions specific to each of the four categories of adaptation practices: Infrastructure Service Changes and Improvements, Data Information, Planning and Evaluation, and Coordination and Cooperation. For each category, specific adaptation/mitigation practices pertaining to that topic are listed and the agency records their level of progress as well as identifies specific examples of how they implement that practice. Figure 2 shows an example of the level of progress for Category #2 (Data and Information) using a stacked bar graph which represents the combined "level of progress" for practices 12, 13 and 14 (based on Table 1). Based on the scale of 1 being "No Knowledge" and 5 representing "Supporting Implementation" there is a minimum of 3 points for each agency (1 point for all 3 practices) and a maximum of 15 points (5 points for all 3 practices).

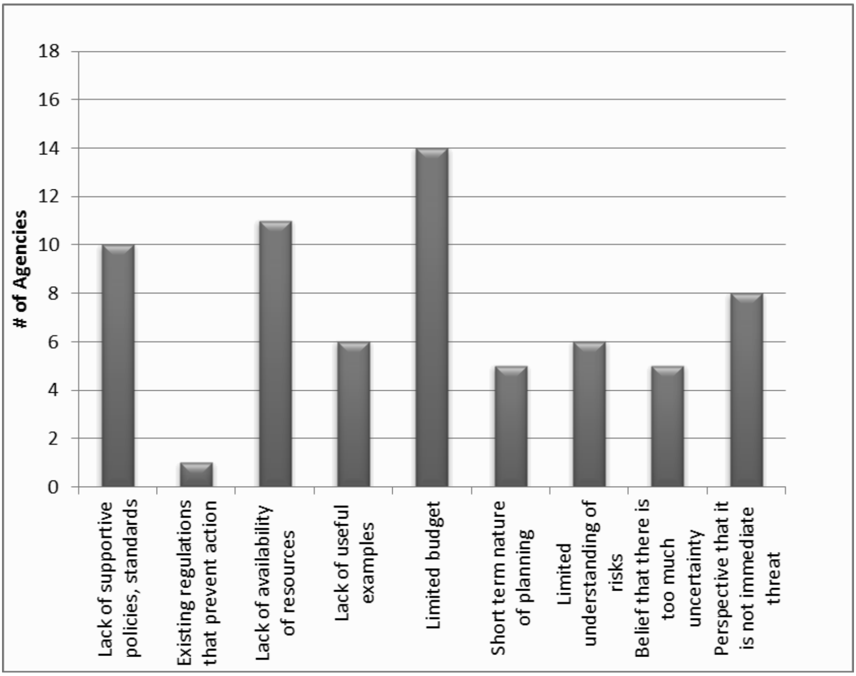

Figure 1. Barriers Preventing Agencies from Adaptation

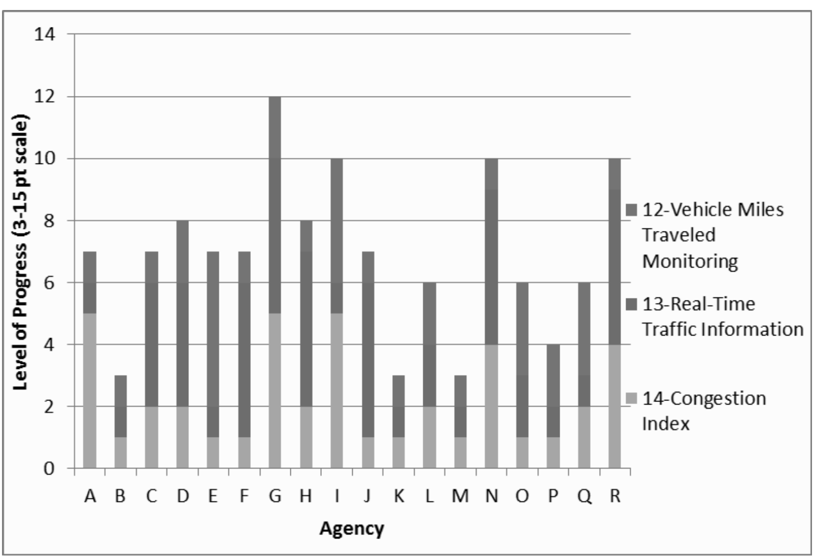

Figure 2. Category #2 (Data and Information) Level of Progress (Practices #12-14)

For this category, it is clear that at least four agencies (Agencies G, I, N and R) have made significant progress (10 points or more out of 15) across the three practices. Also, it can be concluded that real time traffic information is the most supported practice based on these 18 MPOs. In order to identify specific agency progress levels for the other three categories, a similar comparison was completed for all 39 practices.

In addition, identifying trends across specific practices is valuable as it provides insight into which practices are currently being emphasized across jurisdictions. Box and whisker plots are used to show the range in level of progress across all 18 MPOs as well as the average and median results for each individual practice (Figures 3-6). The plots indicate the 1st quartile (25% of the values are less than this point) and the 3rd quartile (75% of the values are less than this point) as well as the median (middle bar) and the average (end point of dotted line which represents the difference between the median the average). The maximum and minimum values identified across all agencies are indicated by the solid error bars above and below the quartile range.

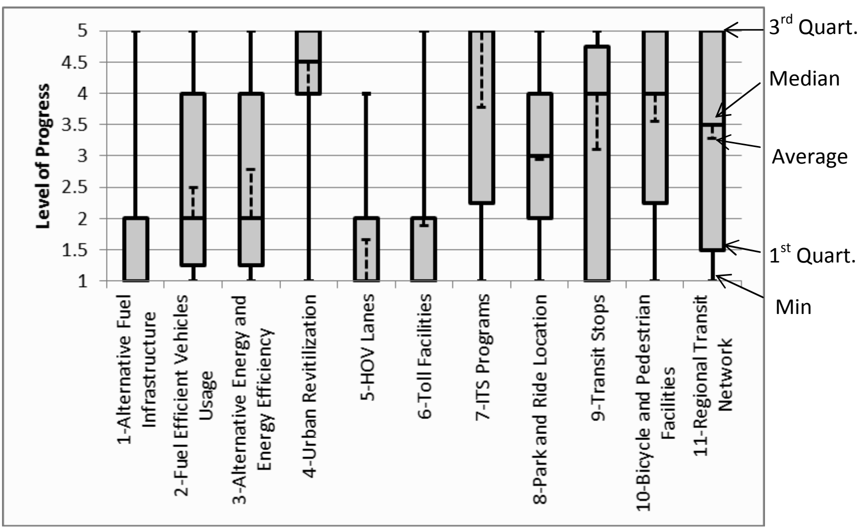

Figure 3. Level of Progress Results for Practices in Category #1 (Infrastructure, Service Changes, and Improvements)

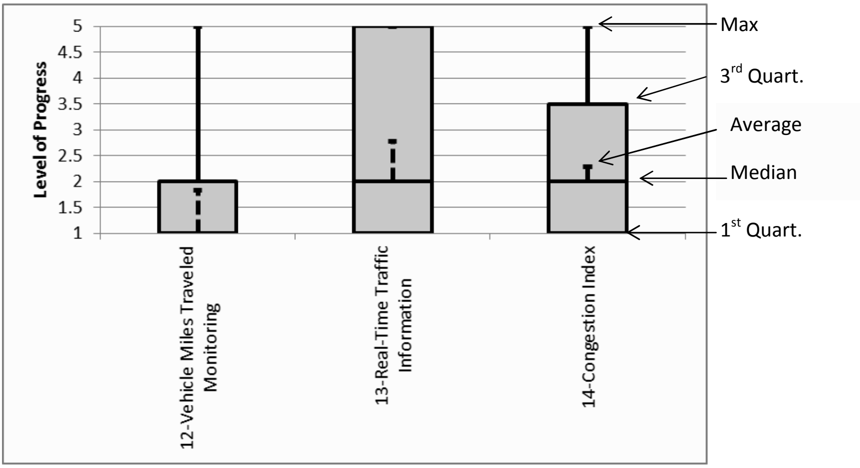

Figure 4. Level of Progress Results for Practices in Category #2 (Data and Information)

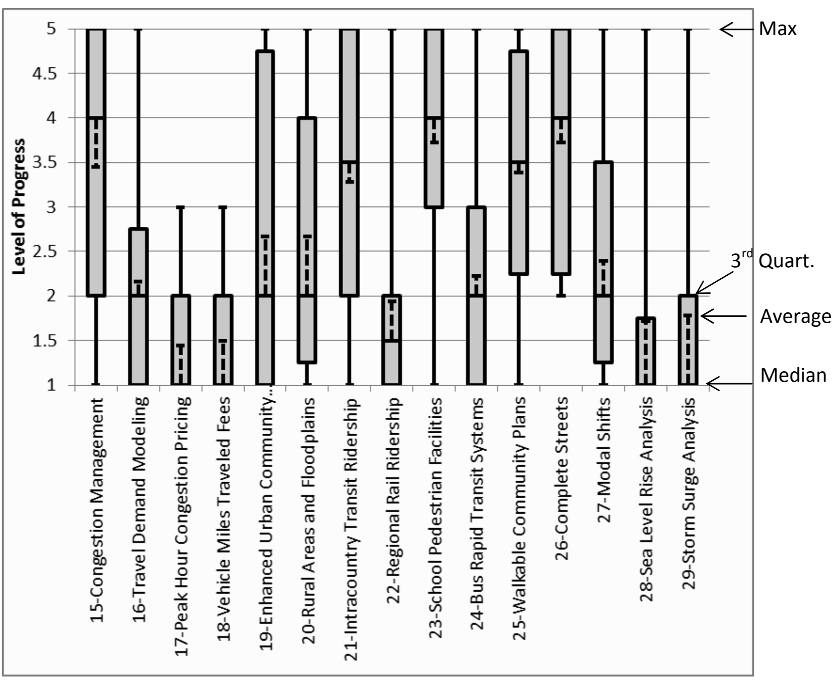

Figure 5. Level of Progress Results for Practices in Category #3 (Planning and Evaluation)

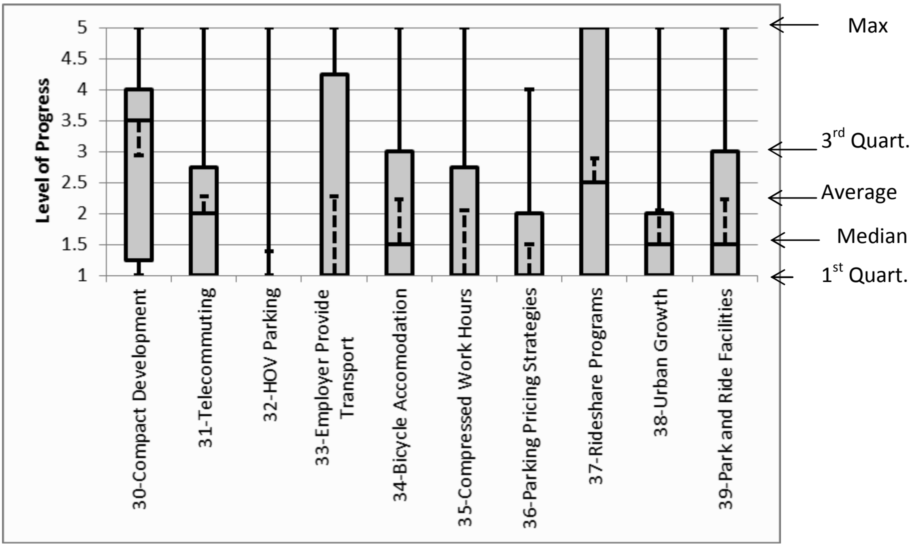

Figure 6. Level of Progress Results for Practices in Category #4 (Coordination and Cooperation)

As shown in Figures 3-6, there is a range in the level of adaptation progress by the 18 MPOs surveyed. In addition, the types of practice, indicating the level of importance of specific adaptation actions, vary throughout. Figure 3 suggests that urban revitalization, ITS programs, and bike/pedestrian facilities are being implemented and are in progress across a majority of the agencies surveyed while HOV lanes is one of the less progressive actions. Figure 4 confirms the conclusions made previously, using Figure 2, that real time traffic information is the most supported data and information-related action being implemented across the agencies. Figure 5 displays the practices related to planning and evaluation which shows that land use/infrastructure related adaptation practices are in progress. Specifically, complete streets, congestion management, walkable community plans, and school pedestrian facilities are a priority. And Figure 6 shows that, in general, less effort is being placed toward coordination and cooperation efforts as all practices within this category have an average level of progress value of 3 (“actively exploring”) or less.

In addition to the level of progress, the agencies ranked the four categories based on their “level of importance” to show which practices they felt were of high priority and goals that the agency will undertake within the next few years. The level of importance was indicated based on the following scale: (1) No Importance, (2) Slight Importance, (3) Moderate Importance, (4) Strong Importance, and (5) Extreme Importance. Based on this scale, the minimum value for an agency is a 4 (1 point for all 4 categories) and the maximum value is a 20 (5 points for all 4 categories). Figure 7 provides the results of the level of importance comparison between adaptation categories based on the individual agency. Figure 8 provides a box and whisker plot (mean, median, 1st and 3rd quartile, maximum and minimum values) of the category importance across all 18 agencies for each of the four categories.

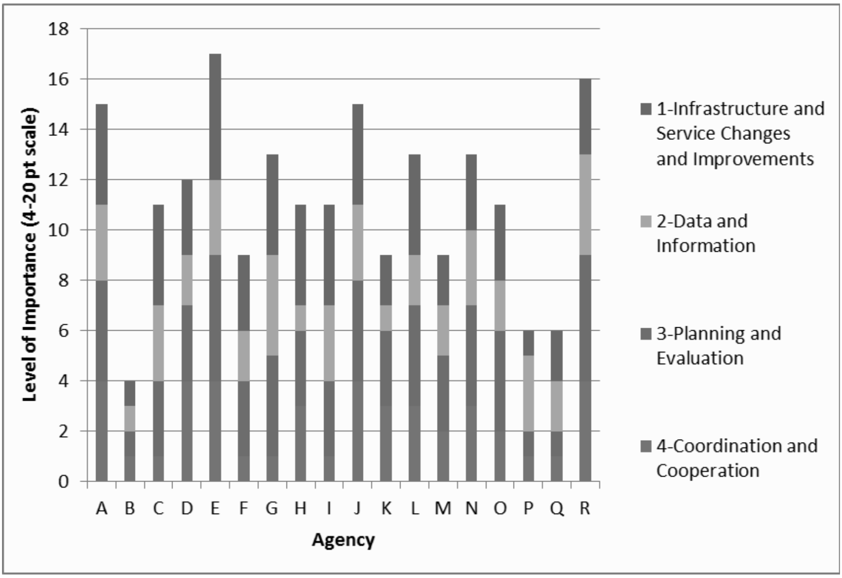

Figure 7. Category Comparison by Agency

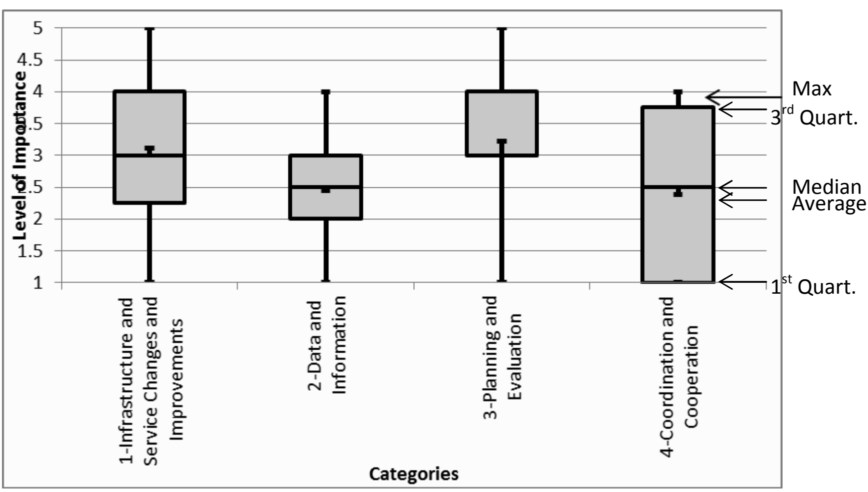

Figure 8. Box Plot of the Level of Importance for Each Category

Based on these results, the two categories found to be the most important and of highest priority (based on average values) are Category #1- infrastructure and service changes and improvements and Category #3-planning and evaluation. This suggests that the actions within these two categories currently provide the most opportunity and benefit toward adaptation within the Mid-Atlantic region. Although data and information as well as coordination and cooperation are essential, perhaps actual change to the infrastructure and planning within the local network is more valuable and realistic from an MPO perspective.

CONCLUSION AND RECOMMENDATIONS

Transportation organizations throughout the country including state Department of Transportation agencies and Metropolitan Planning Organizations (MPOs) should not only be reducing climate change impacts through mitigation but also equally supporting adaptation practices. The adaptation needs required to address climate change impacts, similar to climate change phenomena, are not homogeneous throughout societies, organizations, systems or regions. There are many factors that influence climate change impacts including geography, economy, social norms, and political structures. Therefore, understanding the impacts including temperature variability, precipitation variability, sea level rise, and increases in extreme weather events, specific to each region, is essential.

The survey results found in this study provide insight into the initial efforts toward adaptation planning within transportation agencies in the Mid-Atlantic. The typical barriers of budget and regulatory restrictions continue to pose constraints on the process however, local planning objectives such as walkability, congestion relief, transit access, and compact development are being implemented and serve as adaptation methods to support mitigation. More recently, the pilot programs sponsored by the FTA and FHWA have increased the application of vulnerability assessments. Efforts such as these serve as examples for how agencies can directly determine vulnerable infrastructure in order to protect and prepare infrastructure for future impacts.

Methods learned through these studies and through future adaptation planning initiatives should be shared to increase support and maintain consistency throughout regional agencies. Tools and resources such as the National Research Council (2010) report "Adapting to the Impacts of Climate Change," as well as tools such as Oswald et al., (2012) Climate Change Adaptation Tool for Transportation, and Interactive Storm Surge Maps (NOAA and National Weather Service, 2010) can aid in promoting adaptation planning practices throughout agencies.

A similar state of the practice study is recommended for regions throughout the nation. Agencies within other regions should be served and compared based on their regional climate change impacts. Future work includes expanding the survey and applying it to the other climate change regional areas.

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A Review of Sustainability Rating Systems for Transportation and Neighborhood-Level Developments

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ABSTRACT

Over the past 10 years, there has been a proliferation of methodologies and tools for rating the sustainability of transportation-related projects both in the United States and internationally. These tools provide the ability to evaluate the sustainability of alternative transportation and land development policies, plans and projects. The tools therefore facilitate the process of making transportation and land development decisions that contribute to community sustainability in practice. This study reviews and assesses approaches to rating the sustainability of transportation systems and neighborhood developments by highlighting the state of the practice, outlining similarities and differences in the existing approaches; and determining which tools are more appropriate for various contexts and when it is valuable to combine different tools. The study also identifies opportunities for improving the existing practice.

INTRODUCTION

Over the past 10 years, various methodologies and tools have been created to quantify, compare and rate the sustainability of transportation-related projects both in the United States and internationally. The first systems gained recognition towards the end of the last decade. These tools have been used by some transportation agencies to evaluate the sustainability of transportation and land development policies, plans, and projects. This paper provides a comprehensive review of systems used to rate the sustainability of transportation and neighborhood-level development improvements. It highlights the state of the practice, outlines similarities and differences in the existing approaches and identifies which tools are more appropriate for various contexts and when it is valuable to combine some of them. The study also identifies opportunities for improving the existing practice.

METHODOLOGY

An extensive search was conducted to identify tools used to rate the sustainability of transportation and neighborhood-level developments. Each of the systems identified was researched to determine how the system was developed and is used. Additionally, a literature review on sustainability rating systems was completed to gauge the state of practice. Based on the review of the systems, a comparison table was developed to determine the similarities and differences between the systems.

A set of questions guided the research of each system. These questions are found in Figure 1. In addition, examples of implementation were identified. The information collected was organized in a comparison table. A second comparison table was developed specifically for the rating criteria used in each system.

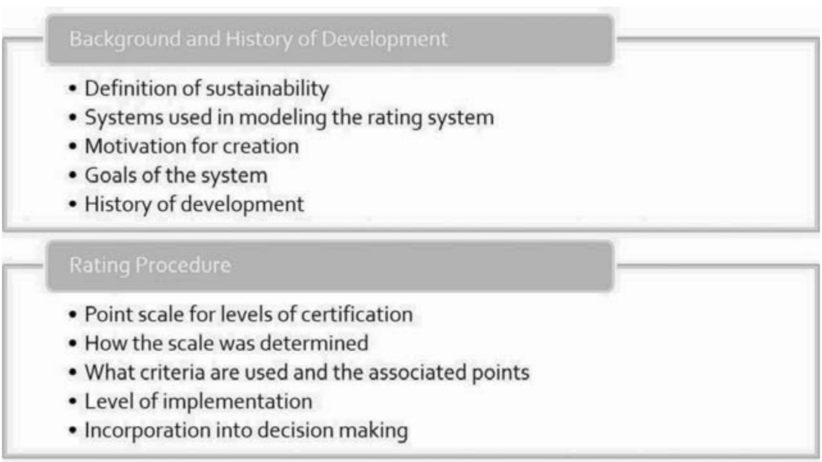

Figure 1: Guiding concepts for review of rating system

RESULTS

Table 1 shows a comprehensive listing of the most prevalent and developed rating systems and a brief description of each of them distilled from the first comparison table.

Table 1: Summary of Transportation System and Neighborhood-Level Development Sustainability Rating System

Year	Rating System	Description	Application
Transportation Systems			
2007	**Greenroads** Developed by the University of Washington and CH2MHILL.	Third-party rating system used across the country and abroad. Roadway design and construction projects that meet a set of required criteria are then scored on their sustainable attributes that surpass current standards.	Roadway design and construction
2008	**GreenLITES** Developed by NYSDOT and modeled on USGBC LEED and Greenroads.	Self-certification program used to integrate NYSDOT sustainability principles into choices for all projects and practices. Scoring is based on a set of criteria and certification levels are determined based on the	All projects and practices at the DOT level
2008	**STARS** Developed by the North American Sustainable Transportation Council based on LEED and Living Building Challenge.	Performance-based system with an emphasis on planning and development. The pilot scoring system evaluates the full life cycle of transportation projects using both required and additional credits.	Planning transportation projects and programming
2009	**Saga Sustainability Database** Developed by the Sustainable Aviation Guidance Alliance.	Comprehensive and searchable catelog of sustainability practices used by airports in an Excel and web database.	Airports
2010	**BE^{2}ST-in-Highways** Developed in part by the University of Wisconsin-Madison.	Software-supported methodology to quantify benefits of sustainable highway construction. Evaluates and rates life cycle performance of highway design and construction projects using mandatory screening	Life cycle performance of highway design and construction projects
2010	**Greenpave** Developed by the Ontario Ministry of Transportation in Ontario, Canada.	Rating system used by contracters and consultants of the Ministry to promote sustainable pavement design and construction practices.	Pavement projects
2010	**I-LAST** Developed by Illinois DOT and state American Council of Engineering Companies and modeled on GreenLITES.	Performance metric system used to provide a relative rating of sustainable improvements for highway projects. An extensive collection of guidelines and specifications is used for a pre-project and post-project assessment of sustainability.	Highway projects
2012	**INVEST** Developed by the Federal Highway Administration.	Web-based tool to assist transportation agencies meet individual sustainability goals. Rates three phases of projects (i.e. planning, development, operations and maintenance) based on criteria developed	Life cycle of tranportation projects
2012	**envISIon** In development by Institute for Sustainable Infrastructure.	Self-assessment tool in development to advance improvements in performance and resilience of the wide range of physical infrastructure. Rating is determined by meeting a minimum number of points in each category.	All infrastructure projects
2012	**Green Guides for Roads** In development by the Transportation Association of Canada.	Self-evaluation tool intended to support decision-making based on sustainability objectives.	Roadway and highway projects
	DuboCalc Developed by Dutch Ministry of Infrastructure and Environment.	Quantifies sustainability over the lifecycle of a project so that environmental performance is used as design principle during the bid process of projects.	Transportation infrastructure projects
Neighborhood-Level Development			
2008	**STAR Community Index** Developed by Local Governments for Sustainability USA.	A framework to assess the triple bottom line of sustainability for communities through a rating system with online support tools.	Community development
2008	**One Planet Communities** Developed by BioRegional (UK).	Five-step process (including planning and review) to support solutions for sustainable living based on ten basic principles.	Neighborhood-scale development (design, construction, and management)
2008; Updated 2011	**Enterprise Green Communities** Developed by Enterprise Community Partners.	Certification system that guides the development of affordable housing with green practices and accounts for residents well-being.	Development of affordable housing
2009	**LEED-ND** Developed by USGBC LEED.	Evaluates sustainable development based on principles of smart growth, urbanism and sustainable construction using a credits system for certification.	Neighborhood-scale planning and development
2010	**EcoDistricts Initiative** Developed by the Portland Sustainability Institute.	Approach to creating sustainable neighborhoods by removing implementation barriers and establishing a focus on the social component of sustainability.	Neighborhood-scale with focus on engagement and governance
2012	**TOD Rating Systems** Development by Northeastern University and the CTOD.	Quantifies "high-quality" transit –oriented projects and neighborhoods to establish a basis for public sector support in TOD.	Transit-related projects and neighborhoods
2012	**Green Star Communities** Developed by the Green Building Council Australia.	Rating system that uses a framework of guiding principles to evaluate sustainability practices at all stages of development.	All stages of community development (e.g. policy making, implementation, monitoring)

To better understand the different rating systems Tables 2 and 3 were developed to compare and contrast the criteria used in each of the rating systems. These tables consider both transportation and neighborhood- level development systems based on the same categories of criteria and identify similarities and differences among the criteria used for evaluating and quantifying the sustainability of a project, program, etc. A detailed survey of the various rating systems' criteria led to the development of general categories seen in multiple systems. These categories are listed along the y-axis of the table.

The various rating systems are listed at the top of the table and if the criteria within the system are related to the general categories, this is indicated with a shaded box. The general categories are also separated into one of three types of sustainability: environmental, economic, or social. The categories were assigned a type of sustainability that was applicable but it must be noted that some of the categories may fit into more than one of the three types of sustainability.

Table 2: Criteria Comparison Table for Transportation Rating Systems

		Transportation							
	Criteria Categories	Greenroads	GreenLITES	STARS	BE^2ST	Green Pave	I-LAST	INVEST	EnvISIon
Environmental Sustainability	Water Conservation								
	Energy Conservation								
	Environmental/Ecosystem Protection								
	Climate Change								
	Waste and Materials Management								
	Noise/Light Pollution								
	Sustainable Land Use								
Economic Sustainability	Innovation/ Design								
	Operations and Maintenance								
	Cost Effectiveness								
	Affordability								
	Economy/Jobs								
	Transportation Impact								
Social Sustainability	Access								
	Safety								
	Equity/Inclusion								
	Health/Well-being								
	Culture/Place-making								
	Food Sustainability								
	Indoor Environment								

Table 3: Criteria Comparison Table for Neighborhood-Level Development Rating Systems

		Neighborhood Development					
	Criteria Categories	STAR Communities	OnePlanet Communities	Enterprise Green Communities	LEED-ND	Ecodistricts	Green Star Communities
Environmental Sustainability	Water Conservation						
	Energy Conservation						
	Environmental/Ecosystem Protection						
	Climate Change						
	Waste and Materials Management						
	Noise/Light Pollution						
	Sustainable Land Use						
Economic Sustainability	Innovation/ Design						
	Operations and Maintenance						
	Cost Effectiveness						
	Affordability						
	Economy/Jobs						
	Transportation Impact						
Social Sustainability	Access						
	Safety						
	Equity/Inclusion						
	Health/Well-being						
	Culture/Place-making						
	Food Sustainability						
	Indoor Environment						

Additional systems were surveyed but are not included in Tables 2 and 3 due to the fact that they are still under development. Some of the systems are at the pilot stage and are not at the level of maturity where comparison is meaningful or even possible. The Saga Sustainability Database was not included in the comparison because of its variations of criteria due to its focus on aviation. Several of the more developed and comprehensive systems are discussed in more detail in the following section.

Greenroads Rating System

Greenroads is a flexible rating system used to rank and score road projects for their overall performance in sustainability as compared to average roadway projects. Greenroads originated at the University of Washington as a research project in 2007 and has been developed over the years. Succeeding versions of the system were created in collaboration with CH2MHILL and a number of other industry groups and consultants who contributed data and commentary through pilot projects, case studies and public comments. Greenroads is currently in Version 1.5, which was developed in 2011. Greenroads is now a voluntary third party rating system under the Greenroads brand, which is a pending trademark of the University of Washington. The Greenroads Foundation, a third-party independent non-profit organization incorporated in 2010, is intended to be the sole licensee of the rating system and will maintain and update Greenroads (Muench et al. 2011).

Greenroads is designed to recognize roadway projects that surpass public expectations for sustainability based on the system's capacity to support natural laws and human values. Greenroads quantifies the sustainable attributes of a roadway project. Although the Greenroads rating system is not equipped to address the decision whether or not to build a road, it is useful in decision making on the project development and project delivery level to help shape decisions. The quantification can be used to:

1. Define what features contribute to sustainability on the project.
2. Provide accountability for sustainability on roadway projects.
3. Measure and track specific sustainability goals over time.
4. Manage and improve roadway sustainability.
5. Encourage new and innovative practices.
6. Promote competitive advantage and other economic or market incentives for sustainability.
7. Communicate sustainable features to stakeholders in an understandable way, especially to the general public. (Muench et al. 2011)

Greenroads is not intended to be used for design or trade-off decisions but to influence decisions on how sustainability options can be incorporated to encourage sustainable practices (Muench et al. 2010). The Greenroads rating system is intended to be implemented in the design and construction phase of roadway development and can be useful in assessing the sustainability of a roadway (Muench et al. 2011).

Rating Procedure. A Greenroads "certification" correlates to a road project that earns points for sustainable practices above the current standards for environmental compliance, roadway design and construction practice. Certified road projects can be denoted with a distinctive sign that communicates substantial achievement (Muench et al. 2011).

Greenroads uses a collection of sustainability best practices that apply to roadway design and construction to rate projects. These best practices are divided into two types of activities: required and voluntary.

> Required: Project Requirements are the minimum activities that must be completed in order to be considered a Greenroad. They can be viewed as characteristics common to all Greenroads. There are 11 such Project Requirements. These activities capture the basic ideas of environmental and economic decision making, public involvement, long-term environmental performance, construction planning, and lifetime monitoring and maintenance. In order to achieve certification, all of the Project Requirements must be met. Greenroads activities are not intended to supersede local, state, or federal regulation or other jurisdictional ordinances and many of the Project Requirements coincide with existing federal requirements (Muench et al. 2011).

An additional number of Voluntary Credit points may also be earned; however, regardless of how many Voluntary Credit points are achieved, if a project does not meet all of the Project Requirements, a Greenroads certification level will not be awarded.

> Voluntary: Voluntary Credits are based on best practices that may optionally be included in a roadway project. There are 37 Voluntary Credits. Each is given a point value weight of 1 to 5 depending upon the sustainability impact of the credit. An additional 10 points can be earned by "Custom Credits," which allows a project or organization to develop individualized Voluntary Credits. Voluntary Credits can be achieved through actions such as cultural outreach, multimodal access, safety and pavement materials. Because of the wide range of activities, it is unlikely that a project will be able to achieve all of the Voluntary Credits. However, the goal of Greenroads is to provide enough variety in Voluntary Credits that any roadway project could implement enough best practices to obtain relevant credits to achieve at least a minimum certification level. This means that Greenroads should work for all roadway projects from basic preservation projects to large construction projects (Muench et al. 2011).

Table 4 shows Greenroads' certification categories and the point levels that must be satisfied to achieve each certification.

Table 4: Greenroads Certification Categories

Greenroads Certification	Required Points	Voluntary Points	% of total points
Certified	All	32-42	30-40
Silver	All	43-53	40-50
Gold	All	54-63	50-60
Evergreen	All	64+	>60

FHWA Infrastructure Voluntary Evaluation Sustainability Tool (INVEST)

The green rating system INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) was built by the Federal Highway Administration with input from AASHTO, ASCE, ACEC and APWA to help transportation agencies meet individual sustainability goals and needs. It is a web-based tool that provides criteria based on best practices to assist transportation agencies in integrating sustainability into their programs. Initial criteria seen in the 2010 beta version were written by subject matter experts and, through stakeholder feedback, the criteria have since been reviewed, modified, and vetted. Consequently, a pilot test version was released for testing and evaluation. After several years of research, analysis and development, the feedback was used to adjust the criteria for the official release of INVEST version 1.0 in October 2012 (Federal Highways Administration 2012). INVEST encourages stewardship, not compliance and to accomplish this, input from a variety of sources including thousands of user comments, was incorporated to make it practical and tangible (Federal Highway Administration, Webinar, October 10, 2012).

The INVEST program defines sustainability using the three principles of the 'triple bottom line' and views sustainability as a concept that balances social, economic, and environmental aspects to capture the broad range of transportation goals and objectives in decision making(Federal Highways Administration 2012). INVEST can be used throughout the entire life cycle of a project; it can be used as a tool to encourage broad participation, evaluate sustainability tradeoffs, communicate benefits and goals, and reward excellence. The user can choose to what extent to measure success against the absolute scale of how many overall points are achieved by a given project or set an achievement level to reach and use this tool to meet those goals (Federal Highway Administration 2012). Additionally, INVEST can be used to:

- Set goals, provide guidance, and measure the sustainability of an on-going project.
- Evaluate the sustainability of a portfolio of potential improvement projects at a statewide, regional or local level to facilitate the decision-making process and prioritization.
- Identify programmatic barriers that might be the result of policies, design standards and specifications, or stakeholder agency policies.
- Use new technologies and best practices in sustainability to anticipate related requirements. Although, INVEST does not include criteria for meeting current expectations and regulations, like NEPA, many of the criteria include meeting requirements that are above and beyond the normal standard of practice.
- Evaluate the sustainability of a completed project or program of projects (Federal Highway Administration 2012).

Rating Procedure. The INVEST tool is equipped to rate projects in three phases of the project lifecycle: System Planning, Project Development, and Operations and Maintenance. Each of these phases has a separate self-standing module. There are a total of 60 specific criteria, based on the best practices for this stage of project. The System Planning and Operations and Maintenance modules have one scorecard each (Federal Highways Administration 2012). The Project Development module evaluates individual projects and has 29 criteria organized into six project scorecards:

- Paving – for projects that are devoted exclusively to pavement preservation; restoration projects that extend the service life of existing facilities and enhance safety; or pavement restoration projects that restore pavement structure, ride quality, and spot safety. Use this scorecard for paving projects in both rural and urban locations.

- Basic Rural – for small, rural reconstruction or rural bridge replacement projects that do not expand capacity of the roadway.
- Basic Urban – for small urban reconstruction or urban bridge replacement projects that do not expand capacity of the roadway.
- Extended Rural – for rural projects for a new roadway facility; structure projects where nothing of its type currently exists; and major reconstruction projects that add travel lanes to an existing roadway or bridge.
- Extended Urban – for urban projects for a new roadway facility; structure projects where nothing of its type currently exists; and major reconstruction projects that add travel lanes to an existing roadway or bridge.
- Custom - for projects that do not fit any of the pre-defined scorecard options, the Custom Scorecard will allow the user to develop a unique set of criteria that is most appropriate for the project being evaluated. The Custom Scorecard starts with a core set of 19 that must be included as part of the score. There are not achievement levels associated with the custom scorecard (Federal Highways Administration 2012).

EcoDistricts

EcoDistricts was launched by the Portland Sustainability Institute (PoSI) in 2009. Subsequent versions refined the system based on feedback and results of the pilot programs. The EcoDistricts program creates an enabling strategy for neighborhood-scale sustainability that seeks to break down barriers to implementation such as project capital, public policy support, and need for comprehensive assessment tools (EcoDistricts 2013). EcoDistricts differs from LEED-ND and other green rating systems in that it works upstream by providing tools and strategies for project implementation in existing neighborhoods. These tools and strategies can then help neighborhoods earn green ratings such as LEED-ND (Portland Sustainability Institute 2010).

A major focus of EcoDistricts is bringing together neighborhood stakeholders, property developers, utilities, and municipalities to form a sustainability plan that leads to real outcomes such as minimizing environmental impact, utilizing and enhancing local technologies, equity in investment, community participation, and economic development (EcoDistricts 2013).

EcoDistricts uses a framework with four phases:

1. District Formation – create a shared vision and governance structure through community engagement.
2. District Assessment – determine priorities and strategies of greatest impact.
3. Project Feasibility and Development – determine overall viability and cumulative impact of priority projects; develop implementation and funding strategy; coordinate stakeholders, developers, public

agencies, and utilities to assess need for joint ventures, comprehensive financing, new governance models, and level of additional community involvement.
4. District Management – conduct on-going monitoring of social, economic, and environmental impacts (EcoDistricts 2013).

PoSI has developed a series of four toolkits for guiding implementation of the program through the four phases. The Organization Toolkit provides a range of options for developing a governance structure and explains various methods for engaging the community. The Performance and Assessment Method Toolkit provides assistance in developing a performance baseline, setting targets, identifying strategy opportunities, project screening, feasibility assessment, alternatives analysis, and project prioritization, implementation, and monitoring. There are eight performance areas, each with a set of objectives as shown in Table 5. There is also an EcoDistrict Assessment Method that provides a ten-step process to develop a baseline for the district's performance. The Financing Toolkit describes financing methods for district organization and staffing, feasibility and small-scale project development, and district utilities and large-scale project development. The Policy Support Toolkit offers policy recommendations for municipality support through regulations, public-private partnerships, financial incentives and assistance, technical assistance, shared ownership of infrastructure, buildings or services, demand management programs, education, third-party certification requirements or incentives for compliance, and infrastructure and project investment (EcoDistricts 2013).

Table 5: EcoDistrict Performance Areas (EcoDistricts 2013)

Performance Area	**Objectives**
Equitable Development	• Ensure neighborhoods investments provide direct community benefit through job creation and investment opportunities • Provide quality and consistent local job opportunities through EcoDistrict projects • Mitigate the forced displacement of existing residents and businesses • Ensure diverse stakeholder involvement in all EcoDistrict activities and decision making
Health and Well Being	• Provide access to safe and functional local recreation and natural areas • Provide access to local, healthy, and affordable food • Ensure safe and connected streets • Expand economic opportunities to support a socially and economically diverse population • Improve indoor and outdoor air quality
Community Identity	• Create beautiful, accessible, and safe places that promote interaction and access • Foster social networks that are inclusive, flexible, and cohesive • Develop local governance with the leadership and capacity to act on behalf of the neighborhood
Access and Mobility	• Provide accessible services through mixed uses and improved street access • Prioritize active transportation • Reduce vehicle miles traveled • Use low and zero emission vehicles
Energy	• Conserve energy use by minimizing demand and maximizing conservation • Optimize infrastructure performance at all scales • Use renewable energy
Water	• Reduce water consumption through conservation • Reuse and recycle water resources whenever possible, using potable water only for potable needs • Manage stormwater and building water discharge within the district
Habitat and Ecosystem Function	• Protect and enhance local watersheds • Prioritize native and structurally diverse vegetation • Create habitat connectivity within and beyond the district • Avoid human-made hazards to wildlife and promote nature-friendly urban design
Materials Management	• Eliminate practices that produce waste whenever possible • Minimize use of virgin materials and minimize toxic chemicals in new products • Optimize material reuse and salvage and encourage use of regionally manufactured products or parts • Where opportunities for waste prevention are limited, maximize use of products made with recycled content • Capture greatest residual value of organic wastes (including food)through energy recovery and/or composting

One Planet Communities

Coordinated by BioRegional in the United Kingdom, the One Planet Communities program is part of the wider One Planet initiative which uses the ten One Planet principles to guide and support local government, companies, organizations and individuals in their efforts to create solutions for sustainable living. The ten One Planet principles are:

1. Zero carbon – Making buildings more energy efficient and delivering all energy with renewable technologies.
2. Zero waste – Reducing waste, reusing where possible, and ultimately sending zero waste to landfill.
3. Sustainable transport – Encouraging low carbon modes of transportation to reduce emissions, reducing the need to travel.
4. Sustainable materials – Using sustainable healthy products, with low embodied energy, sourced locally, made from renewable or waste resources.
5. Local and sustainable food – Choosing low impact, local, seasonal and organic diets and reducing food waste.
6. Sustainable water – Using water more efficiently in buildings and in the products we buy; tackling local flooding and water course pollution.
7. Land use and wildlife – Protecting and restoring biodiversity and natural habitats through appropriate land use and integration into the built environment.
8. Culture and heritage – Reviving local identity and wisdom; supporting and participating in the arts.
9. Equity and local economy – Creating bioregional economies that support fair employment, inclusive communities and international fair trade.
10. Health and happiness – Encouraging active, sociable, meaningful lives to promote good health and well being (BioRegional 2013).

The principles are applied during the design, construction, and long-term management stages of the project to undertake three sustainability challenges of ensuring a sustainable ecological footprint, which is measured as consumption of natural resources in global hectares of land and sea, ensuring a sustainable carbon footprint and ensuring activities are be clean or non-polluting (BioRegional 2013).

BioRegional is incorporated into the development process and acts as an advisor throughout the lifetime of the project to guide sustainable development. BioRegional assists the project management team to apply the ten principles through five steps:

1. Development of an action plan – This enables the provision of a framework for considering sustainability, identification of specific challenges and opportunities, development of strategies, and resolution of key targets, performance indicators, and process for One Planet Community endorsement.

2. Endorsement – BioRegional reviews and endorses action plan.
3. Implementation – BioRegional assigns a Sustainability Integrator who helps team put strategies into practice.
4. Annual Review – Lessons are learned and action plan is updated.
5. Expert Panel – Panel provides support to keep the initiative on track (BioRegional 2013).

Further assistance in found in two toolkits, BedZED Parts 1 and 2, that provide guidance on carbon neutral developments and green materials sourcing, respectively. Communities earn the One Planet designation when they have sufficiently thorough action plans with targets and strategies for each of the ten One Planet principles and have committed to monitoring until 2020 (BioRegional 2013).

DISCUSSION

Sustainability rating systems are at various levels of development and implementation. Over time they have built upon each other and incorporated components of prior systems. Although several transportation rating systems are well known and used in practice, many of the neighborhood-level systems are in the pilot stage. More recent systems in transportation are increasingly comprehensive and context sensitive.

Reviewing various rating systems revealed that sustainability is defined differently among them. The definition of sustainability ranges from "Reduce, Reuse, Recycle," to consideration for future generations, to balancing human and natural needs, to the "triple bottom line." The review revealed that there is a heavy focus on environmental aspects of sustainability and often social and economic considerations are missing from transportation rating systems. Neighborhood-level development rating systems do generally include social factors.

All systems are based on industry best practices in sustainability. Systems award points based on some minimum set of criteria that is influenced by best practices. Criteria vary among systems; however, there is some overlap. This comparison is depicted graphically in Tables 2 and 3. For example, all but one of the systems have criteria related to energy conservation. Although, the rating processes of all the systems are based on the criteria derived from best practices, the process of rating projects and programs varies. Several systems, including Greenroads, require select criteria to be met for each level of certification or for certification in general. The classification for certification levels is also derived differently across systems.

The differences in the systems make some more or less applicable in different contexts. Tables 2 and 3 can be useful in identifying which types of criteria are evaluated in each system and help an agency, company, etc, in determining which system would be most applicable based on their sustainability goals.

In addition to different criteria, rating systems can be used in different capacities. Systems are developed to be applied at various stages of the project lifecycle: planning, design, construction, operations, and maintenance. Systems may be useful at one or more of these stages. Along the same grain, rating systems can be used for ex post evaluation or ex ante planning. Neighborhood systems exhibit this: some are more like planning frameworks than rating systems. For both types of rating systems, the use of these tools in an ex ante manner to incorporate sustainability considerations in the planning stages (rather than in solely an ex post manner), is potentially more valuable in enabling identification and inclusion of sustainability-oriented features. In both cases rating systems can be used in the decision making process, whether they provide a sustainability-oriented planning process or allows evaluation of alternatives based on sustainability ratings.

The review also showed that rating systems take two different approaches to evaluating improvements: Project-based or Systems-based. Transportation systems typically had a focus on projects. Systems designed for rating road construction were very project-based; however, some transportation rating systems did incorporate land use considerations. Generally, neighborhood development systems have a holistic approach, evaluating sustainability at a systems level and including transportation components. It is conceivable that project-based rating systems could give a high rating to projects that may not be rated quite as highly on a systems level; for example, a project-level transportation rating system without land use criteria may rate a roadway project more highly than if a more comprehensive system was used. Table 1 provides an overview of each system identifying its most applicable uses.

The use of sustainability rating systems encourages improvement in sustainable practices in transportation and neighborhood-level development; however, a very pressing concern is measuring sustainability in light of trade-offs. For example, a project may be rated very high on many criteria but low in environmental protection and still receive a gold rating. If this project is in the vicinity of a wetland and vulnerable species, is it still deserving of a gold rating? These complications are not necessarily accounted in the rating systems.

CONCLUSIONS

Reviewing the range of rating systems reveals some of the comparisons discussed in the previous section. Specifically, these differences and similarities are presented in Tables 2 and 3.

As mentioned previously, most systems focus on environmental impacts such as water and energy conservation, climate change and other ecological concerns. The two categories of rating systems, transportation and neighborhood-level development, do however, have some clear differences. For instance, Food Sustainability and Health/Well-being are not included in any transportation systems. Additional areas of human impacts that may be considered social sustainability are also absent in many transportation rating systems. Equity/Inclusion was included in several systems with a focus on inclusionary participation and criteria relating to Economy/Jobs was not included in any of the transportation systems. Still, where some of the transportation systems focus, the neighborhood-level development systems overlook. Areas like, Waste Management and Cost Effectiveness are not clearly accounted for in any of the neighborhood-level systems. Innovation and Design is another area missing in the neighborhood-level systems. Transportation systems include this area to encourage and spur creative solutions to sustainability issues. The lack of it at the neighborhood development level is curious as one would see value in encouraging innovative solutions, especially within the development community. The area of Safety was only included in two of the transportation systems and in none of the neighborhood-level systems.

An area where the two types of systems overlap but do not necessarily cover are Sustainable Land Use and Transportation Impact. The land use-transportation interaction is commonly accepted; however, in these rating systems, it is not commonly included. While most systems have some measure of sustainable land use, neighborhood-level systems do not incorporate the area of Transportation Impact. Most do have criteria in the area of Access but do not explicitly focus on Transportation Impact.

In conclusion, there is a range of rating systems that can be applied to transportation and neighborhood development projects. These systems all are used to quantify or provide a measure of sustainability for the finished project; however, this is done in a variety of different ways accounting for a variety of criteria. Some systems are specific to certain types of projects while others are more comprehensive. All the systems, however, are based on best practices in sustainability. Because of their differences, but also because of their fundamental similarities, one might conclude that these systems are most useful for identifying, streamlining, simplifying and enabling sustainable practices and not only in rating and evaluating the sustainability of projects.

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Carbon Sequestration by Roadside Filter Strips and Swales: A Field Study

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ABSTRACT

As legislation continues to focus on greenhouse gas (GHG) and carbon dioxide (CO_2) emissions and reductions, the terrestrial biome offers an attractive possibility to sequester carbon. Currently, the terrestrial pool is regarded as a CO_2 sink, but scientists are unsure to what extent this trend will continue. Urbanization modifies the existing landscape, and little study has focused on the carbon (C) dynamics of specific urban land uses. In this research, the roadway environment, specifically the grassed right-of-way (ROW), was studied for carbon sequestration potential, an important ecosystem service. Transportation corridors exist world-wide, and the vegetated filter strip and swale (VFS/VS), two common stormwater control measures (SCMs), often constitute the grassed right-of-way adjacent to roadways. Carbon pools within roadway VFS/VS soils of North Carolina were specifically examined in this study.

This research was conducted in two North Carolina physiographic regions: the Piedmont (characterized by clay-influenced soils) and the Coastal Plain (predominantly sandy soils). Approximately 700 soil samples were collected in VFS/VSs and wetland swales alongside major highways and analyzed for percent total soil C (% total C) and bulk density, which aided in obtaining the C density. Mean soil C densities were 2.55 ± 0.13 kg C m^{-2} (mean ± standard error, n=160, 0.2 m depth) in the Piedmont and 4.14 ± 0.15 kg C m^{-2} (n=160, 0.2 m depth) in Coastal Plain highway VFS/VSs. Because grasslands were reported to have similar carbon density values, they could be used as a surrogate land use for roadway VFS/VSs if no specific roadside data were available.

Using a 37-year soil chronosequence, the carbon sequestration rate using a simple linear regression within Piedmont VFS/VSs was calculated at 0.053 kg C m^{-2} yr^{-1}. Utilizing segmented linear regression models, the sequestration rate was calculated to be 0.155 kg C m^{-2} yr^{-1} for 15 years and 0.099 kg C m^{-2} yr^{-1} for the remaining 21.5 years. The roadside grass sequestration rate assumed by the Federal Highway Administration Carbon Sequestration Pilot Program (0.17 kg C m^{-2} yr^{-1}) overestimates carbon accumulation by a factor of 3 in the linear model, and by a factor of 1.1 to 1.7 with the segmented linear models.

Carbon density did not differ between dry and wetland swales, although % total C was significantly greater in wetland swales. Because C density and % total C

in swales were not well defined by age, it appeared more appropriate to assess wetland swales and dry swales using a range of carbon values, rather than a rate of carbon sequestration. The mean VS C density was 3.05 ± 0.13 kg C m^{-2} (n=40, 0.2 m depth), while that for wetland swales was 5.04 ± 0.73 kg C m^{-2} (n=44, 0.2 m depth). If promoting C sequestration becomes a factor in ROW management, wetland swales would be more desirable than dry swales.

While the VFS/VS sequestration rate is comparable to other grassed systems, the estimated 320-480 tons C per lane-mile expelled during roadway construction (Cass and Mukherjee 2011) is marginally offset through terrestrial sequestration in roadside VFS/VSs. Per kilometer of roadway constructed, Piedmont VFS/VSs would offset between 4% and 7% of C emitted during construction, depending on predictive model of C sequestration rate was used.

INTRODUCTION

Climate change and land use changes are two of the largest and interconnected environmental issues facing society today. While fossil fuel combustion is the largest anthropogenic greenhouse gas (GHG) source, land use conversion, either implicitly or through additional agricultural emissions, is the second leading contributor (IPCC, 2007). Land use conversion, or the conversion of native or long standing vegetation to cultivated or mixed use urban land, produces a carbon (C) source to the atmosphere (IPCC, 2007). Leaders and policymakers recognize the need to mitigate climate change through better land use management (Litynski et al., 2006; Murray et al., 2007; Post et al., 2009). Carbon storage within biomass and soil is becoming an increasingly valuable ecosystem service (Davies et al., 2011).

In the terrestrial system, the majority of C is usually held below ground (soil) rather than in vegetation (IPCC, 2001; Golubiewski, 2006; Post and Kwon, 2000). Land use conversion, which exposes otherwise protected soil to oxygen and microorganisms, oxidizes soil C to CO_2 and reduces soil C (Post and Kwon, 2000; IPCC, 2007). The decrease in soil C from agricultural cultivation and silviculture has been studied (Lal, 2004), but the effects of urban land use development, like roadway construction, on soil C have been largely undocumented (Golubiewski, 2006). Globally, urban land use is expected to increase; by 2050 2.3 billion new inhabitants will be living in urban areas (United Nations, 2010). Therefore, it is important to understand what effect new urban land uses will have on soil C and the global C budget.

VFSs, VSs, and wetland swales, all popular SCMs, have been used along roadways to trap sediment and pollutants as they drain from the road (Wu et al., 1998). VFSs convey sheet flow from highway shoulders and trap sediment and pollutants; VSs are broad open channels that receive sheet flow from the VFS and convey stormwater to a water body (Deletic and Fletcher, 2006; Winston et al., 2012). The VS may exhibit wetland characteristics - hydrophytic vegetation and hydric soils - due to the presence of a near-surface water table. These linear wetlands have the potential to regulate discharge of nutrients associated with runoff (Moore et al., 2011), a current driver for their use. While these practices have been extensively studied for runoff mitigation and pollutant control, other ecosystem services, such as C sequestration, remain relatively unknown.

In the U.S., the Federal Highway Administration (FHWA) estimates the National Highway System is 262,000 km long with approximately 2 million ha of right-of-way (USDOT-FHWA, 2010). The FHWA estimates 45% of ROWs, or 900,000 ha, is grassed area, effectively serving as a VFS and VS combination (VFS/VS) (USDOT-FHWA, 2010). The capacity for VFS/VSs to accumulate C is undocumented. The purpose of this study is to establish average and maximum C density values of roadside VFS/VSs and wetland swales within North Carolina.

RESEARCH OBJECTIVES

Currently, there are little to no C density or sequestration data available for roadside SCMs. The primary objective of this study was to quantify C densities and determine if VFS/VSs within the roadside environment possess soil C sequestration potential. Two additional objectives were to determine whether physiographic region affected the ability of VFS/VSs to sequester C, and if wetland swales (WS), or swales with wetland hydrology and hydrophytic vegetation, offered greater potential for C sequestration than dry swales. The offset of emitted carbon during highway construction by vegetated SCMs over the life of the highway was explored.

MATERIALS AND METHODS

Study Area

Highway VFS/VS and wetland swales that border four lane highways in central and eastern NC were the focus of this study. Wetland swales in the Coastal Plain were also compared to their counterpart, the dry swale. Because soil type and structure affect carbon accumulation (Post and Kwon 2000; Jastrow et al. 2007), the sampling regions, the North Carolina Piedmont and Coastal Plain, were further narrowed by soil system type. Sites in the Piedmont were selected from the felsic crystalline and mixed felsic and crystalline soils, while in the Coastal Plain the lower coastal plain (Wicomico Talbot) soil system was used. The mixed mafic and crystalline soils were dominated by clayey soils, while the lower coastal plain soils are predominately sandy (Griffith 2002). Clayey soils have a higher cation exchange capacity (CEC) which generally allows the soil to accumulate C more readily than sandy soils (Jastrow et al. 2007). However, the slightly higher annual precipitation in the Coastal Plain may also benefit C accumulation in this region.

Site Selection

Roadside VFS/VSs of different ages within the Piedmont and Coastal Plain were sampled to evaluate C accumulation within the soil over time within the linear environment. Hence, many sites of various ages throughout North Carolina were selected instead of continuously monitoring one site's C accumulation over several years. In soil literature, this common practice is termed a *chronosequence,* where space is substituted for time and related soils are believed to be comparable based on climatographical features (Vreeken 1975).

Using ArcGIS, each site was identified and systematically sampled from May to July 2011. Roadway ages were discerned from NCDOT GIS data, which listed the date of construction or most recent road repair. Site age is considered to be the years since VFS/VS vegetation establishment, so construction dates were selected as time zero. Temporal distribution of sites was needed to represent roadways of various ages, thus age classification groups were established prior to site selection. Figure 1 displays the selection criteria. Within each age group, 5 VFS/VS sites were selected. An additional 22 wetland swale sites were sampled in the Coastal Plain region. In the Piedmont, the mean ages for the 1, 2, 3, and 4 age classes were 4, 11, 19 and 32, respectively. Mean ages in the Coastal Plain for the 1, 2, 3, and 4 age classes were 4, 13, 19, and 34 years, respectively. Wetland swale sites within the Coastal Plain had mean ages of 5, 11, 20, and 32 years, for age classes 1, 2, 3 and 4, respectively.

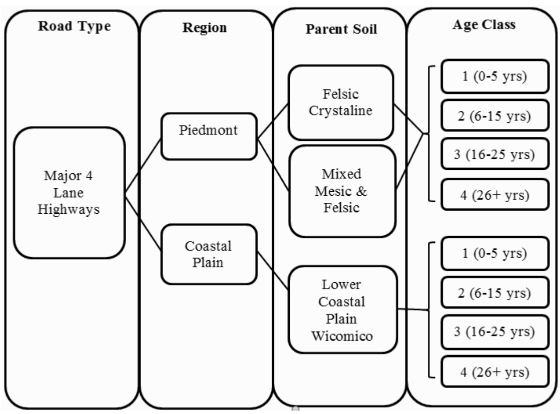

Figure 1. VFS/VS and wetland swale site selection criteria.

Experimental Design

Each site was comprised of a VFS and a VS, except in the case of wetland swales which were sampled separately. The length of the VFS from the edge of pavement (EOP) was recorded and transects were marked with flags before sampling. Two transects, 1 m apart, were established at each VFS/VS site (Figure 2). The first sample position was 0.5-1 m from the EOP. After position 1 was established, the remaining sample points were spaced equidistantly to the swale invert. Posistions 1 through 3 were in the VFS, while position 4, taken at the swale invert, represented the swale (Figure 2). At each sample location, individual soil cores were taken at 0-0.1 m and 0.1-0.2 m depths. Each VFS/VS site consisted of n=16 soil cores; each wetland swale was the equivalent of position 4, and had n=4 soil cores. Therefore, a total of 640 VFS/VS and 88 wetland swale soil cores could be obtained. However, due to compaction of roadside soils, 32 soil cores at the 0.1-0.2 m depth were not extractable in the VFSs. Thus, the complete data set consisted of 696 of a possible 728 soil cores.

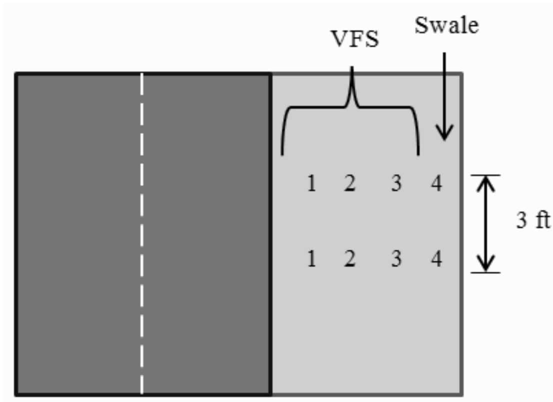

Figure 2. Site sampling regime, where position 1 is closest to the roadway. Positions 1, 2 and 3 constitute the VFS. Position 4 represents the swale or wetland swale. At each position two soil cores were taken at 0-0.1 m and 0.1-0.2 m depths. (not to scale)

Sample Collection and Analysis

At each sample location, the vegetation and thatch was removed, and an AMS hammer corer (ring diameter of 5 cm; AMS American Falls, Idaho, USA) was used to capture an intact soil core (Qian et al., 2010). Samples were taken at depth 1 (0-0.1 m) and then a pit (approximately 0.3 m x 0.3 m) was dug approximately 0.1 m below soil surface and soil cores were taken at depth 2 (0.1-0.2 m). The samples were then transported to the laboratory for further analysis. All analyses were performed on individual cores and all VFS and VS results were pooled for each sampling location.

For bulk density measurements, the cores were oven-dried at 40.6˚F over a 24-hour period and weighed (Blake and Hartge, 1986). Fine bulk density (FBD), or the mass of fine fraction (<0.2 cm) per volume (Golubiewski, 2006), was also determined. Because C is actively accumulating in the soil, not the rock or gravel fragments found within roadside soils, the FBD, rather than the bulk density, was used to quantify the C density of these soils.

Next, each core was ground and sieved to less than 2 mm. A subsample was taken from the 2 mm fine fraction, and further ground to less than 250 µm and analyzed for % total C (g C g^{-1} dry soil) at the NC State University Environmental and Agricultural Testing Services lab through dry combustion at 550^{o}C with a Perkin-Elmer 2400 CHN Elemental Analyzer (Golubiewski, 2006). The addition of 4.0N HCL (a strong acid) to a subset of samples produced no result, therefore % total C was assumed equal to organic carbon (Conant et al., 2001). Additionally, each transect at each depth was composited for particle size analysis via the hydrometer method, and then assigned to a texture class based upon USDA classification (Gee and Bauder, 1986).

Carbon Accumulation

This research utilized a soil chronosequence to discern how the variable of interest, C density, behaved with respect to time. The increase in soil C density is a better basis by which to evaluate C sequestration rather than simply the mass of C or the % total C in the soil, as it accounts for potential changes due to soil erosion or compaction. The areal C density (kg C m^{-2}) of each soil core was determined using equation 1 (Pouyat et al. 2009). To estimate rates of C sequestration, the C densities were regressed with VFS/VS or WS age (Golubiewski 2006; Neill et al. 1998). This is a convenient methodology when long term monitoring and data sets are not available.

$$C_{den} = FBD * d * \%C \qquad (1)$$

Where C_{den} is areal C density (kg C m^{-2}), FBD is fine bulk density (kg soil m^{-3}), d is sample depth (m), and % C is percentage total C (kg C kg^{-1} soil).

Statistical Analyses

SAS © 9.2 statistical software was used to test the effects of site factors on the response variable, C density. Due to physiographic, soil, and climate differences between the two regions, the statistical analyses were performed on the Piedmont and Coastal Plain data independently. The data were log transformed to stabilize variance. A PROC MIXED type III model was used to fit the data and make statistical inferences; throughout this document, significance was established at $\alpha = 0.05$.

Estimates of C sequestration rates and maximum C densities were made using simple linear regression (PROC GLM) and segmented linear regression (PROC NLIN and NLMIXED) where each site was regressed with actual site age, not age class. The models were evaluated to determine the most appropriate representation of C density accumulation. The linear regression equation is as follows:

$$C_{Denx} = C_{Den0} + C_{Seq} * Age \qquad (2)$$

Where C_{denx} is C density (kg C m^{-2}) at site age equal to x years, C_{den0} is baseline C density (kg C m^{-2}) at site age equal to zero years, C_{seq} is C sequestration rate (kg C m^{-2} yr^{-1}), and age is site age (yr).

Segmented linear regression, or piecewise regression, splits the independent variable in multiple intervals where separate line segments are fit to each interval. A breakpoint defines the point where the relationship between the x and y variable changes. In this analysis, the x variable was site age and C density was the y variable; thus the breakpoint signifies the site age where C density no longer followed the same trend, or slope, of earlier data. The linear segmented regression equations are as follows:

$$C_{Den1} = C_{Den0} + C_{Seq1} * Age_1 \qquad (3)$$

$$C_{Den2} = Plateau \qquad (4)$$

Where C_{den1} is C density (kg C m^{-2}) when site age is less than the breakpoint age, C_{den0} is baseline C density (kg C m^{-2}) at site age equal to zero years, C_{seq1} is C sequestration rate (kg C m^{-2} yr^{-1}) when site age is less than the breakpoint age, Age_1 is site age (yr) with site age less than the breakpoint age, C_{Den2} is C density (kg C m^{-2}) when site age is greater than or equal to the breakpoint age, and plateau is the maximum C density (kg C m^{-2}). Equation 3 quantifies C density prior to reaching C saturation, and equation 4 quantifies the plateau, or maximum C density.

RESULTS AND DISCUSSION

Carbon Density

The mean areal C density for the soil profile sampled of VFS/VSs were 2.55 ± 0.13 kg C m^{-2} and 4.14 ± 0.15 kg C m^{-2} within the Piedmont and the Coastal Plain, respectively (Figure 3). Wetland swales had a mean C density of 5.04 ± 0.73 kg C m^{-2}; VSs without wetland characteristics had a mean C density of 3.05 ± 0.13 kg C m^{-2} (Figure 3).

The mean C density of Piedmont VFS/VSs and VSs is similar to that reported for grasslands (Table 1). The mean C density of Coastal Plain VFS/VSs is comparable to grasslands, and the higher C density to managed residential turf land use. The mean C density of wetland swales is comparable to that of turf.

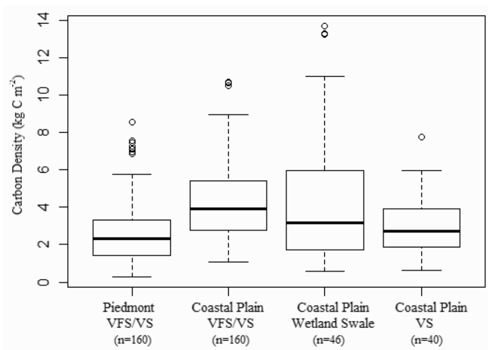

Figure 3. Boxplot of C density of upper 0-8 in soil depth within Piedmont and Coastal Plain VFS/VS, wetlands swales, and swales (reproduced with permission from Bouchard et al. 2013).

Table 1. Carbon density and sequestration rates from the literature.

Reference	Land Use	Depth Sampled (m)	Carbon Density (kg C m^{-2})	Sequestration Rate (kg C m^{-2} yr^{-1})
Pouyat et al. (2009)	Residential Turf	0-0.2	2.0-6.0	0.09
Golubiewski (2006)	Residential Turf	0-0.2	3.2-6.7	0.072
Kaye et al. (2005)	Residential Turf	0-0.15	4.4-5.0	NM
Conant et al. (2001)	Grassland	0-0.32	N/A	0.054
Unger (2009)	Grassland	0-0.2	3.5	N/A
Kaye et al. (2005)	Grassland	0-0.15	2.56-3.14	N/A

Maximum C Density

Each SCM in each region was tested independently to determine if site age affected C density. Per the ANOVA results, age class was significant in the Piedmont VFS/VSs only. No statistical relationship was found for any of the Coastal Plain sites: Coastal Plain VFS, dry VS, and Wetland Swale. Therefore, only the Piedmont VFS/VSs were investigated for C accumulation potential. Carbon density values were modeled with segmented regression (PROC NLIN) (Figure 4).

The segmented regression model predicted a maximum C density of 3.34 kg C m^{-2} (95% confidence interval of 2.51-4.16 kg C m^{-2}) at age ≥ 21.5 years. This "saturation age" range was somewhat similar to literature values; West et al., 2004 (modified from Jastrow et al., 1996) found land converted to grassland accumulated C at a higher rate (0.074 kg C m^{-2} yr^{-1}) within the initial 15 years, as compared to slower rates (0.065 and 0.054 kg C m^{-2} yr^{-1}) at 15-30 and 30-45 years, respectively. Figure 4 illustrates the individual mean Piedmont VFS/VS site C densities, as well as the segmented regression prediction. Barring abrupt physical, climatological, or anthropogenic disturbances, terrestrial systems are expected to accumulate C more rapidly following initial vegetation establishment, and decrease sequestration rates with time (West et al., 2004; Neill et al., 1998).

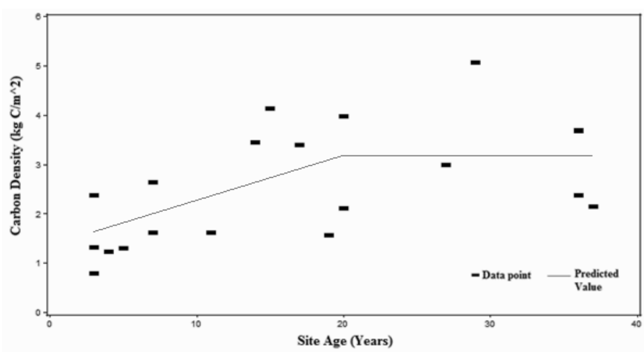

Figure 4. Results of segmented linear regression analysis of carbon sequestration versus age class.

The segmented model produced a C sequestration rate of 0.099 (PROC NLMIXED) or 0.155 kg C m^{-2} yr^{-1} (PROC NLIN), for the initial 21.5 years, and 0 kg C m^{-2} yr^{-1} thereafter. This higher C accumulation rate was comparable to residential turf land use (Table 1). Residential turf often receives varying levels of nutrient, and water management (Osmond and Hardy, 2004) which benefits biomass production and facilitates soil C accumulation (Conant et al., 2001; Pouyat et al., 2009; Golubiewski, 2006). Highway VFS/VSs receive fertilizers and lime at establishment but rarely thereafter. Stormwater runoff from adjoining impermeable road surfaces increases water content relative to a non-irrigated lawn. Another key difference between residential turf and highway VFS/VSs is mowing. Nearly half of residents remove grass clippings and therefore remove the ability for turf to accumulate soil C (Osmond and Hardy, 2004); grass clippings remain post-mowing in highway

VFS/VSs. Per Qian et al. (2003) when turf clippings were left on site, the turf increased C sequestration by 11-59% when compared to turf where clippings were removed during mowing. Perhaps the grass clippings left on highway VFS/VSs and the additional run-on water/nutrients partially offset the absence of either fertilizer or irrigation.

Ability of VFS/VS to Offset Carbon Emissions of Roadway Construction

Carbon footprints are associated with the mass of equivalent CO_2 released during the lifecycle of a product or project (Scipioni et al. 2010). Carbon accounting, or footprinting, sums C sources and sinks over a lifecycle. A large footprint indicates high GHG emissions. Globally accepted accounting standards do not exist, although agencies like the IPCC, the International Organization for Standardization (ISO), and the World Business Council for Sustainable Development (WBCSD) offer C accounting methodology (Scipioni et al. 2010; IPCC 2006).

Highway construction is C intensive, expelling GHGs through the mining and transportation of materials and installation of the roadway. Federal and state transportation agencies need to quantify possible terrestrial C offsets within the ROW. Cass and Mukherjee (2011) list the identifiable sources of CO_2 and GHG emissions of road construction and maintenance: 1) embodied C in construction materials, 2) direct emissions via fossil fuel combustion in material transport and construction, 3) embodied C in fossil fuels (processing and production of fuels, etc.), 4) removal of existing vegetation, 5) road resurfacing, and 6) direct emissions due to fossil fuel combustion in mowing and road maintenance.

Carbon dioxide emissions are impossible to precisely predict due to fluxes in vehicle fuel economy, transportation distance of materials, grade of road, necessary vegetation removal, and exact materials used. Cass and Mukherjee (2011) estimated that highway construction emitted between 200 – 300 tons C per lane km. Using the average measured width for VFS/VSs (5.9 m) in the Piedmont, the available VFS/VS footprint per km of roadway was calculated. Tons C sequestered by roadside VFS/VSs were compared to total emissions during roadway construction (Table 2).

Per kilometer of roadway constructed, the Piedmont VFS/VSs would offset between 3.9% and 6.8% of C emitted during construction, depending on which statistical model was used. The C accumulation of roadside VFS/VSs is small, but not unsubstantial, in the overall C footprint of roadway construction. However, increasing fuel efficiency, selection of less CO_2 intensive materials, and better management of construction practices would decrease the CO_2 emissions of construction and therefore require less offsets from other measures such as terrestrial sequestration.

Table 2. Piedmont VFS/VS C sequestration and fraction of recovered C within data timespan (37 years) to partially offset C emissions of roadway construction.

Factor	Piedmont Linear	Piedmont Segmented	Piedmont NLMIXED
ROW area (sq. km [km road]$^{-1}$)	0.0059	0.0059	0.0059
C sequestration rate (kg C m^{-2} year^{-1})	0.053	0.155	0.099
C sequestration rate (ton C [km road]$^{-1}$ year^{-1})	0.313	0.915	0.584
Years accumulating C	37	15	21
Plateau C Density (kg C m^{-2})	3.62	3.34	3.19
Tons C sequestered km road^{-1}	9.38	13.72	12.27
Expelled C in construction (tons C [km road]$^{-1}$)	200 - 300	200 - 300	200 - 300
Fraction of Construction C offset	3.9 - 5.7%	4.5 - 6.8 %	4.1 - 6.1%

CONCLUSIONS

Global quantification of terrestrial C stocks fails to identify specific urban land uses like roadside VFS/VSs and wetland swales. This study offers C density values to quantify the unique and extensive roadside environment. Average soil C densities within roadway VFS/VSs ranged from 2.55 ± 0.13 to 4.14 ± 0.15 kg C m^{-2} through a 0.2 m sample depth within the Piedmont and Coastal Plain, respectively. Wetland swales were found to have a higher C density (5.04 ± 0.73 kg C m^{-2}) than dry swales (3.05 ± 0.13 kg C m^{-2}). Thus, swales should be valued differently per their hydrologic condition, if C accounting should be implemented.

Piedmont VFS/VSs were the only SCM examined to have a temporal relationship with C density. The C sequestration rate within Piedmont VFS/VSs was measured at 0.099 kg C m^{-2} yr^{-1} until the C plateau at age=21.5 years. Utilizing the segmented model, roadway VFS/VSs were estimated to reach a C maximum of 3.34 kg C m^{-2}. The age range where VFS/VSs reach C maximum presented herein were comparable to literature values for grasslands and turf. The C density of roadside VFS/VSs was comparable to literature values for grasslands, and accumulation rates from this study were similar to grassland and turf values. Perhaps grasslands could be a surrogate land use for roadway VFS/VSs if no specific roadside data were available.

While no data regarding C sequestration in roadway soils have been reported in refereed literature, the Federal Highway Administration conducted a feasibility study to discern sequestration potential of vegetated ROWs and assumed a C sequestration rate of 0.17 kg C m^{-2} yr^{-1} for VFS/VSs based upon data from the Chicago Climate Exchange for grasslands (USDOT-FHWA, 2010). This perhaps overestimates true performance of highway VFS/VSs for carbon sequestration since (1) VFS/VSs (unlike grasslands) do not have deep rooted grasses, (2) the soils in VFS/VSs are highly compacted during construction, and (3) grasslands are often fertilized, while roadside shoulders typically are not. When compared to the segmented model, the C accumulation rates presented herein (0.099 and 0.155 kg C m^{-2} yr^{-1}), the FHWA model would substantially overestimate the C sequestration rate by a factor of 1.1 - 1.7. Furthermore, the rate assumed by the FHWA was not constrained to a timeframe. Utilizing the timeframe of maximum accumulation (21.5 yr), the Piedmont VFS/VS would accumulate 2.13 kg C m^{-2} (segmented model). If the FHWA C sequestration rate were applied using the 37-year timespan, it would predict an accumulation of 6.29 kg C m^{-2}, which is roughly three times the amount predicted in this study for the Piedmont. Since there was no increase in C in the coastal plain, the FHWA C sequestration rate grossly overestimates the ability of this practice to sequester C in this ecoregion. Consequently, it is important for any agency wishing to account for roadway vegetation and soil as a C sink to consider an appropriate timeframe when applying C accumulation rates. If an agency were granting C credits (or C offsets) for roadside VFS/VSs, the results associated with this research are more conservative than those associated with the FHWA calculator.

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Construction Ahead: Moving towards Sustainable Transportation Management Plans

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ABSTRACT

While transportation management plans (TMPs) are commonly developed to address work-zone safety and mobility needs of the traveling public during construction of highway projects, TMPs have yet to be firmly ingrained in the transit planning process. Coordinating and streamlining TMP strategies for both types of transportation projects is increasingly critical given the overlapping needs to maintain the operations of existing transportation systems during construction activities and the growing trend towards sustainability in transportation, including reducing traffic congestion and related air quality impacts. Beyond their traditional application, TMPs can serve as a means for accommodating the construction of transportation improvements while supporting the shift to more sustainable travel patterns after a project is in operation. This paper discusses the process for developing TMPs, while integrating strong sustainability principles. Topics that are addressed include: 1) current national and regional TMP guidelines; 2) harnessing the use of the internet, social media and mobile-based applications as part of the overall approach to informing the traveling public of construction-related transportation impacts and alternative means of travel; and 3) balancing cost-effective TMP strategies with promoting alternative transportation modes during construction and after a project opens. Proposed recommendations include how to integrate sustainability elements into TMP strategies, how to leverage TMPs to engage the public in minimizing transportation impacts during construction, and how to approach developing TMPs, especially for transit projects.

INTRODUCTION

A Transportation Management Plan (TMP) identifies a wide range of strategies to address work zone safety and mobility needs during construction of a project. Typically, a TMP is developed to address construction activities that affect highways or major roadways, with an emphasis on maintaining automobile access and circulation. This is not surprising, since for the past sixty years, the United States has been focused on the development, expansion and maintenance of the national highway system and roadways in metropolitan areas. Now with growing efforts to support alternative modes to driving, the resurgence of transit projects and a shifting mindset towards sustainability (including fostering livable communities and reducing greenhouse gas emissions), TMPs should evolve to address more than temporal traffic impacts to the roadway system.

In fact, TMPs have the potential to be part of a continuum of change that helps to achieve sustainability goals. When coordinated with broader sustainability efforts, a TMP can create synergy with related plans or programs aimed at balancing multiple needs on the transportation system. For example, TMPs could align with state climate action plans, regional transportation plans, long range transit plans, bicycle and pedestrian master plans, community plans, transportation demand management programs, and/or other sustainability initiatives. Furthermore, a TMP that incorporates sustainability principles is not necessarily more costly or complex, but instead can yield greater value for the thousands to millions of dollars spent on TMP strategies (depending on the size and intensity of a project, a TMP typically reflects a small percentage of the project cost up to 20 percent) (Pyeong et. al., 2012).

With this updated viewpoint, a “sustainable” TMP is a means not only for accommodating the construction of transportation improvements but also supporting the shift to more sustainable travel patterns after a project is in operation. The period of change during construction of a project (highway or transit) can be a time of trepidation, spurred by fear that businesses will be adversely affected by closures or that major routes of travel will potentially be disrupted. But it can also be a time of promoting flexibility, trying out new ways of travel, and anticipating positive changes to communities.

This paper examines current national and regional TMP guidelines and offers recommendations for developing a new prototype of TMPs that help with the transition to a more sustainable transportation system in the future. In particular, this paper discusses how TMP strategies, such as public information and demand management, can tie into sustainability goals. Demand management strategies are especially important in TMPs for transit projects, since they support longer-term plans for station access and transit-oriented development.

CURRENT NATIONAL AND REGIONAL TMP GUIDELINES

While TMPs are commonly developed to address work-zone safety and mobility needs of the traveling public during construction of highway projects, TMPs have yet to be firmly ingrained in the transit planning process. The Federal Highway Administration (FHWA) has established a set of guidelines and provides online resources for developing TMPs on projects that involve federal funding. In contrast, the Federal Transit Administration (FTA) does not have separate procedures governing work zone safety and mobility during construction of transit projects, suggesting an opportunity for TMPs on transit projects to adopt an approach that provides adequate attention to transit planning needs, and that fosters multi-modal access to planned station areas.

National TMP Guidelines

Nearly a decade ago, FHWA issued updates to the *Rule on Work Zone Safety and Mobility* (23 Code of Federal Regulations Part 630 Subpart J). The Work Zone Safety and Mobility Rule (Rule), published on September 9, 2004 in the Federal Register, required all state and local governments that receive federal-aid funding to comply with the provisions of the Rule no later than October 12, 2007. One of the requirements in the Rule stipulates that project-level procedures must identify projects that an agency expects will cause a relatively high level of disruption (referred to in the Rule as significant projects) and develop and implement TMPs for all projects.

The primary TMP guidance document provided by FHWA is *Developing and Implementing Transportation Management Plans for Work Zones* (December 2005). The three categories of TMP strategies discussed include: 1) Temporary Traffic Control, 2) Public Information, and 3) Transportation Operations (including demand management strategies and safety/incident management). FHWA also provides three other related guidance documents, including an overall Rule implementation guide, work zone public information and outreach strategies guide, and work zone impacts assessment guide.

State TMP Guidelines

Table 1 provides a summary of states, identified on the FHWA Work Zone Mobility and Safety Program website, which offer examples of state-developed TMP resources. All 12 states have, at a minimum, a checklist of TMP strategies or at least one resource document related to development of TMPs. Some states have multiple TMP resources and a few states, such as California, Maryland and New Jersey, provide greater depth of information on various topics, including public outreach, demand management, and other issues. For many of the states, the focus of TMPs is on traffic mitigation and maintenance of traffic plans. However, the requirements and needs of TMPs have been changing.

Table 1. Example State TMP Guidelines

State	TMP Resource		
	Date	Name(s)	TMP Strategies
California	2009	• TMP Guidelines • TMP Fact Sheet • Delay Calculation Example • Lane Closure resources	• Public Information • Motorist Information • Incident Management • Construction • Demand Management • Alternate Routes
Illinois	2007	• TMP Checklist • Significant Route Location Maps • Work Zone Safety and Mobility Process Flowchart	• Temporary Traffic Control • Public Information • Transportation Operations
Kansas	N/A	• TMP Checklist	• Temporary Traffic Control Plan • Traffic Operations • Public Information
Maryland	2006	• TMP Guidelines • Maintenance of Traffic Red Flag Summary • Work Zone Design Checklist • Work Zone Analysis Guide • Summary of Work Zone Impact Management Strategies • Public Information and Outreach Plans Development Guide • Public Information and Outreach Template	• Temporary Traffic Control • Project Coordination, Contracting and Accelerated Construction Methods • Transportation Operations • Public Information and Outreach • Incident Management
Missouri	N/A	• TMP Strategy Database • MoDOT's TMP Approach • Examples of TMP Executive Summaries	• Temporary Traffic Control • Public Information • Transportation Operations
Montana	2008	• TMP Presentation	• Temporary Traffic Control • Public Information • Transportation Operations
New Jersey	2007	• Traffic Mitigation Guidelines for Work Zone	• Construction and contracting • Traffic control and operations

State	TMP Resource		
	Date	Name(s)	TMP Strategies
		Safety and Mobility	• Public information • Motorist information • Travel demand management (TDM) • Incident management
Oregon	2010	• Project-Level TMP Guidance	• Motorist Information/ITS • Construction Strategies • Demand Management • Alternate Route Strategy • Incident Management • Public Information
Rhode Island	2009	• TMP Templates (for four levels of TMPs)	• Traffic-Related Work Restrictions • Temporary Traffic Control Plans • Public Information Plan • Transportation Operations Plan • Performance Monitoring Plan
Tennessee	2007	• TMP Workbook • Work Zone Safety and Mobility Manual	• Temporary Traffic Control • Transportation Operations • Public Information
Virginia	2009	• TMP Requirements Document	• Temporary Traffic Control • Public Information • Transportation Operations
Wisconsin	2011	• Facilities Development Manual • Work Zone TMP Development Courses	• Public Information • Transportation Operations Plan • Incident Management Plan

Source: Federal Highway Administration, Work Zone Mobility and Safety Zone website, http://ops.fhwa.dot.gov/wz/resources/final_rule.htm.

The California Department of Transportation (Caltrans) is one state that has taken steps to shift attention to other modes in addition to the automobile. The *Caltrans TMP Guidelines* (Caltrans, 2009) state that the "needs and control of all road users (motorists, bicyclists, and pedestrians within the highway, including persons with disabilities in accordance with the Americans with Disabilities Act of 1990 [ADA]) through a Temporary Traffic Control [TTC] zone shall be an essential part of highway construction, utility work, maintenance operations, and the management of traffic incidents."

In addition, Caltrans has issued guidance in support of promoting complete streets and pedestrian accessibility. Caltrans Deputy Directive 64-R–Complete Streets

(Caltrans, 2008) requires integration of the transportation systems with full consideration of non--motorized travelers (including pedestrians, bicyclists, and persons with disabilities) in all programming, planning, maintenance, construction, operations, and project development activities and products. This Caltrans directive supports California Assembly Bill 1358, the Complete Streets Act, which passed in 2008.

Some of the state-developed TMP resources were developed up to seven years ago (between 2006 and 2011), following the period when the national TMP guidelines were established by FHWA in 2005. Since then, there have been advances in technology and emerging trends that should be taken into consideration in developing TMPs, such as the rapid spread of social media, growing use of car-sharing in urban areas, and greater interest in promoting active transportation (walking and bicycling). As discussed further in the following sections, two key areas where TMPs can incorporate sustainability principles, as well as other emerging trends, are through public information and demand management strategies.

The following sections provide more detailed discussion and recommendations for public awareness campaigns and demand management strategies in TMPs to support sustainability. Working in concert, these strategies promote choice and balance in meeting transportation needs during construction, while maintaining economic vitality and reducing environmental impacts. In other words, the proposed approach to public awareness campaigns and demand management strategies can complement supply-side strategies that are focused on roadway capacity and operations, to more effectively achieve the triple bottom lines of sustainability – social, economic and environmental goals.

THE NEW AGE OF PUBLIC AWARENESS CAMPAIGNS

Engaging, accurate, and timely public information is a key element of a successful TMP. This section describes best practices for crafting a Public Awareness Campaign (PAC) during construction of a project, which can easily build upon outreach efforts conducted during the project development phase and incorporate sustainability themes. An effective, wide-reaching PAC uses a variety of communication methods, including web-based tools, to keep the public informed of transportation conditions and safe travel options during project construction.

The PAC should engage the public in efforts to minimize transportation impacts and maintain accessibility during construction – with the key objective of encouraging travelers to plan ahead. The proposed approach to the PAC, as part of a sustainable TMP, includes the following main steps: 1) Coordinate with key stakeholders and maintain involvement through a TMP Working Group, 2) Develop consistent branding and messaging on travel preparedness, along with a positive outlook on longer-term project benefits, 3) Promote ongoing public participation through technology and resources such as a project website, 511, trip-planning tools, social media, and mobile applications.

Coordination with Key Stakeholders

Public information and outreach efforts can be time consuming and resource intensive. However, when citizens feel their concerns have not been adequately addressed, costly project delays, lawsuits, and even project cancellations can occur (Maryland State Highway Administration, 2006). Key stakeholders that should be included in the development and implementation of TMPs are elected officials, local jurisdiction representatives, transportation agencies, transit operators, bicycle and pedestrian advocates, institutions, major employers, goods movement representatives, schools, community groups, and other interested parties. These stakeholders are typically engaged during the project development phase and environmental process through participation in groups such as a Community Advisory Committee or Technical Advisory Committee. Similarly, they should be engaged during the construction phase through a TMP Working Group.

One of the most important outreach efforts in a sustainable TMP is supporting the business community. Project support is often swayed by the perceived effect on businesses during construction. Transit projects especially require careful attention towards maintaining local access to businesses during construction, since transit alignments may be located along local streets as well as major travel corridors.

For the Central Corridor light rail project in Minnesota, outreach to businesses has been a critical component of the PAC. The Metropolitan Council contributed $2.5 million of $4 million to a small business forgivable loan fund being administered by the City of St. Paul (Metropolitan Council, 2013). The Metropolitan Council also partnered with the cities of St. Paul and Minneapolis and nonprofit organizations to create the Business Resources Collaborative. As part of a $1.2 million marketing campaign, the Metropolitan Council provides free bus side ads and billboards for corridor businesses and print and online business directories.

Still, the business community along the Central Corridor indicated that project construction has resulted in loss of business above anticipated levels. The head of the Asian business group, Va-Megn Thoj said, "he knows of business owners who have reported losses up of to 60 percent. He notes that the Federal Transit Administration and the Met Council last year issued a report predicting construction would lead to revenue losses of 0 to 2.5 percent" (Yuen, 2012). Estimating potential revenue loss due to construction impacts is difficult, which is why engaging the business community through the TMP Working Group is necessary to gain input on the effectiveness of mitigation measures.

Close coordination with key stakeholders, such as the business owners and surrounding community, can help to focus and refine TMP strategies. Maintaining access to businesses through a multi-modal approach can also help alleviate impacts due to the reduced traffic flow through a construction zone or adjacent neighborhoods. For local jurisdictions, the fiscal impact related to reduced economic revenues is a major concern during construction. Therefore, it is important to reduce construction-period congestion and provide viable alternatives for travelers to access local businesses, as well as promote businesses through marketing efforts.

Branding and Messaging

Using distinctive project names and trademark graphics, logos and catchphrases, otherwise known as branding, can be an effective method of getting the target audience(s) to easily recognize any information related or pertaining to the work zone (Maryland State Highway Administration, October 2006). By obtaining input and monitoring issues raised through stakeholder coordination, the branding and messaging related to a project during construction can be tailored to engage the public in mitigating transportation impacts.

On the one hand, negative perceptions of potential transportation impacts, such as use of the term "Carmaggedon" in anticipation of major closures on the I-405 Improvement Project in the Sepulveda Pass Corridor in Los Angeles County, can be effective in modifying travel behavior. However, as a result of reduced travel during the closures, businesses within the project corridor are adversely affected and the public may avoid the construction area during prolonged periods, not just during major closures.

Positive messages that encourage the public to be proactive can be equally effective and support sustainability efforts. For example, the FHWA Work Zone Public Information and Outreach Strategies Guide includes an example of such a campaign developed in Arkansas. In 2000, the Arkansas State Highway and Transportation Department (AHTD) set out to rebuild or resurface over 350 aging Interstate miles in a five-year time frame. Realizing that serious crashes and traffic delays could have a negative effect on the program's accelerated time frame, AHTD created a safety and information campaign entitled "Pave The Way" along with the sub-theme, "Think Ahead." Through the campaign, motorists were encouraged to plan for construction while staying focused on the end result of the improvements (FHWA 2005).

More recently, the City of Santa Monica has engaged its residents through a "Be Excited, Be Prepared" campaign featuring the catchphrase "Know Before You Go" in anticipation of the construction impacts due to the Expo 2 light rail and other near-term projects affecting the city roadways. The campaign encourages residents to plan travel routes ahead of time and adjust travel patterns as needed based on available construction-related information.

Internet-Based Resources: Information on the Go

Traditional communication methods for disseminating information about project construction include: brochures and mailers, media releases and public notices to local print, radio, and television sources; print notices displayed at activity centers along the corridor (e.g. community and shopping centers), public open house meetings, and a telephone hotline. Disseminating information via these sources forms a strong foundation for a PAC. As smart phones are more accessible than in years past, employing the use of internet-based resources is becoming increasing popular among the traveling public and transit agencies. Internet-based resources can be more cost-effective and sustainable in comparison to print-based communication. Internet-based resources include: project website, e-mail blasts, trip planning websites, and social media.

People are increasingly accessing the internet using mobile devices, allowing them to access information “on the go.” In 2012, 88 percent of American adults owned a cell phone or smart phone, 57 percent owned a laptop, 19 percent owned an e-book reader, and 19 percent owned a table computer (Zickuhr, 2012). Mobile access is also changing the nature of the traditional digital divide. Among smart phone users, young adults, minorities, and those with lower household incomes and educational attainment levels are more likely than other groups to report that their phone is their main source of internet access (Zickuhr, 2012).

Multimodal trip-planning tools include web-based planning tools that help the traveling public plan trips in advance. To the degree possible, information about the duration, location and types of construction activities should be provided to the organizations that maintain these websites. Commonly used trip-planning websites in include: 511, Google Transit/Maps, Bing Maps, Waze, NextBus. In addition, many transportation agencies provide a trip-planning tool on their own websites. Trip-planning websites also provide users with information on how to use alternative modes of travel during construction, such as walking, bicycling, public transit, car-sharing, and ride-sharing/carpooling, thus encouraging commuters to travel more sustainably in both the short and long term. Travelers who try an alternative mode of travel during construction may be encouraged to continue using an alternative travel mode after construction is complete, contributing to a healthier, more sustainable environment.

Social media are defined as a group of web-based applications that encourage users to interact with one another, such as blogs, Facebook, LinkedIn, Twitter, YouTube, Flickr, Foursquare, and MySpace (Bregman, 2012). Different social media networks have different strengths, and should be utilized according to the reach and purpose of the message (Kaufman, 2012). Twitter offers immediate, short-form messaging, as the number of characters in each tweet restricted to 140. An example of a message appropriate for twitter would be: “Delays on the northbound I-405 due to emergency vehicle access to work zone.” Facebook works best for non-urgent messaging of shareable content, such as advance notification of construction activities and planned roadway closures. Flickr, YouTube, and Instagram offer dynamic content and illustrative information, such as photographs of construction progress or maps of detour routes. Web-based resources have the added benefit of reinforcing important message across multiple channels. For example, updated information about closures on the project website can be reinforced by linking to it through a tweet or Facebook post. The reach of this information spreads as users share this information to their networks. At the same time, comments and feedback from the public can also be easily collected and shared.

Engaging the traveling public at the project-level is important and is generally received well by the traveling public. For example, during construction of the LA Express Lanes, a high-occupancy toll lane project implemented by the Los Angeles County Metropolitan Transportation Authority, multiple social media platforms were employed using both English and Spanish language. The use of social media platforms boosted engagement by 300 percent in the first three months, in terms of number of followers who took action in response to a post by liking, commenting, and/or sharing the message within their networks (Cole, 2013).

PROMOTING ALTERNATIVE TRANSPORTATION MODES

In coordination with public information strategies, TMPs should include demand management strategies that support multiple travel modes and traveler choices on how and when to travel. Demand management strategies may be aimed at encouraging motorists to travel in carpools or vanpools, providing shuttles for construction workers to park off-site, or promoting variable work hours to reduce the typical peak-hour traffic volumes within areas affected by construction. Demand management strategies should also support the continued use of alternative modes of transportation such as walking, bicycling, or public transit, even during temporary closures of roadways, bicycle paths, and pedestrian facilities required for construction. If the correct incentives and disincentives are used to facilitate shifts to alternative modes, demand-side strategies can reduce vehicle trips and vehicle miles traveled (VMT) by 10 to 20 percent (Association for Commuter Transportation, 2004).

There are several ways to integrate sustainability elements into demand management strategies, including the following steps: 1) support state, regional, local and community sustainability goals by promoting multi-modal travel options; 2) build on demand management programs already available within the project corridor or area; and 3) consider station access needs and transit oriented development plans related to transit improvement projects.

A Multi-Modal Approach

According to the FHWA Work Zone Public Information and Outreach Strategies Guide (2005), during the Springfield Interchange Project, the Virginia Department of Transportation (VDOT) developed a wide range of commuting options that it publicized on its project website and elsewhere. Transit, bicycling, ridesharing, and telecommuting were among the transportation alternatives that were promoted. Transit services and promotions included extra commuter trains and buses for residents to avoid the Springfield Interchange, a local bus service to travel throughout the Springfield business district, free parking and a shuttle running from the nearby Springfield Mall to the Franconia-Springfield Metro Station, information for employers and employees on how to get tax-free transit benefits, and directions on how and where to buy transit tickets and to get more information. Bicycling information that was disseminated by the project covered taking bikes on transit, good bicycling routes, and lockers. To promote ridesharing, the project provided information on starting a buspool, carpool, or vanpool, new and bigger park and ride lots in the I-95 corridor affected by the project, and a guaranteed ride home program. In addition, the project implemented a program known as "telework!va" that was designed to help a company start or expand a telework program with financial support from the State of up to $35,000.

Based on VDOT's aggressive congestion mitigation effort, record numbers of commuters took advantage of a variety of VDOT-funded alternatives to driving alone through the construction area. With the help of VDOT funding, patrons took advantage of the Springfield Mall shuttle bus to the Metro; dozens of new vanpools were created, and passengers used the Mixing Bowl Express bus from Prince William County to Washington. During the construction between 1999 and 2007, the project area did not see any marked increase in traffic congestion, likely because drivers modified their travel patterns accordingly, and because of VDOT's congestion management plan (Roads to the Future, 2007).

Supporting and Augmenting Existing Demand Management Programs

For many projects, especially those that are smaller in scale than the Springfield Interchange Project discussed above, there might be limited funding for demand management strategies. However, careful consideration can be given to developing detours that also accommodate the needs of bicyclists and pedestrians, improving the convenience of relocated bus stops for transit riders, and including construction-period signage to encourage travelers to share the road. In addition, targeted funding and additional marketing to enhance existing demand management programs can help to encourage carpooling/vanpooling, alternative transportation modes and other strategies that support transit use.

One emerging trend that TMPs can leverage is carsharing, as an innovative alternative to vehicle ownership. Car-sharing services are generally short-term rental car programs that provide members a means to use a car on an as-needed basis, without the cost and responsibilities of auto ownership. Examples of carshare programs include Zipcar, Car2Go and RelayRides. College campuses, dense urban cores, and communities with high rates of transit-dependence are just a few of these places where carsharing has grown rapidly (TCRP, 2005).

The emergence of carsharing has potential implications for improving mobility and access during the construction phase of projects. For a given project, delays associated with closures and detours can decrease the level of access that people have within the affected area. Carsharing can support reduced use of automobiles and allow transit users to complete "first- and last-mile" connections. For example, carsharing might allow commuters to use transit for their main mode of travel, either by providing the means to drive to a transit station or to use a car at their arrival station to reach their final destination. Additionally, carsharing located in proximity to transit hubs (current and future) can prepare travelers to continue using transit service when a new transit extension or improvement opens for service. Thus, carsharing can function as a short-term solution to mitigate mobility and access issues associated with construction of projects and as a potential long term strategy to make it easier for people to shift at least a portion of their trips from car to transit. This could generate beneficial effects for the environment over the long-term by reducing greenhouse gas emissions from private vehicle trips.

An important concern for transit agencies and cities is the cost of implementing such strategies. Cities across the U.S. have recently begun pursuing strategic partnerships to leverage their existing resources and the strengths of their partners, with the goal of financing projects and other programs in cost-effective ways. For instance, Smart City San Diego is a multi-year collaboration for developing innovative and sustainable energy initiatives throughout the City of San Diego, including carsharing. Smart City leverages the resources of the City of San Diego, San Diego Gas & Electric, General Electric, UC San Diego and CleanTECH San Diego (Smart City San Diego, 2012). Demand management strategies included in TMPs can be cost-effective by promoting existing carsharing programs and other similar initiatives already in place, and supplementing marketing efforts and funding where feasible.

Transit Planning Considerations

TMP preparation can effectively supplement demand management programs by incorporating transit oriented development (TOD) goals, supporting station access and circulation, and providing short- and long-term transit and alternative transportation options. Transit projects in particular benefit from shifts to alternative transportation modes that can be appealing to travelers during period of construction. With increases in mode share by non-motorized travel alternatives, less parking might be needed at transit stations and the walkability of a station area is enhanced, thereby supporting transit-oriented development goals in the long run. Transit-oriented development is typically defined as more compact development within easy walking distance of transit stations (typically a half mile) that contains a mix of uses such as housing, jobs, shops, restaurants and entertainment (Reconnecting America, 2013). Transit-oriented development creates walkable, sustainable communities for people of all ages and incomes and provides improved transportation and housing choices (Reconnecting America, 2013).

Transit-oriented development is an area of sustainability that is anticipated to receive funding under the recently passed federal transportation legislation. MAP-21, the Moving Ahead for Progress in the 21st Century Act, signed into law by President Obama on July 6, 2012, creates a new $10 million planning pilot program for transit-oriented development that will provide funding to communities with a New Starts grant to do station area planning (National League of Cities, 2012). The pilot program includes transit-oriented development planning grants, which provide funding for projects that enhance economic development, ridership, and other goals; facilitate multimodal connectivity and accessibility; increase access to transit hubs for pedestrian and bicycle traffic; enable mixed-use development; identify infrastructure needs associated with the project; and include private sector participation (FTA, 2012). TMPs for transit projects can help to foster progress towards transit-oriented development during construction through supportive measures in the areas of public information and demand management strategies.

SUMMARY OF RECOMMENDATIONS

As discussed above, the proposed approach for developing a sustainable TMP includes engaging the public to plan ahead for construction-period travel conditions, encouraging flexibility in travel patterns, and supporting accessibility for multiple transportation modes. A summary of key recommendations is provided below.

Public Awareness Campaign (PAC)

Public information strategies are already identified by FHWA and various states as a key component of a TMP. To enhance the effectiveness of TMPs, a public awareness campaign (PAC) should build upon outreach efforts established during the project development process and capitalize on the use of the internet, social media, and mobile-based web applications to keep the public informed of transportation conditions and available options during project construction. Tapping into the public's desire for reliable travel information and the popularity of social media allows the public to be an active and important participant in the implementation of a TMP. Specific recommendations related to public awareness campaigns to support sustainability include:

- Coordinate with key stakeholders (elected officials, local jurisdiction representatives, transportation agencies, transit operators, bicycle and pedestrian advocates, institutions, major employers, goods movement representatives, schools, community groups, etc.) and maintain involvement through a TMP Working Group.
- Develop consistent branding and messaging related to preparedness during project construction and a positive outlook on longer-term project benefits.
- Provide timely information, in concert with media partners, on travel conditions through the project area during construction and options for adjusting travel patterns and/or mode choices.
- Promote ongoing public participation through a project website, 511, trip-planning tools, social media, mobile applications, etc.

Demand Management Strategies

Demand management is often a subset of transportation operations strategies, rather than given similar weight as temporary traffic control and public information strategies. Aside from providing detours for roadway closures, one of the critical strategies to reduce construction-period traffic congestion is to promote alternative ways of traveling, including public transit, telecommuting, variable work hours, car-sharing, ridesharing/carpooling, and active modes such as walking and bicycling. Rather than serve as a stand-alone program, a TMP should tie together relevant transportation demand management programs that might already be in place within the project area or corridor, and add enhancements where deemed necessary and cost-effective. The benefits of supporting alternative transportation modes during construction are especially important for transit projects, which require consideration of 'first and last mile" connections to stations over the long-term. Therefore, demand management strategies should also be a critical component of TMPs, as they directly support sustainability goals. The approach to demand management strategies in TMPs should include the following:

- Maintain consistency with state, regional, local and community sustainability goals.
- Coordinate with strategic partners/key stakeholders representing multi-modal perspectives.
- Build upon demand management programs already available within the project corridor or area, including existing transit services, rideshare programs, carshare services, and other transportation demand management programs or plans.
- Focus in particular on audiences who may be receptive to demand management strategies (such as schools, universities, major employment and activity centers, etc.).

TMPs for Transit Projects

With respect to TMPs for transit projects, additional recommendations include:

- Use a similar framework as developed for highway projects, but also consider multi-modal access needs to support businesses along local routes affected by transit construction.
- Tailor PAC and demand management strategies to support transit-oriented development goals, station area plans, and alternative transportation plans.

CONCLUSION

A TMP can be a powerful tool for helping to shape changes in travel behavior that support sustainability goals. While they are used to manage construction impacts of a project, a TMP can be more than a mitigation measure or a box that must be checked off to address environmental regulations. The proposed new form of a TMP aligns with emerging trends in how a community envisions travel that is more environmentally friendly, while serving the needs of residents, businesses, and visitors. By supporting broader livability and sustainability goals, a sustainable TMP helps to maximize the value of project funds used for mitigating transportation impacts and supports positive change in travel behavior and the transportation system.

Integrating sustainability principles in TMPs will help to achieve the following long-term benefits:

- Promote increased awareness of transportation alternatives
- Engage the traveling public in making informed decisions on when and if to travel, what routes to take, and what modes to use

- Evaluate transportation issues during construction holistically and develop TMPs that contribute to the overall effort towards sustainability, including the triple bottom lines of social, economic and environmental goals
- Maximize the value of limited transportation dollars
- Support positive changes in travel behavior that can continue past the construction period

This paper represents a first step towards redefining TMPs to incorporate sustainability principles, particularly through public information and demand management strategies. In addition, TMP strategies for transit projects should be coordinated with transit-oriented development planning to support the vitality of future station areas. Proposed next steps should involve updating TMP development resources (including guidelines, example documents, and templates) to reflect this shift in focus towards sustainable TMPs and to reassess the appropriate measures of effectiveness used to evaluate TMPs (including mode split and local accessibility as well as mobility and safety).

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Applying Sustainable Practices to the Roadway Improvements of East Rosedale Street in Fort Worth, Texas

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ABSTRACT

This paper describes the Envision™ Sustainable Infrastructure Rating System, recently published by the Institute of Sustainable Infrastructure (ISI), and how the sustainable practices outlined by the rating system were applied to the East Rosedale Street Improvement project in Fort Worth, Texas. The design team at Freese and Nichols, Inc. (FNI) and the City of Fort Worth (City) used collaborative efforts to look at the project as a whole and evaluate how the project impacts the community, the environment, and the economics of the area. While looking through the lenses of the Envision™ Sustainable Infrastructure Rating System, the engineering team at FNI, along with the team at the City, collaborated to develop a roadway that would improve pedestrian and vehicular safety and efficiency, incorporate the priorities of the local community, improve the local environment, and showcase the rich history of the region. The Envision™ Sustainable Infrastructure Rating System proved to be a beneficial guide for decision making by providing a framework for meeting sustainability goals. Through the use of the Envision™ Sustainable Infrastructure Rating System, FNI and the City designed the East Rosedale Street Roadway Improvement project in a manner that will be beneficial to the surrounding community now and for years to come.

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EAST ROSEDALE STREET ROADWAY IMPROVEMENTS

Introduction

The East Rosedale Street project corridor is located in East Fort Worth, southeast of the Interstate 30 and Interstate 35 West Interchange. This project spans approximately two miles between US 287 and Miller Avenue. The roadway, East Rosedale Street, is of high importance to the City of Fort Worth (City) and was the main street for the Polytechnic Heights community in 1900 and is still considered, by many in the community, to be the heart of Southeast Fort Worth. Along the roadway corridor lie many influential businesses, parks, places of worship, schools, and, most notably, Texas Wesleyan University.

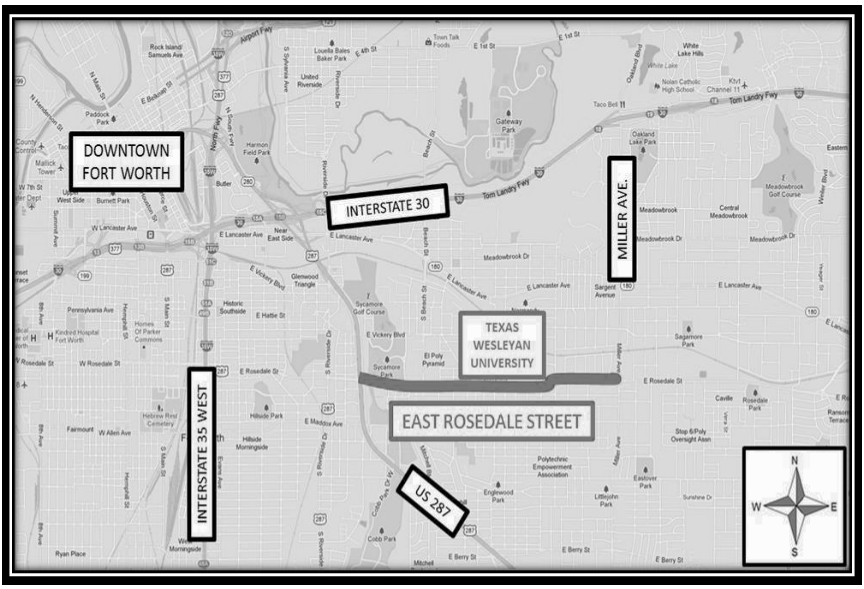

Figure 1 – East Rosedale Street Project Location Map.

In the early 1990's the City of Fort Worth began discussions with local stakeholders along East Rosedale Street about reconstructing the roadway and the importance of the Polytechnic region to the City of Fort Worth, which hadn't seen major construction since the 1930's. The eagerness and the excitement over the roadway project and its possible revitalization of the Polytechnic sector of Fort Worth was apparent from all involved. Due to the anticipation and the expectations that came along with this project, the design team at Freese and Nichols (FNI) and the City had a heavy task on their hands. All involved parties knew that this proposed project needed to be special, unique, and meaningful. In an effort to improve the project and design, the team adopted the Envision™ Sustainable Infrastructure Rating System, using it as a check criterion to the project decisions and design elements.

THE ENVISION™ SUSTAINABLE INFRASTRUCTURE RATING SYSTEM

Introduction

Recognizing the need for a collaborative approach to improve the nation's infrastructure the American Society of Civil Engineers (ASCE), American Public Works Association (APWA), and American Council of Engineering Companies (ACEC) formed the Institute of Sustainable Infrastructure (ISI) in 2010. ISI then partnered with the Zofnass Program for Sustainable Infrastructure at Harvard University to develop the Envision™ Sustainable Infrastructure Rating System in 2011. This rating system is dynamic in nature and evaluates sustainable performance of all types of infrastructure projects. A few goals of this system are to promote higher performance solutions that consider the life-cycle of the project, to provide infrastructure projects that have a positive impact on a community, and to incorporate restorative and innovative designs into the infrastructure project. The Envision™ Sustainable Infrastructure Rating System was created to evaluate an infrastructure project through a holistic approach and across the economic, social, and environmental sectors. These three sectors of an infrastructure project are considered to be the "triple bottom line" and are of highest importance when evaluating a design. This rating system is unique in nature because it challenges design teams to ask themselves the question, "Am I doing the right project?" rather than the typical question, "Am I doing the project right?"

The Envision™ Sustainable Infrastructure Rating System evaluation metric consists of five evaluation categories. These five categories are Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. Within these five categories, there are fourteen subcategories and sixty overall credits. These credits are numerical values given to a certain aspect of an infrastructure project to help assess the infrastructure project's sustainable performance. The credits range in value according to the level of achievement of the proposed actions. The levels of achievement in order of lowest to highest credit value are as follows: Improved, Enhanced, Superior, Conserving, and Restorative.

Quality of Life

The purpose of the Quality of Life category is to evaluate and assess the impact that the project is making on the surrounding community in a physical, economical, or social fashion. This category requires the engineer or designer to research and ensure that the infrastructure project meets the current and future goals of the community and the roadway system surrounding the project. Due to these requirements, the designer must meet with the stakeholders along the project corridor to verify the project they are designing will be seen as a benefit now and in the future.

The FNI design team and the City wanted to give the Polytechnic community a roadway that would be a clear investment into their community and one that would reflect their historic community. The design team achieved this through creative roadway elements along the project corridor.

First, FNI and the City wanted to make East Rosedale Street a more pedestrian friendly and walk able corridor. This was achieved by increasing sidewalk widths, reducing the roadway width to encourage slower vehicular speeds, the addition of street furniture, the addition of wayfinding signs, increasing the amount of pedestrian and street lighting, and creating safer pedestrian crossings across East Rosedale Street. The hope is that the addition of these elements will encourage citizens to walk the roadway corridor, accessing local business, places of worship, and schools and be safe while doing so. See Figure 2 for a picture of the existing sidewalk conditions and an artistic rendering of the proposed decorative sidewalk and street furniture near Texas Wesleyan University.

Figure 2 - Existing and Proposed Pedestrian Elements along Texas Wesleyan University.

Secondly, the design team wanted to display the history of the community through the roadway improvement project. To learn more about the history of the area, the design team met with a local historian and conducted numerous interviews with community members. These meetings and interviews allowed the design team to understand the important historical landmarks, views, and persons within the community. After these interviews, the design team identified four locations along the roadway where the history of the area would best be showcased. At these four locations, a historical kiosk was designed to be placed in a common area along the sidewalk. These historical kiosks would include pictures and a description of the historical element. See Figure 3 for an artistic rendering of the proposed historical kiosk at the intersection of Binkley Street and East Rosedale Street. Along with the historical kiosks, banners were designed to be placed on the light poles to showcase a color, shape, or set of words that represent the local community. The purpose of these elements is to bring a sense of pride out of the community and into the roadway design.

Figure 3 – Existing and Proposed Elements at Binkley Street and East Rosedale Street.

Third, the design team designed one roundabout on the west end of the project (Mitchell and East Rosedale intersection) and one roundabout on the east end of the project (Ayers and East Rosedale intersection). These roundabouts not only will help traffic flow through these intersections, but they are also intended to give drivers the feeling of entering and exiting of a community. These roundabouts will have a combination of public art and decorative landscaping. With public art and decorative landscaping as centerpieces, these roundabouts are designed to "book-end" the community and once again give the Polytechnic community a sense of pride. These proposed elements will be a far cry from the overhead span wire traffic signals and excessively large areas of impervious, asphalt pavement that currently litter these intersections. Figure 4 shows the existing conditions and the proposed roundabouts at the Mitchell and Ayers intersections with East Rosedale Street.

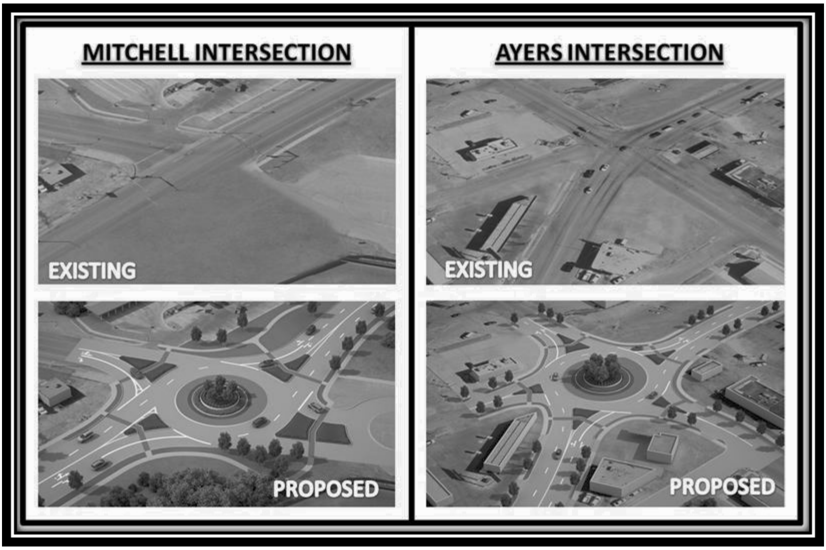

Figure 4 - Existing Conditions and Proposed Roundabouts at the Mitchell and Ayers Intersections.

Finally, the design team re-aligned the existing Nashville Street and East Rosedale Street intersection to increase the safety of the intersection. The original intersection at Nashville and East Rosedale Street was at a forty-five degree skew, had inadequate sight lines, and was dangerous to maneuver. Many local citizens expressed that they avoided the intersection at all costs. To help increase the safety of the intersection, the alignment of Nashville Street was modified to intersect East Rosedale Street at a ninety-degree angle. As the design team coordinated with the City, it was determined that the best use for the original Nashville Street right-of-way would be as an expansion to an existing public park. This right-of-way conversion allowed the existing public park, adjacent to Nashville Street, to grow to almost double its original size and be a benefit to the local community.

Leadership

The purpose of the Leadership category is to evaluate, assess, and promote collaboration between the design team, the client, the stakeholders, and the general public. This collaboration allows all ideas, goals, and perspectives to be shared early on and throughout the design process. It is important to keep this long-term project view so that potential pitfalls can be avoided and future plans can be made and accommodated in the proposed project design.

To meet the criteria of the Leadership category FNI and the City held numerous meetings with stakeholders and the public. A Citizen Advisory Committee was also created to incorporate the ideas and goals of the community into the East Rosedale Street design.

FNI and the City held three public meetings during the design phase of the project. All public meetings were held along the project corridor, one of the meetings was held at the local Polytechnic High School and two were held at Texas Wesleyan University, giving the local community a sense of inclusion and involvement. These public meetings we held to inform the public of the design process, provide stakeholders the opportunity to speak to the public, and provide proper roundabout maneuvering education to the public. Through these public meetings, the local citizens gave helpful insight to the City and the project team on areas of concern and aspects of the existing roadway they would like to see improved.

Along with public meetings, FNI and the City also conducted three meetings with an Advisory Committee which represented the local high school, Texas Wesleyan University, local churches, and other various entities. This committee was formed to gather community input to incorporate into the project design. During these three meetings, the Advisory Committee was able to give their input and preference on roadway elements such as street lights, site furniture, sidewalk configuration, and roadside parking. These meetings proved to be beneficial to the design team and gave the community a sense of involvement in the design process.

Finally, FNI and the City also held 14 meetings with numerous stakeholders along the project corridor. These stakeholder meetings provided value to the project, specifically to the proposed roundabout design, roadside parking layout, sidewalk alignments, and sidewalk widths. These elements were able to be designed to accommodate the future plans of the stakeholders along its corridor. Through research and meetings, the design team discovered plans for a street car to be installed along East Rosedale Street in the future. Knowing this, the roadway was designed at a one and a half percent cross slope, versus a typical two percent cross slope, and all of the underground utility lines were removed from the outside travel lanes where the future street car would run. These requirements were uncovered through stakeholder meetings and saved the client future time and money in reconstruction and relocation costs.

Resource Allocation

The purpose of the Resource Allocation category is to guide the design team in being mindful of and reducing the amount of natural resources used during the construction and the operations phase of an infrastructure project. Not only does this category have an emphasis on the natural resources itself, but it requires the design team to be mindful of the energy usage required during both the extraction process and the transportation process of these resources. There is potential that extracting a natural resource not only depletes the amount of that particular natural resource, but the fossil fuels required to extract that resource can also be depleted. One key natural resource that is emphasized numerous times throughout the Envision™ Sustainable Infrastructure Rating System is water. In the future, as the population increases and the availability of potable water decreases, the reduction of use and the reuse of water will be more important than ever. The Envision™ Sustainable Infrastructure Rating

System is built to have the design engineer study and report the balance between water consumption during the lifecycle of the project and water availability.

During the design and planning phase of the East Rosedale Street Roadway Improvements project, the Resource Allocation category was used to evaluate and reduce the use of natural resources during the construction of the project as well as in the future.

Through historical research and soil borings, it was determined that East Rosedale Street was once a brick roadway. Over the years, asphalt overlay projects created a barrier from the roadway surface to the top of the original brick roadway. The City found value in the existing brinks, so measures were taken to salvage the existing brick. During the construction phase, the contractors will remove, palletize, and relocate the bricks to a location directed by the City. By salvaging the mentioned bricks, the City will be diverting waste from local landfills and stockpiling quality resources for future use.

Natural World

The purpose of the Natural World category is to have the design team study the project location and evaluate the potential impacts that the proposed actions may have on the surrounding environment. With the complex and high levels of biodiversity surrounding many project sites, it is important that the proposed actions interact with these surroundings in both a synergistic and positive fashion. These areas of biodiversity not only exist on land, but they exist in water as well. The Envision™ Sustainable Infrastructure Rating System sees the geologic and hydraulic conditions as having high value and any negative impact to these areas should be reduced or eliminated.

During the design of the East Rosedale Street Roadway Improvement project, one of the goals of the City was to improve the bridge and creek conditions at the intersection of Sycamore Creek and East Rosedale Street. Currently, when larger, more intense storm events occurred, the Sycamore Creek Bridge causes a backup in the floodwaters and local homes and business have a high potential of flooding. As seen in Figure 5 below, the pre-project 100-year floodplain encompasses many homes and businesses. Due to the existing bridge's historical significance to the City of Fort Worth, the existing bridge was to remain unmodified and a floodplain relief bridge, adjacent to the existing bridge, was designed. The relief bridge was designed to lower the floodplain upstream of the bridge by increasing area in which the floodwaters could pass through the crossing at East Rosedale Street. As seen in the post-project boundary in Figure 5, the proposed floodplain relief bridge design successfully removes twenty-two structures from the 100-year floodplain.

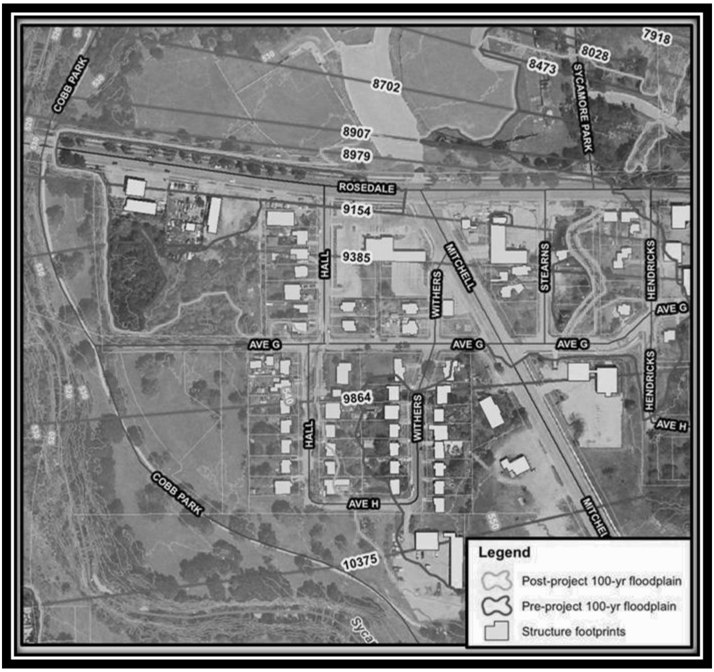

Figure 5 – 100-Year Floodplain Reduction Map at Sycamore Creek.

Climate and Risk

The purpose of the Climate and Risk category is to have the design team research and minimize the harmful emissions from the proposed infrastructure project over the entire life-cycle of the proposed action. Along with reducing the emissions during the life-cycle of the project, the Envision™ Sustainable Infrastructure Rating System challenges the design team to look at increasing the adaptability and decreasing the vulnerability of the project to ensure a longer useful life. This requires the design team to think through many short-term and long-term risk scenarios and design an infrastructure project that can adapt accordingly. As with many of the other categories within the Envision™ Sustainable Infrastructure Rating System, it is critical that the design team examines that the project being constructed will meet not only the current needs of the community, but the future needs as well.

During the design and planning phase of the East Rosedale Street Roadway Improvements project, the Climate and Risk category was used to evaluate and assist the design team in making key decisions on the short term and long term risks of the project. Two actions were taken by the design team to design a roadway that reflects heat rather than absorb heat and to help reduce harmful emissions through its life cycle.

FNI and the City decided to construct a reinforced concrete roadway to replace the existing asphalt roadway. With the installation of the concrete roadway, a high solar reflectivity index (SRI) value will be given to the roadway relative to the low SRI value that the previous asphalt roadway section achieved. This increase in SRI value will minimize the localized heat acumination, or heat island effect, along the roadway corridor.

Sustainability Performance

With the proposed actions as described above, the design team at FNI believes that the East Rosedale Street Roadway Improvement project would be able to achieve a total of 232 points, yielding a Silver level of recognition from the Institute of Sustainable Infrastructure.

CONCLUSION

The use of the Envision™ Sustainable Infrastructure Rating System as a guiding tool for the planning and design of the East Rosedale Street Improvement project was beneficial to the design team. The rating system was beneficial to the team in the following sectors of the design process:

- Gauging the sustainability efforts of the team and where efforts were sufficient and where efforts needed improvement
- Guiding the decision making process based on economic, social, and environmental factors
- Incorporating community priorities in the design
- Facilitating collaborative efforts between the design team, the client, and the community
- Changing the team's perception from "Are we doing the project right?" to "Are we going the right project?

Like many project application processes, there are requirements for documentation outside of the typical construction documents that are both quantitative as well as qualitative. This additional documentation requires a time commitment from the design team. To complete a submittal and meet the requirements of the Envision™ Sustainable Infrastructure Rating System, the design team has to prove that they met the evaluation criteria by performing calculations, creating an action plan, meeting with stakeholders, consulting experts of various fields, and possibly other actions. The design team for the East Rosedale Street Improvement project found the Envision™ Sustainable Infrastructure Rating System to be a helpful tool that guided the design to publish a superior product. The design team intends to use the Envision™ Sustainable Infrastructure Rating System tool while designing future infrastructure projects.

Construction on the East Rosedale Street Improvement project began in April of 2013 and construction is scheduled to be completed by December of 2014.

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Defining Livability for Freight-Centric Communities: Identifying Priorities of Residents of the Lamar Avenue Corridor in Memphis, TN

M. Doherty[1], V.A. Wise[2], M.V. Hart[3], S.S. Ivey[4], and T.M. Adams[5]

ABSTRACT

Community livability is increasingly being examined and promoted as exemplary practice. This is due in part to the recognition of environmental, infrastructure, and land use variables contributing to sustainable, vibrant, and healthy places for people to live and work. The impact of freight on an urban community is significant, yet few efforts in the United States have been devoted to creating policies and practices that support livability while also recognizing the critical importance of freight transport to economic vitality.

This paper summarizes an approach to understanding freight impacts on neighborhoods, defining what constitutes a freight-centric community, and identifying the livability priorities of residents. The methodology for the current study is presented, outlining stakeholder survey instruments and recruitment approaches. The livability priorities identified through the stakeholder surveys will be used to develop strategies or plans for improvement that include private sector-led operational changes, infrastructure improvements, public-sector policies, and placemaking. This research also tests the effectiveness of the term 'livability' among stakeholder groups. While this work is based on Lamar Avenue, a high volume, heavily congested freight corridor in Memphis, TN, this research will also benefit other freight-centric communities across the country.

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INTRODUCTION: LIVABILITY FROM A TRANSPORTATION PERSPECTIVE

What does livability mean to you?

The response will invariably change according to the context. Differing definitions attribute responsibility for livability to both the individual and society. Other definitions make references to the health and well-being of individuals and communities while satisfying the human requirement for social amenity (Pacione, 1990; Veenhoven, 1996; Hortulanus, 1996; Newman, 1999; Duyvendak and Veldboer, 2000).

According to the Federal Highway Administration (FHWA), "livability is about tying the quality and location of transportation facilities to broader opportunities such as access to good jobs, affordable housing, quality schools, and safe streets." Under the FHWA framework, livability refers to personal mobility, but also to the "effect" of an increase or an introduction of freight activity in a community. Many communities experience change in response to an increase in freight traffic, including physical, environmental and economic aspects associated with the movement of freight.

In 2009, the US Department of Transportation, Housing and Urban Development (HUD), and the Environmental Protection Agency (EPA), created the Partnership for Sustainable Communities focusing on six livability principles which have served as a framework for the advancement of performance measure development (Marshall, 2013). The principles or goals and associated performance measures are listed in Table 1.

Freight or goods movement is represented indirectly under the economic competitiveness principle. However, literature shows freight's intrinsic tie to many other aspects of a community that are not accounted in the federal approach.

Table 1: Livability principles and corresponding performance measures (Cambridge Systematics, 2011)

Partnership principles	Associated performance measures
Provide more transportation choices	Walkability rating
	Multimodal (road) level of service
	Transit accessibility
	Mode share
Promote equitable, affordable housing	Jobs/housing balance
	Location efficiency
	Housing and transportation index (Housing and transportation cost/affordability)
Enhance economic competitiveness	Travel time reliability
	Workforce accessibility
	Job accessibility
	Travel time index
Support existing communities	Multimodal accessibility to essential destinations (e.g., store, healthcare, schools)
	Safety (crash by mode)
	Speed suitability
Coordinate and leverage federal policies and investment	Consistency with local land use and transportation plans
	Return on investment
Value communities and neighborhoods	Connectivity index
	Community character (e.g., resident satisfaction)
	Partnerships and public involvement

Freight in the Urban Core

There are many issues and impacts related to freight in the urban area. Common issues are described by Maria Lindholm as (Lindholm and Behrends, 2012):

- *Traffic flow/congestion problems - Caused by high traffic intensity, insufficient road infrastructure and poor planning*
- *Transport policy-related problems - Limited access for vehicles, based on hour of the day and/or size, weight of the vehicle*
- *Parking and loading/unloading problems - With regulations, charges, lack of loading zones and handling problems of goods*
- *Customer/receiver-related problems - Including queuing for delivery and reception, difficulties finding the receiver and adapting to the receivers' demands on delivery and pick-up*

Other issues like, air quality and noise pollution, common externalities of freight, are always identified as livability issues but are not incorporated in strategies to change freight *operations* (urban deliveries, freight movement through a city, etc.). For freight moving through a city, the focus has generally been on infrastructure expansion to address mobility or safety. Efforts in logistics changes in Japan and London focused on reducing air and noise emissions and resulted in optimization and trip consolidation solutions decreasing delivery frequency by 60-70 percent in London and a change to natural gas for the fleet accessing the city center in Japan (Browne et al. 2012; Lindholm and Browne et al. 2010).

There are many reasons why freight and livability need to be integrated.

Freight is expected to increase globally and nationally (Long and Grasman 2012; Chandler and Gwin 2008; Browne et al. 2012). Industry and the public sector continue to approach this problem by improving efficiency or by infrastructure expansion. In the US, freight is projected to increase 70 percent over 2008 truck freight volumes by 2020 (FHWA, 2008). The projected increase is spurring investments within the freight industry to solve the most congested bottlenecks and is forcing policymakers to examine the costs and benefits of increased freight volumes.

There is a growing awareness of the relationship between health and transportation and of measuring all costs and benefits to society. This approach is compelling researchers and practitioners to begin to advance holistic approaches to urban freight movement.

DEFINING FREIGHT-CENTRIC COMMUNITIES

Freight-centric communities are those residential areas that bear spillover effects from the movement of freight through a neighborhood. The characteristics of a freight-centric community include proximity to a freight hub: a port, an inland port, intermodal terminal, airport, logistics center, or an agglomeration of these types of freight generators and lack of buffers between industrial and residential land use. The residential communities are traversed by arterials with high percentages of trucks, and increasing periods where level of service (LOS) measures reflect congestion. There may be a high frequency of trains, a rail yard in proximity, or long delays at grade crossings. There may also be a high frequency of air traffic or truck traffic generated by air cargo operations.

Other characteristics of freight-centric communities may include:

Loss of community identity
There may be a lack of “a voice” that represents the interests of the community. This may be due to the transient nature of the community. In such cases local government serves as the voice (Holden and Scerri, 2012). In reality, governments must balance priorities among all of its citizens and across many departments.

Lack of stakeholder involvement
There may be a lack of stakeholder involvement. Efforts to improve freight flows within the area need to include residents and create partnerships between community

or neighborhood leaders and freight interests. Stakeholders can be categorized depending on their "public" or "private" perspective. Public stakeholders include but are not necessarily limited to: "traffic authorities, infrastructure authorities, municipalities, railway terminal/port authorities, as well as road users and residents" (Anand et al. 2012). Private stakeholders include but are not necessarily limited to: "producers, suppliers, shippers, freight forwarders, trucking firms, truck drivers, and shopkeepers" (Anand et al. 2012). Overall, public generally refers to society as a whole and any institutions working on a societal level. Voting citizens and legislators passing relevant policy will represent this group, as well as any other means for public "voice". Private can be thought as the business side, or anyone hoping to profit from transportation activities.

Lack of places
Without places for neighbors and nonresidents to visit, shop, or congregate, there is a precipitated degradation of services in the freight-centric community. Placemaking, the process of conjuring a collective vision of how lives should be lived, enables communities to see the potential of parks, downtowns, waterfronts, plazas, neighborhoods, streets, markets, campuses and public buildings. Placemaking is at the heart of livability as it creates destinations that encourage community, walking and biking.

Compromised Health
There may be higher incidence of health problems attributable to the concentration of freight facilities and operational practices. There may also be a lack of outdoor spaces for exercise or sidewalks reducing walkability. Health Impact Assessment (HIA), a new tool that communities can measure the impact of the built environment.

Isolation
The construction of the interstates during the 1950s and 60s often fragmented neighborhoods in the urban core. Freight-centric communities may be detached from the rest of the city due to freight traffic that can also make travel to work and home difficult and expensive in terms of time and delay. A long-term effect may be low property values and lack of new businesses to support consumption needs of the community.

Measuring the Freight Community: Indicators

Table 2 summarizes a set of indicators and measures[6] that this research has identified as a baseline database. The relevant stakeholder is also indicated.

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[6] *Indicators offer knowledge and insights about the health and well-being of a community. Measures use quantifiable data, preferably collected over time, to identify trends and assess whether conditions are improving, continuing at a steady pace or deteriorating. Measures can change over time to reflect relevance, avail- ability of new data and development in society (Balsas, 2004).*

Table 2: Baseline indicators for measuring the characteristics of freight-centric communities

Characteristics/Data	**Economic**		**Environmental**		**Community**	
	Public	*Private*	*Public*	*Private*	*Public*	*Private*
Population						
Percent of households near freight hub *(US Census Bureau)*	x	x			x	
Percent of households near freight hub who are low income *(US Census Bureau)*	x				x	
Property values in proximity to freight hub *(US Census Bureau)*	x				x	
Percent of jobs near freight hub (*Bureau of Labor Statistics)*	x				x	
Percent of low-income jobs accessible by transit (*Bureau of Labor Statistics)*	x		x		x	
Condition of Housing Stock *(US Census Bureau)*	x				x	
Percent Homeowners /Renters *(US Census Bureau)*	x				x	
Percent of Population employed in Freight Hub (*Bureau of Labor Statistics)*	x	x			x	
Wage (median or average) *(US Census Bureau)*	x				x	
Percent of commuters who take transit *(TN DOT)*	x		x		x	x
Migration in and out of community *(US Census Bureau)*	x	x			x	x
Percent Migrant *(US Census Bureau)*	x	x			x	x
Percent Children *(US Census Bureau)*					x	
Voice *(Survey)*					x	x
Condition of Sidewalks					x	
Transportation						
Bike Lane Miles *(Transportation for America)*			x		x	
Transit Frequency *(TN DOT)*	x		x		x	
Average vehicle miles traveled per household *(TN DOT)*	x	x	x	x	x	x
Congestion *(TN DOT)*	x	x	x	x	x	x
Deaths Avoided *(TN DOT)*					x	x
Crashes Rates by Functional Class *(TN DOT)*	x	x			x	x
Reduction in VMT target			x			
Health						
Percent pop. not getting regular physical activity *(National Center for Health Statistics)*	x				x	
BMI Index *(National Center for Health Statistics)*	x	x			x	x
Asthma *(National Center for Health Statistics)*	x	x	x	x	x	x
Health costs attributed to freight	x	x			x	x

Gallup Healthways Well-Being Index *(Gallup)*					x	x
Places/Amenities						
Medical Facilities *(Census County Business Patterns)*					x	x
Number of grocers/locally sourced *(Census County Business Patterns)*			x	x	x	x
Number of restaurants *(Census County Business Patterns)*					x	x
Number of support service food shelters *(Census County Business Patterns)*					x	x
Library*(Census County Business Patterns)*					x	x
Community centers *(Census County Business Patters)*					x	x
Support services-Hairdressers *(Census County Business Patterns)*					x	x
Parks/percent green space			x	x	x	x
Public landscaping			x	x	x	x
Environmental						
Cost of increased carbon emissions *(EPA)*	x	x	x	x		
Cost of decreasing carbon emissions *(EPA)*		x		x		
Percent change air pollution *(EPA)*			x	x	x	
Sound level *(CDC WONDER Environmental)*			x	x		
FEMA rating (*FEMA)*					x	x
Economic						
Percent GDP from freight *(Bureau of Economic Analysis)*	x	x				
Freight legal settlements		x				x
Percent jobs provided by freight hub (*Bureau of Labor Statistics)*	x	x			x	
Tax revenue generated by freight hub *(Bureau of Economic Analysis)*	x	x			x	
Level of investment in community	x				x	x
Livability						
Walkability *(Walk Score)*			x	x	x	x
EPA environmental measures *(EPA)*			x	x		
Economic impact studies multiplier effect	x	x			x	x
Percent of commuters who walk or bike			x		x	x
Life-Space Index- UAB						
TBD						
Pedestrian Danger Index					x	x
Resident surveys					x	x

STUDY AREA: MEMPHIS AND LAMAR AVENUE

Tennessee and Memphis are highly ranked in terms of jobs in the transportation and material moving occupations. In 2012, Tennessee had 242,840 persons employed in the transportation and material moving occupations (BLS, 2012). Memphis is at the crossroads of three interstates and five Class I railroads. From a location quotient (LQ)[7] perspective, Tennessee ranked second in the country in this category after North Dakota. From a LQ lens, the Memphis metropolitan statistical area (MSA), which includes parts of Arkansas and Mississippi, ranks third nationally in the transportation and material moving occupations (BLS, 2012).

Lamar Avenue (US Highway 78) is a 6.5 mile-long corridor in Memphis, which becomes I-22 when it crosses the Mississippi. It serves as both a commuter route to downtown Memphis as well as a critical freight corridor due to a number of freight generating facilities. For the current project, the corridor being evaluated runs from I-240, south to E Holmes Road. Some of the main facilities and industrial sites that are within this study area include the Burlington Northern Santa Fe (BNSF) rail yard with a capacity of 300,000 twenty-foot equivalent units (TEUs) a year and parking for 6,000 trucks, as well as the Memphis International Airport, the second busiest air-cargo hub in the world due to FedEx. Truck volume on Lamar is found to be 8,000 average daily trucks constituting approximately 27 percent of the average daily traffic. Overall, the corridor operates at level-of-service (LOS) D during all time periods and as an average throughout the day with the exception of the mid-afternoon time period which operates at LOS C (Cambridge Systematics, 2011). Roughly 3-5 freight trains per day run parallel to Lamar and are grade separated.

The corridor is primarily industrial with pockets of closed businesses and vacant rundown lots. Recent engineering studies have evaluated a number of alternatives for Lamar Avenue. Completion of 1-269, an outer ring that connects to Lamar was an assumption in all alternatives, with the most effective in travel delay but costliest alternative being a conversion of the Lamar corridor to an interstate. The alternative with the highest cost/benefit ratio was the conversion of Lamar Avenue to a six and eight-lane road. Despite all the scenarios, findings also showed that by 2030 Lamar would be congested (Cambridge Systematics, 2011).

There are five neighborhoods that border the study segment (Figure 1). The five neighborhoods are completely enclosed in the zip code boundary of 38118. As of 2010, the population in the zip code was 41,465 people with a median age of 28.7 years. Most of the population is Black or African American (77.8 percent), while 11.6 percent are Hispanic or Latino and 11.2 percent are white. Of the 13,809 occupied housing units within this boundary, 49.2 percent are being rented (US Census Bureau-American FactFinder, 2010). Fifty-two percent of the workers who live within zip code 38118 earn between $1,251 and $3,333 per month, while 22 percent make more

[7] *Location quotient (LQ) is a ratio that compares a region to a larger reference region according to some characteristic or asset. LQ is a valuable way of quantifying how concentrated a particular industry, cluster, occupation, or demographic group is in a region as compared to the nation.*

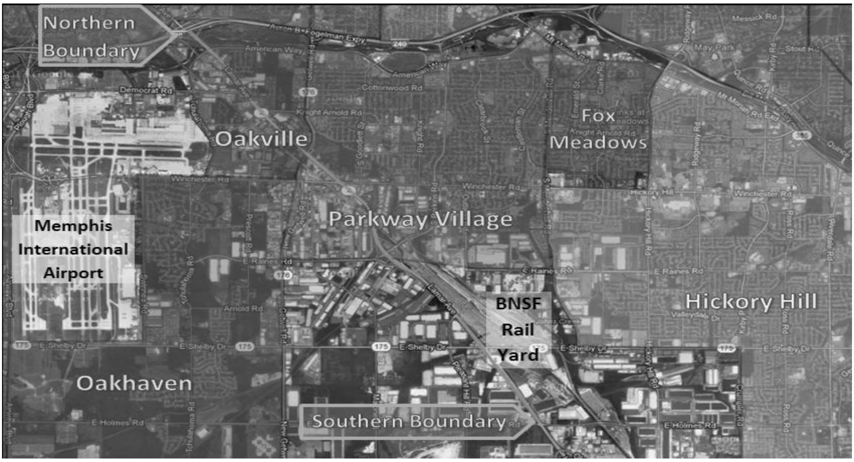

Figure 1: Lamar Avenue and bordering neighborhoods (Google maps)

and 26 percent make less than $1,251 per month (US Census Bureau-OnTheMap, 2011). This zip code also has four establishments categorized as transportation or warehousing with 1,000 or more employees (Census, 2011).

LIVABILITY PRIORITIES METHODOLOGY

Two survey instruments were designed to understand livability in this heavily congested corridor. One will be administered in a focus group setting. A second survey will be conducted door-to-door and/or online (depending on needs of the neighborhoods). The research team has partnered with Livable Memphis, a nonprofit organization that maintains relationships with neighborhood associations. Through this partnership, neighborhood leaders will assist the door-to-door/online survey team and will facilitate and recruit focus groups.

Responses from the focus groups and survey events will be analyzed to identify factors affecting livability of freight-centric communities, relative importance of these factors, and perceptions regarding the impact of high freight volumes in a neighborhood. The data will be analyzed in aggregate, as well as by demographic characteristics (i.e., age, gender, income, and ethnicity).

Focus Groups
A comprehensive survey will be administered to a focus group, and it will include a number of open-ended, ranking, and rating questions that will explore the residents' opinion about how freight traffic affects the livability of their neighborhood. Participants will be asked for information about their perceptions of how their neighborhood has changed over time, what livability means in their own opinion, what the contributors and barriers to livability are, and what factors need improvement in their neighborhood.

Residents will also be asked about their personal commuting patterns (including whether or not a heavy freight presence alters these patterns), and to evaluate transportation facilities around their neighborhood. Additionally, participants will be questioned as to how the freight traffic on Lamar compares to other parts of the city, as well as asked to describe the impact of this freight presence. These questions, joined with a demographic section, will provide researchers insight on the residential perceptions about freight and livability characteristics. The survey will also provide insight into the effectiveness of using *livability* as terminology.

Door-to-Door Survey

This survey is based on the assumption that livability, from a stakeholder's perspective, is both subjective and multifaceted making it difficult to define and measure. Framing livability from a values perspective is an approach that allows for a customization of livability strategies for a given community. The values (questions) are grouped to represent health—both at a community level (clean air, clean water, noise), and an individual level (exercise, access to food and medicine); and economy (jobs, school, amenities).

The methodology used is the Analytic Hierarchy Process (AHP), a problem-solving technique for organizing and analyzing complex, multi-criteria and multi-stakeholder decisions based on quantifiable and unquantifiable variables. By using relative rankings among pairs of livability criteria, this approach forces decisions among criteria and produces a representation of stakeholders' judgments and values. The outcome of this survey will serve as a prescription on the mix of transportation versus non-transportation strategies that will improve livability.

FINDINGS & NEXT STEPS

Survey administration and focus groups will take place in July 2013 with analysis following in August. Survey findings will serve as input to two more stakeholder surveys to be conducted in the fall. One group will consist of industry representatives. The second group will target public/municipal officials.

Once all survey events are completed, the project team will begin simulation of advanced technology and planning strategies to determine the potential effectiveness for mitigating the impact of freight on the Lamar Corridor.

The ultimate goals of this project include:

- Determining how various stakeholders define livability and inform education and communication initiatives regarding the term,
- Identifying factors most affecting livability of freight centric communities,
- Investigating the potential for advanced technologies and innovative planning strategies to ameliorate negative impacts of freight, and
- Developing a set of best practices for improving livability of urban, freight-centric communities across the country.

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Innovative Methods to Inventory Sustainability Practices on State Route 76, San Diego

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ABSTRACT

District 11 of the California Department of Transportation (Caltrans) has been a leader in instituting sustainability practices to minimize transportation project impacts and enhance communities through which its facilities cross. Many of Caltrans' practices exceeded typical environmental mitigation commitments, but had not been gathered collectively into one set of sustainability practices or evaluated against industry standards. Parsons Brinckerhoff led an analysis for Caltrans District 11 to inventory sustainable practices implemented as part of the widening and realignment of State Route (SR) 76 in San Diego County. The team assessed the project against two leading national green infrastructure rating systems (FHWA and Greenroads™) to help inventory the project's performance, developed a preliminary project "score" and gathered associated supporting documentation. The overall intent of this project was to help Caltrans raise the bar on their sustainability practices through identifying tangible steps that could be taken during both design and construction. This analysis found that the SR 76 would achieve most of the credits under the Environment and Water and Access and Equity categories, but not under Pavement Technologies. Assuming the Greenroads™ project requirements were met, the project would likely receive a Silver rating. Under the extended scorecard from the INVEST beta version rating system, the project would likely score a Gold rating. Enhancing pavement technology applications would help boost the rating under both systems. The analysis also confirmed that selection of a sustainability rating system would depend greatly on the needs and goals of an agency or project considering utilizing such a system.

OVERVIEW

Caltrans District 11 has instituted sustainability practices to minimize transportation project impacts and enhance communities through which its facilities cross. The $850 million *TransNet* Environmental Management Program (EMP) exemplifies the San Diego region's commitment to sustainability by protecting, preserving, and restoring native habitats along project corridors. Many of Caltrans' practices exceed typical environmental mitigation commitments, but have not been gathered collectively into one set of sustainability practices. Using recently developed transportation infrastructure sustainability rating systems, this analysis is intended to raise awareness about Caltrans' recent efforts in sustainability and identify areas in which to strengthen.

In order to evaluate current Caltrans District 11 sustainability practices against national standards and identify areas in which to improve upon or consider for future projects, the Caltrans State Route (SR) 76 project was assessed as an example project using national green infrastructure rating systems. The status of these rating systems is currently in flux. No single system has emerged as the national leader and all vary in their strengths and applicability. As such, SR 76 sustainability practices were collected and evaluated against two of the leading green infrastructure rating systems: the FHWA Sustainable Highways Self-Evaluation Tool (Project Development Checklist) and the Greenroads™ Version 1.5 Checklist.

SR 76 is part of the SANDAG *TransNet* program and is being constructed in segments with completion of the final segment anticipated in 2015. Servicing the North County inland areas of San Diego County, SR 76 starts at I-5 and links to I-15 and SR 79 traversing the City of Oceanside, and the unincorporated communities of Bonsall, Fallbrook, Pala, Pauma Valley, Rincon and Lake Henshaw. Project improvements consist of realignment and widening of SR 76 from two lanes to four lanes with shoulders, as well as traffic and safety improvements. The purpose of the project is to "reduce congestion, increase the transportation of people, goods and services, and improve the mobility of local, regional and interregional traffic, while minimizing environmental impacts." The project is being completed in three segments (West, Middle and East), but for purposes of this analysis the sustainability practices were evaluated with a focus on the Middle and East segments, which have a combined value of approximately $371 million. A map of the project area is provided in Figure 1 (*Keep San Diego Moving*).

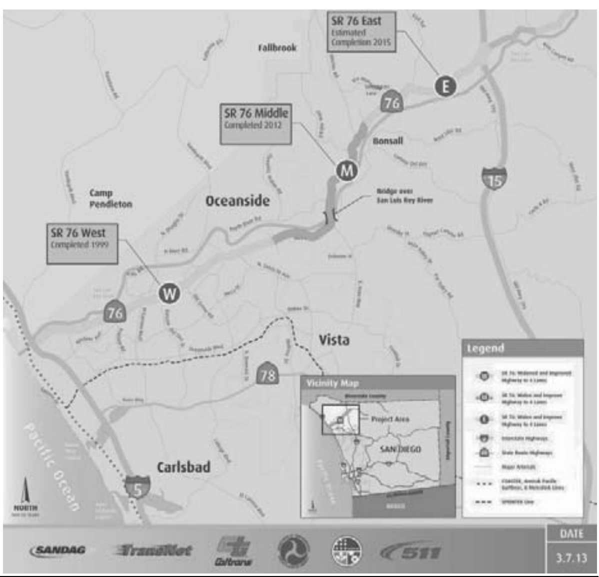

Figure 1: State Route 76 Improvements Map

CALTRANS AS A NATIONAL LEADER IN SUSTAINABILITY

California has a number of statues, plans and policies that seek to integrate sustainable practices in the development of transportation infrastructure. The state has become a national leader in addressing climate change and the integration of land use and transportation through such legislation as the California Global Warming Solutions Act of 2006 (Assembly Bill 32); the Sustainable Communities and Climate Protection Act of 2008 (Senate Bill 375); and the California Complete Streets Act of 2008 (Assembly Bill 1358).

In some instances, Caltrans adopts department-wide policies to reflect policies made at the state legislative or executive levels. For example, Caltrans has a Deputy Directive on Complete Streets that elaborates the department's policy. Caltrans also has other sustainability-related policies that may not be related to state laws, such as policies related to Bus Rapid Transit (BRT) and Context Sensitive Solutions (CSS). Based on these Caltrans policies, Caltrans has developed implementation plans such as the Complete Streets Implementation Action Plan and Context Sensitive Solutions Implementation Plan which identify actions and responsible actors to implement Caltrans policies throughout the department.

GREEN INFRASTRUCTURE RATING SYSTEMS ANALYSIS

To track and measure transportation sustainability strategies, a number of green rating systems have been developed. These systems are generally modeled after the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) system for buildings with criteria organized under different themes. While some states and agencies utilize these systems "off the shelf," others have developed their own systems customized to their existing policies and geographical conditions.

National and agency- or state-level green infrastructure rating systems vary in scope, applicability, and variation of criteria. The systems also differ in their execution; some are brief checklists that require only a few hours of staff time whereas others are third-party rating systems that require substantial time and resources to compile and submit. Two national systems utilized to evaluate SR 76 were Greenroads™ and the FHWA INVEST tool. These systems were selected for this analysis as they had been fully developed at initiation of this project and they cover both the design and construction phases of projects.

SR 76 project information was provided by Caltrans staff including design and construction project managers. This material was compiled into a spreadsheet which inventoried performance against Greenroads™ and FHWA criteria. Additionally, a digital appendix of relevant Caltrans documents and sources that support each green credit was developed. Evaluation of SR 76 sustainability practices against the two systems follows.

Greenroads™

This system is a collection of sustainability best practices that apply to roadway design and construction. Initiated as a Master's degree thesis published in 2007, Greenroads™ is now managed by the Greenroads Foundation, a non-profit third party corporation established to manage certification reviews. Version 1.5 of the Greenroads™ Manual was published in February 2011. Greenroads™ has 11 project requirements as well as 37 voluntary categories that total 108 possible credits. The project requirements represent a minimum set of credits that must be met and are considered characteristics common to all Greenroads^{TM}. Project applicants submit materials to the Greenroads Foundation to review for a fee.

Project Requirements: Greenroads^{TM} has 11 project requirements; many of these represent the standard documentation and reports utilized on National Environmental Policy Act (NEPA) projects. The SR 76 project fulfills the Environmental Review Process requirement through completion of NEPA and California Environmental Quality Act (CEQA) documentation for all segments of the project. The Lifecycle Cost Analysis Report for the project compared three pavement alternatives: hot mix asphalt, rubberized hot mix asphalt and jointed plain concrete pavement. By combining initial construction costs with future maintenance and rehabilitation costs, the report found that hot mix asphalt had the lowest life cycle cost and was the selected option. The remaining required credits, including quality control plan, noise mitigation plan, waste management plan, pollution prevention plan, low-impact development, pavement management, site maintenance, and educational outreach were all completed as part of Caltrans' project development process. In terms of educational outreach, the project incorporated a comprehensive outreach program including a project website, fact sheets, quarterly construction updates and presentations to schools and other community groups.

Voluntary Credits: Figure 2 displays the possible voluntary credits that can be achieved in each of the Greenroads^{TM} categories, showing that the greatest percentage of possible credits can be achieved in the Access and Equity category (28%), while Construction Activities comprise the smallest portion of possible credits (13%). The following sections discuss the credits that would be attained by the SR 76 project in each of these categories.

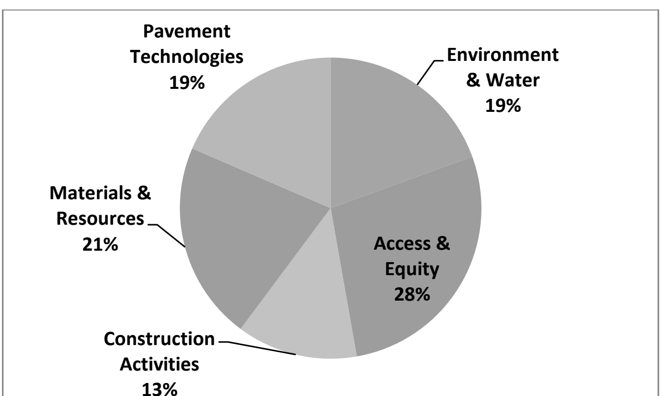

Figure 2: Greenroads^{TM} Voluntary Credits by Category

Environment and Water: Stormwater management is evaluated through the Runoff Flow Control and Runoff Quality credits. These credits require demonstration of Best Management Practices to control runoff and reduce sediment loads. The SR 76 project complies due to the requirements of the General Permit. In terms of natural resource protection, the project fulfills site vegetation, habitat restoration and ecological connectivity credits. Under Runoff Quality, the project fulfills the maximum of three credits by using non-invasive plant species, native plants, and temporary irrigation for landscaping.

Both habitat restoration and ecological connectivity are evident in the project efforts to enhance the river valley, preserve open space, and install wildlife and exclusionary toad fencing. One of the most notable ecological connectivity commitments involved installation of new dedicated wildlife crossing structures (see Figures 3 and 4) along the corridor. Finally, SANDAG and Caltrans have worked to preserve close to 1,600 acres of open space in the corridor via the *TransNet* EMP.

Figures 3 and 4: Wildlife crossings under construction on the SR 76 middle segment

Access and Equity: This set of credits pertains to the elements embodied in context sensitive design. Context sensitive design emphasizes that transportation facilities should fit their physical settings and preserve scenic, aesthetic, historic and environmental resources, while maintaining safety and mobility. Specifically, the credits focus on improving transportation safety, ensuring multi-modal connectivity and access, and enhancing access to scenic views, destinations, and cultural resources.

The SR 76 project embodies the principles of context sensitive solutions (CSS). The design seeks to preserve scenic views within the corridor and work with preexisting contours. Efforts include constructing naturally-appearing graded slopes that reflect contours before grading and simulate natural terrain. Enhanced access to recreational and historical resources will be provided through new trails and access to a historic bridge in the project area. In terms of multi-modal connectivity, the project enhances pedestrian, bicycle and transit access through widened (8-foot) shoulders, pedestrian crossings at signalized intersections, new trails, and improved park-and-ride facilities. The project constructed a new park-n-Ride along the corridor and expanded the facility at the I-15 interchange.

Construction Activities: Construction activities refer to a variety of practices implemented during the construction phase, including environmental training, recycling, reduction in fossil fuel in construction equipment, equipment and paving emission reductions, water use tracking and contractor warranty. SR 76 strengths in this category include environmental training for construction personnel, pavement reuse, and paving emission reduction through use of EPA Tier 3 compliant paving equipment.

Materials and Resources: SR 76 scores well in this category through reuse of a minimum of 90% of the project pavement materials, balancing of cut and fill to within 10% of average total volume, and energy efficiency in roadway lighting through the use of Low Pressure Sodium (LPS) lighting.

Pavement Technologies: Greenroads™ devotes a full category to pavement because pavement and its supporting structure makes up a majority of roadway infrastructure cost and quantities. As SR 76 did not implement the Greenroads™ sustainable pavement technologies, suggestions for additional improvements are provided in the "Sustainability Considerations for Future Projects" section of this paper.

Greenroads™ Credits Attained: The voluntary credits in each category that SR 76 would attain are shown in Figure 5 as the darker portion of each bar. As shown in the figure, SR 76 achieves many of the credits in the Environment and Water and Access and Equity categories, but much fewer Pavement Technologies.

FHWA Sustainable Highways Self-Evaluation Tool:
The FHWA tool, also referred to as the Infrastructure Voluntary Evaluation Sustainability Tool or "INVEST," is a voluntary rating tool that can be used by states or other project sponsors to measure sustainability on roadway projects (www.sustainablehighways.org). This project used the Beta Version criteria, released in the fall of 2010, as it was the one available at the time of the analysis. The Beta Version contained two sets of scorecards for project development; basic and extended. SR 76 fell under the Extended Scorecard (30 credits). FHWA launched INVEST 1.0 in October 2012 which has one project development scorecard with 29 credits.

A number of credits in the Greenroads™ system are also reflected in INVEST. Additional credits in the FHWA tool include freight mobility, low-emitting materials, creation of renewable energy and tracking of environmental commitments. The following describes SR 76 performance on these credits:

- *Freight Mobility*: This credit applies to anti-idling policies, signage, safety improvements, and electrified rest stops, among others. The SR 76 project adjusted roadway grade and alignment to account for truck safety and mobility, and instituted safety improvements (signage) on steep grades.
- *Low-Emitting Materials:* The intent of this credit is to minimize the use of toxic paints and coatings by using materials that comply with Green Seal-11 requirements. This project did not utilize paints or coatings that comply with this standard.
- *Create Renewable Energy:* Irrigation controls and traffic count stations are powered by renewable energy on the SR 76 project; however it is unlikely that these meet a minimum of 20% of the total lifetime energy for the project.
- *Tracking Environmental Commitments:* All commitments on the SR 76 project are being tracked in a comprehensive Environmental Commitments Record.

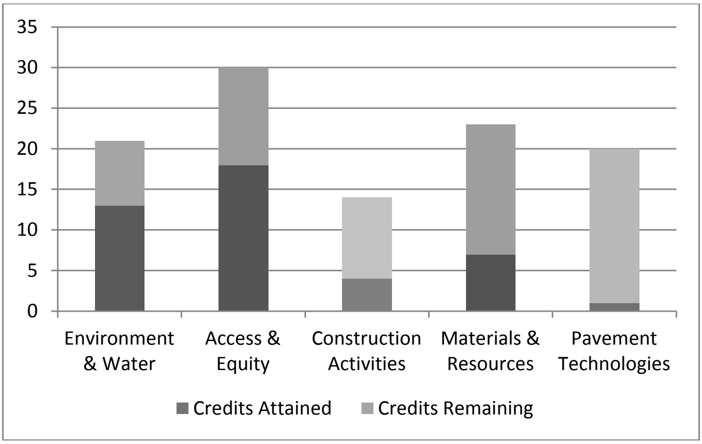

Figure 5: SR 76 Voluntary Credits Attained by Greenroads™ Category

Note: Darker shades represent credits attained by SR 76. Lighter shades represent remaining credits not attained.

The possible credits in the FHWA system were allocated into the different Greenroads™ categories and are shown in Figure 6. Compared to the possible credits in Greenroads™, FHWA has a stronger emphasis on Access and Equity (36%) and less emphasis on Pavement Technologies (7%).

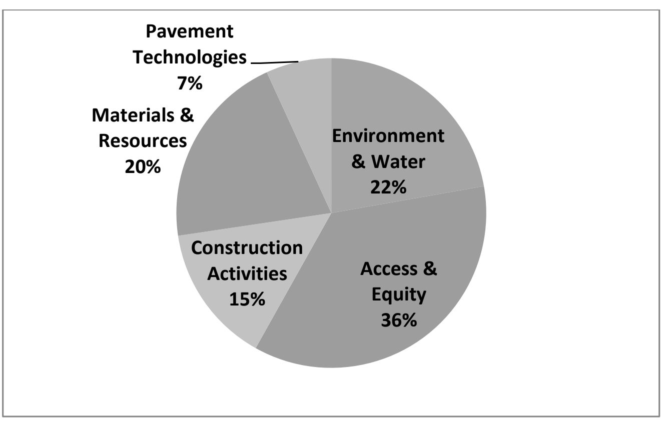

Figure 6: FHWA Possible Credits by Greenroads™ Category

FHWA Credits Attained: The FHWA credits that SR 76 would attain in each Greenroads™ category are shown in Figure 7 as the darker portion of each bar. The lighter shade indicates the remaining credits that have not been attained. Similar to the performance of SR 76 in the Greenroads™ system, as shown in the figure, SR 76 achieves most of the credits in the Environment and Water and Access and Equity categories, but no credits for Pavement Technologies.

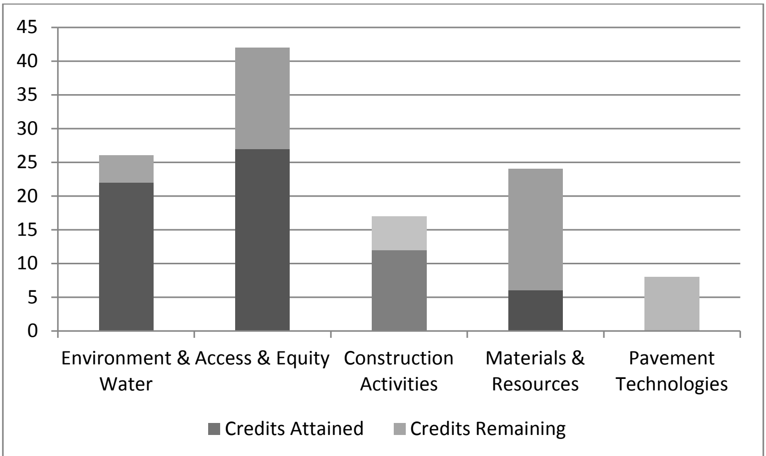

Figure 7: SR 76 FHWA Credits Attained by Greenroads™ Category
Note: Darker shades represent credits attained by SR 76. Lighter shades represent remaining credits not attained.

SR 76 Sustainability Practices - Potential Custom Credits

SR 76 incorporated additional sustainability practices that are not reflected in the Greenroads™ or FHWA rating systems. These practices could potentially be formalized as custom credits. Practices include:

- Net Benefit: Project provides a "net benefit" to species and habitat above and beyond traditional mitigation requirements. Instead of a project-by-project approach, land was acquired in advance of projects, in larger parcels, and at lower costs so that habitat could be protected and restored earlier. This includes protection, preservation and restoration of open space, water quality, and wildlife habitat.
- Staging: Construction staging efforts avoid working in areas affected by seasonal high-water to protect water quality.
- Energy savings in transportation: Provision of electric vehicle plug-ins at park-and-ride.
- Vegetation: Rather than contracting separately to plant vegetation, project is allowing for earlier plant establishment periods.
- Cultural monitoring: A cultural resources expert is on-site through construction to take immediate action if archaeological or paleontological resources are uncovered.

SUSTAINABILITY CONSIDERATIONS FOR FUTURE PROJECTS

The following are practices that Caltrans could potentially pursue in an effort to enhance sustainability of future projects.

Stormwater: Greenroads^{TM} Credit EW-4 requires calculation of lifecycle costs for Low Impact Development (LID) techniques and Best Management Practices (BMPs) for stormwater utilities. The total capital cost of various items was documented in the Preliminary Drainage Reports for the project. However, future costs including the annual maintenance cost, salvage value, interest rate and design life were not documented, nor were these costs combined to determine the annual cost for the new stormwater system over its lifetime.

According to Greenroads^{TM}, the intent of EW-4 is to consider not only the initial capital costs of infrastructure but also long-term operations and maintenance. Some LID and BMPs may have higher upfront capital costs but may be less expensive in the long term; thus, Caltrans could consider completing stormwater cost analyses for projects.

Access and Equity: Designing projects to be context sensitive is at the core of the Greenroads^{TM} credits under Access and Equity. Caltrans has a Director's Policy on CSS as well as an Implementation Plan. In many respects, SR 76 embodies the principles of designing in harmony with the project's surroundings. To document this formally, Caltrans District 11 could develop a process to capture CSS strategies across projects.

Energy Efficiency and Emissions Reduction: Multiple measures could be considered to increase energy efficiency and reduce emissions. According to the Caltrans Division of Research and Innovation, unless biodiesel fuel is specified as an operation requirement under the verification executive order, biodiesel is not an accepted fuel for use. The North Carolina DOT conducted a pilot study to demonstrate the use of B20 biodiesel fuel in 1,000 construction vehicles. The use of B20 compared to petroleum diesel led to a slight decrease (approximately 2 to 10% depending on vehicle) in Nitrogen oxide (NO) emission rate and significant decreases (up to 30%) for hydrocarbons and carbon dioxide.

Pavement: Pavement technologies are one of the primary categories within Greenroads^{TM}. The credit categories include long-life pavement, permeable pavement, warm-mix asphalt, cool pavement, quiet pavement and pavement performance tracking. These practices are not typically part of Caltrans projects and were not implemented on SR 76. Many of these practices are still in the testing phase, and the benefits and drawbacks need to be weighed carefully.

COMPARATIVE ANALYSIS

This analysis showed that SR-76 would score well under both systems. Assuming the 11 project requirements are met under Greenroads, the project would anticipate a silver rating. Based on the INVEST beta version extended scorecard, the project would score 67 credits out of a total of 117 possible credits, putting it at a gold level.

With the rollout of INVEST 1.0 in 2012, three modules were issued for agencies to self-evaluate the entire lifecycle of transportation services, including System Planning (SP), Project Development (PD), and Operations and Maintenance (OM). Each of these modules is based on a separate collection of criteria. Thus, unlike Greenroads, projects can utilize the modules based on their specific project phase, and complete new modules as they move from phase to phase. Greenroads is primarily focused on the design and construction phases.

Both systems are similar in their criteria (if comparing the INVEST project development scorecard to Greenroads). One of the primary differences between the two systems is the format of the two. Greenroads certification involves a fee based third party review; INVEST is a voluntary self-evaluation tool. Because INVEST is not based on third-party validation of scores, FHWA does not confirm a certain achievement level for a project. Thus, depending on the goals of the agency and the specific project, either may be more applicable.

CONCLUSION

Through this research process, Caltrans District 11 took inventory of their existing sustainability practices by utilizing SR 76 as a sample project. Comparison against infrastructure rating systems showed that SR 76 exceeds industry norms in many sustainability criteria, particularly with natural resource preservation. The SR 76 analysis also revealed areas for further consideration, including construction practices and pavement design.

The green infrastructure rating systems described above are useful tools in evaluating and enhancing transportation project sustainability. The level of time and resources needed to achieve certification under these different systems varies. The following are considerations for Caltrans or other agencies in deciding between rating systems:

- Budget available for each project: Can a budget be allocated to gather materials and pay a certification fee to a third party?
- Integration with existing agency sustainability policies: How will the rating system further statewide goals of addressing climate change and reducing greenhouse gas emissions?
- Primary users: Project managers? External to agency? What is the level of training needed?
- Required versus voluntary: How widespread will the system be applied?
- Project tracking: How will innovative practices be tracked over time? How will Caltrans continue to improve and innovate?

Moving forward, Caltrans could utilize the results of this analysis by considering modifications to existing strategies and testing new sustainable practices. One method for testing the viability of these practices is to conduct pilot programs. If successful, their use can be broadened and solidified into policy. Dialogue with project contractors is key to understanding willingness to partner and to try new technologies and approaches such as biodiesel fuel, equipment emission reduction, and other practices. The contractors must be in agreement with construction-related sustainability practices, and these need to be solidified in project bid documents to ensure implementation. Through innovation, communication and adoption of sustainability practices across all projects, Caltrans District 11 will continue to be a leader in the delivery of sustainable transportation projects.

APPLICABILITY TO OTHER AGENCIES

Sustainability rating systems can be useful tools for agencies to document, identify and baseline sustainability practices; to identify areas for improvement; to compare practices across their own projects as well as others; and to recognize high levels of project performance. With many rating systems currently in use, agencies should consider their needs and goals before selecting a rating system.

National systems may not reflect the unique geographical conditions of a local or regional area. If one of these systems is selected for a project, custom credits provide an opportunity to highlight project-specific innovative practices.

ACKNOWLEDGEMENTS

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Spatial Variations in Pedestrian and Bicycle Level-of-Service (LOS) for Infrastructure Planning and Resource Allocation

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ABSTRACT

The objective of this paper is to compute pedestrian and bicycle level-of-service (LOS) for 578 signalized interactions, to examine spatial variations in the computed LOS and compare them with the pedestrian and bicycle crash locations. Data for Charlotte, North Carolina was used to compute LOS, examine spatial variations in LOS and crashes, assess walkability, bikeability and their effect on livability, and present the outcomes from the research. Data and analysis showed 37.17 percent of the selected signalized intersections have a pedestrian LOS of D or worse while 85.39 percent of the signalized intersections have a bicycle LOS of D or worse. The computed LOS (indicators of walkability and bikeability) for the selected signalized intersections was observed to vary by area type. As expected, the LOS was observed to decrease with an increase in the distance from the downtown/uptown area. While the LOS at the selected signalized intersections is good in downtown/uptown area, it is relatively low at the selected signalized intersections in other areas. However, pedestrian and bicycle crashes tend to be relatively higher in number and distributed throughout the core urban area while they are lower in number in the suburban area. Integrating the computed pedestrian and bicycle LOS for the signalized intersections with activity levels or surrogate data such as land use, demographic, and socio-economic data along with pedestrian and bicycle crash locations would help identify critical locations and assist in efficient allocation of resources based on the actual need.

KEYWORDS: Pedestrian, bicycle, level-of-service, LOS, crash, GIS

INTRODUCTION

People who live or work in communities with pedestrian and bicycle friendly facilities tend to drive significantly less and rely more on alternate modes of transportation such as walking and bicycling than they would in more auto oriented communities. Practitioners, therefore, have been emphasizing on building infrastructure facilities and implementing safety improvements that support these users of alternate modes of transportation in recent years. Regional and local agencies have been working on building/retrofitting communities to support such users of alternate modes so as to achieve sustainability, reduce congestion, lower the number of crashes, improve air quality and enhance quality of life (livability).

The infrastructure that provides support to users of the alternate modes of transportation varies geographically within a city or town. In other words, the quality of life offered by the transportation system for different system users varies by area type. Facilities and traffic control devices that aid pedestrians and bicyclists can be more seen in core urban areas (extends beyond downtown/uptown area) when compared to suburban areas. However, congestion mitigation strategies and solutions that lead to decentralization and improved access to offices, shopping locations and community resources cannot be successful without providing better amenities for pedestrians and bicyclists in the under-represented areas (say, suburban areas). While the differences in the allocation of resources for infrastructure and safety improvements may not be intentional, it could be due to lack of better understanding and recognition of the actual needs. An understanding will help implement these proactively (and improve livability) rather than as an afterthought.

Though the impacts of not providing adequate amenities to pedestrians and bicyclists are significant, they are often overlooked or undervalued in conventional transportation planning studies. Research on methods to quantify pedestrian and bicycle level-of-service (LOS) based on these amenities or facilities is also limited. Neither the methods are widely (or universally) adopted nor are very popular. Further, literature does not document on spatial variations in pedestrian and bicycle LOS (indicators of walkability and bikeability) and how it could be used to identify the need, plan infrastructure improvements and efficiently allocate limited available transportation resources.

The objective of this paper is three-fold. The first objective is to compute pedestrian and bicycle LOS for the selected signalized intersections using the methodology developed by the staff of the city of Charlotte Department of Transportation (CDoT). The second objective is to assess the magnitude and spatial variations in pedestrian and bicycle LOS at the selected signalized intersections. The third objective is to examine if pedestrian and bicycle LOS changes by area type i.e., if pedestrian and bicycle LOS changes (decreases) as the distance from downtown/uptown increases. Also, it is to evaluate the spatial relationship between the computed LOS and spatial distribution of non-motorized (pedestrian and bicycle) crashes at intersections. This will help assess the effect of walkability and bikeability on safety and quality of life (livability) offered by the transportation system.

LITERATURE REVIEW

Researchers and practitioners have developed and used different pedestrian LOS methods in the past. Sarkar (1993) and Khisty (1994) defined pedestrian LOS based on subjective ratings of safety, security, comfort and convenience, continuity, system coherence, and attractiveness of pedestrian environment facility. The Highway Capacity Manual (TRB, 2000) defines pedestrian LOS in terms of delay while waiting to cross the street and space available at crosswalks and corner of the streets for both signalized and unsignalized intersections. Petritschet et al. (2005) developed a pedestrian LOS method for intersections based on right-turn-on-red traffic volumes, permissive left-turn volume, traffic volume of the street being crossed, 85th percentile speed of the vehicles, the number of lanes, delay of pedestrian, and right-turn channelization islands.

Agencies, in the past, have adopted different methodologies to quantify bicycle LOS. Botma (1995) suggested a LOS method for bicycle and bicycle-pedestrian paths. The method was based on events occurrence of two users crossing each other, in the same direction or opposite excluding the impact of riding in a motor vehicle environment. Davis (1987) proposed a Bicycle Safety Index Rating (BSIR) tool that comprises two parts: one for roadway segments and the other for intersections. Traffic volume, speed limit, outside lane width, pavement condition, and many other geometric factors were considered for evaluating the safety aspects of roadway segments. Traffic volume, type of signalization, and several geometric factors were the basis for intersection safety analysis of that study. Epperson (1994) developed a Roadway Condition Index (RCI) for intersections considering the interaction between curb-lane width, speed limit, and traffic volume. Sorton and Walsh (1994) related bicycle LOS to stress levels of bicyclists ranging from 1 to 5 based on experience due to varying proficiency on roadways with various characteristics. The factors considered for stress level calculation include peak-hour traffic volume in the curb-lane, motor vehicle speeds in the curb-lane, and curb-lane width. Landis (1994) developed an Intersection Hazard Score (IHS) to assess bicyclists' level of hazard likelihood based on the traffic volume, speed limit, outside lane width, pavement condition, and the number of driveways. However, the model did not include crashes or conflicts. Landis et al. (2003) developed an intersection bicycle LOS based on the user rating of comfort and safety while crossing an intersection.

Literature also documents two other methods to determine pedestrian and bicycle LOS. The Florida Department of Transportation (FDoT) has been successful in applying approaches to determine the LOS for pedestrians and bicycles (FDoT, 2009) along a corridor. These approaches are considered superior when compared to the one proposed by HCM 2000 (TRB, 2008). The CDoT has developed and adopted a method to measure pedestrian and bicycle LOS at intersections so as to provide amicable and safe facilities to pedestrians and bicyclists in the city of Charlotte, North Carolina (Steinman and Hines, 2004; CDoT, 2007). The FDoT pedestrian and bicycle LOS methodology is based on the convenience, security and overall satisfaction that a user experiences while using a roadway (quality of service between two intersections). The CDoT pedestrian and bicycle LOS methodology is based on intersection design features that reduce traffic conflicts, minimize crossing distance, slowdown traffic speeds and raise user awareness. However, no study has examined spatial variations in pedestrian and bicycle LOS or related pedestrian and bicycle LOS and compared them with pedestrian and bicycle crash locations.

METHODOLOGY

As a first step, a large sample of signalized intersections was selected to compute pedestrian and bicycle LOS and examine spatial variations. These signalized intersections were selected such that they are spatially distributed throughout the study area.

The pedestrian and bicycle LOS for the selected signalized intersections were measured using pedestrian and bicycle LOS methodology developed by the staff of CDoT. The methodology helps quantify pedestrian and bicycle LOS using several on-network characteristics. The pedestrian and bicycle LOS methodology considers data such as crossing distance, the presence of crosswalks, the presence of bicycle lane and corner radius dimension in addition to traffic signal characteristics and other key features. The pedestrian LOS is a factor of intersection geometry, signalization, crosswalks, turning vehicle conflict, and adjustment for one-way street crossings. The bicycle LOS depends on motor vehicle speed, signal features, intersection geometry, width of bicycle lane, and conflicts with turning vehicles.

Integer scores are assigned to each factor based on the intersection and traffic characteristics. The minimum possible score based on the CDoT pedestrian and bicycle LOS method is 0 whereas the maximum possible score is 93. The pedestrian and bicycle LOS is classified into 6 classes based on accumulated points: A (93+), B (74 – 92), C (55 – 73), D (37 – 54), E (19 – 36), and F (0 – 18).

The latitude and longitude were extracted for each selected signalized intersection. A spatial data file was then developed and overlaid on the street network of the study area in Geographic Information Systems (GIS) environment. A Kernel density map was then generated for both pedestrian and bicycle LOS scores using a cell radius of 0.5 miles. The Kernel density values were classified into high, medium and low values using Jenks natural breaks (or groupings) inherent in the data (ESRI, 2007). The ideal classifications is based on break points by picking the class breaks that best group similar value and maximize the differences between classes (or minimizes within-class sum of squared differences).

The pedestrian and bicycle crash data for the city of Charlotte, North Carolina for 2008 were collected from the CDoT in a spatial format. The crash data were spatially overlaid on the Kernel density maps to examine the spatial relation between pedestrian and bicycle LOS and crash locations.

ANALYSIS AND DISCUSSION

Data for 578 signalized intersections in the city of Charlotte, North Carolina were used to compute pedestrian and bicycle LOS. Table 1 summarizes the number and percent of selected signalized intersections in the city of Charlotte, North Carolina in each pedestrian and bicycle LOS category.

About 32.53 percent of the selected signalized intersections have a LOS of C for pedestrians. This is followed by 25.26 percent of the selected signalized intersections with a LOS of D for pedestrians. On the other hand, 38.96 percent of the selected signalized intersections have a LOS of E for bicyclists while 36.52 percent of the selected signalized intersections have a LOS of D for bicyclists. Overall, 37.17 percent of the selected signalized intersections have a LOS of D or worse for pedestrians (below average walkability levels) while 85.39 percent of the selected signalized intersections have a LOS of D or worse for bicyclists (below average bikeability levels).

Figure 1 shows the spatial distribution of pedestrian LOS (walkability indicator) at the selected signalized intersections in the city of Charlotte, North Carolina. Figure 2 depicts the spatial distribution of the Kernel density of pedestrian LOS (walkability indicator) with the year 2008 pedestrian crash locations. From the maps, it can be observed that pedestrian LOS (or walkability indicator) decreases with an increase in the distance from the downtown/uptown Charlotte. The figure illustrates that pedestrian-traffic crashes occurred regardless of the pedestrian LOS at the signalized intersections. The number of pedestrian crashes is high in spite of relatively good pedestrian LOS in the downtown/uptown area. The underlying reason of high pedestrian crashes in uptown/downtown area may be the high pedestrian activity. In general, data showed that the number of pedestrian crashes is high at selected signalized intersections with medium pedestrian LOS (C or D).

Figure 3 shows the spatial distribution of bicycle LOS (bikeability indicator) at the signalized intersections in the city of Charlotte, North Carolina. Figure 4 depicts the spatial distribution of the Kernel density of bicycle LOS (bikeability indicator) with the bicycle crash locations in the year 2008. As in the case of pedestrian LOS, it can be seen that the bicycle LOS (or bikeability indicator) decreases with an increase in the distance from the downtown/uptown Charlotte. It can also be seen that almost all the bicycle crashes occurred where the bicycle LOS is medium (C or D). In other words, the intersections having medium to poor comfort and safety aspects for the bicycles are more prone to bicycle crashes.

Table 1. Pedestrian and bicycle LOS at the selected signalized intersections in Charlotte, North Carolina - Summary.

LOS	Pedestrian LOS		Bicycle LOS	
	# of Signalized Intersections	% of Signalized Intersections	# of Signalized Intersections	% of Signalized Intersections
A	73	12.63	0	0.00
B	101	17.47	10	1.74
C	188	32.53	74	12.87
D	146	25.26	210	36.52
E	47	8.13	224	38.96
F	23	3.98	57	9.91
Total	578	100	575	100

CONCLUSIONS

Results from analysis and evaluation of pedestrian and bicycle LOS for the city of Charlotte, North Carolina showed that 37.17 percent of the selected signalized intersections have a LOS of D or worse for pedestrians while 85.39 percent of the selected signalized intersections have a LOS of D or worse for bicyclists. Both pedestrian and bicycle LOS (indicators of walkability and bikeability) was observed to decrease with an increase in the distance from the downtown/uptown area. In other words, socio-economic or demographic profile of block groups, on-network and land use characteristics do seem to influence the planners to provide high or low LOS for pedestrians and bicyclists in an area. Such an approach has to be amended to build more sustainable and livable communities and increase the use of alternate modes of transportation.

Results from spatial overlay indicate that pedestrian and bicycle crashes are high at signalized intersections with medium LOS (C or D). A relatively fewer number of pedestrian and bicycle crashes were observed at signalized intersections with poor LOS. This could be attributed to extra caution used by motorists, pedestrians and bicyclists when traversing through these signalized intersections.

Results from spatial overlay also show that pedestrian crashes occurred even at the intersections with good pedestrian LOS. But this situation is only confined to signalized intersections in the downtown/uptown area. High pedestrian activity may be the underlying reason for these pedestrian crashes.

The pedestrian and bicycle LOS methodology developed and used by CDoT does not include the activity levels or safety aspects of the pedestrians and bicyclists. Therefore, it is recommended that future studies should be carried out to determine LOS by incorporating activity levels (the number of pedestrians and bicyclists or related surrogate data) and safety (number of pedestrian and bicycle crashes) aspects. As such data (in particular, the number of bicyclists) may not be typically collected, it is recommended to collect these data regularly as a part of traffic data collection programs. Further, research needs to be conducted to examine the relationship between demographic, socio-economic and land use characteristics, and spatial distribution of pedestrian and bicycle LOS. Such an analysis will help better understand the trends and conclude if provision of facilities and devices are proven to be successful irrespective of the area type. This will not only help identify amicable solutions to growing safety concerns but also implement proven countermeasures by area type.

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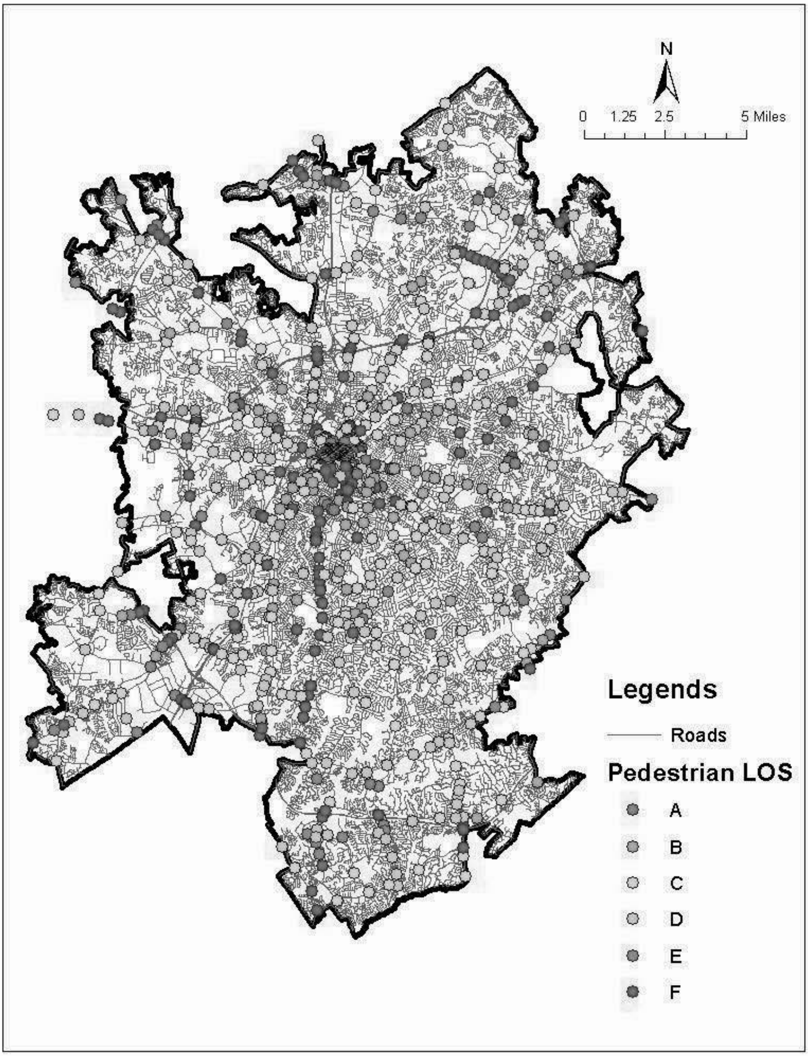

Figure 1. Spatial distribution of pedestrian LOS at the selected signalized intersections in Charlotte, North Carolina.

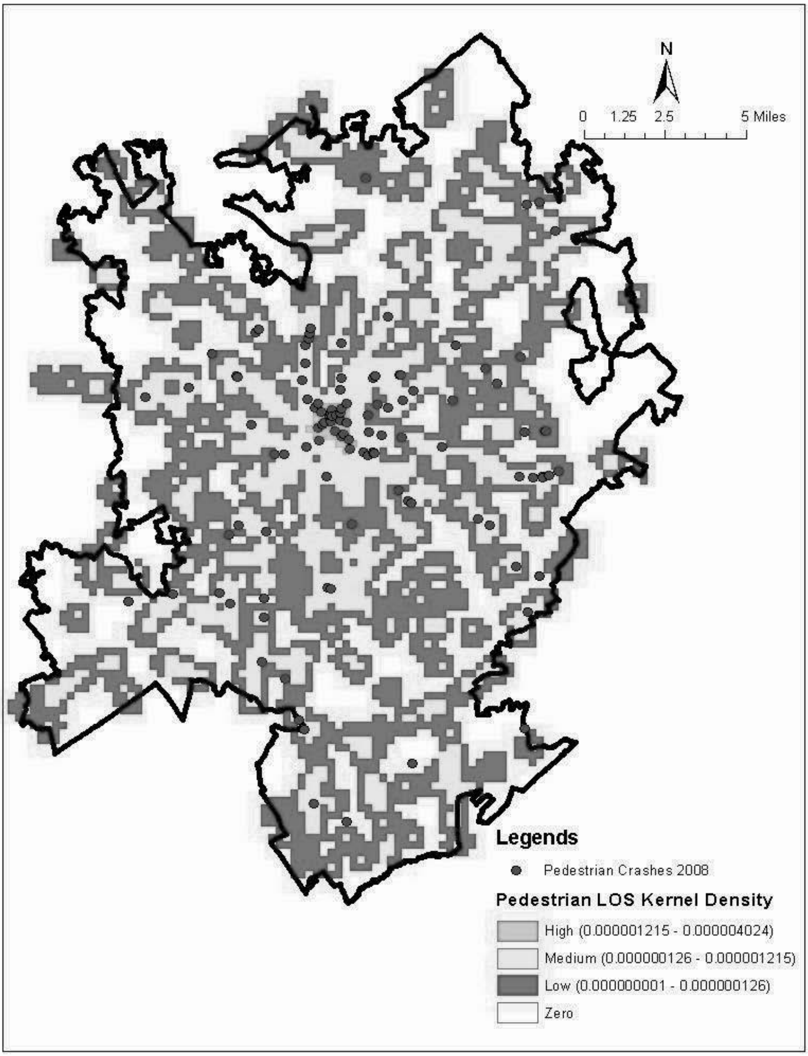

Figure 2. Spatial overlay of pedestrian crashes on Kernel density of pedestrian LOS at the selected signalized intersections in Charlotte, North Carolina.

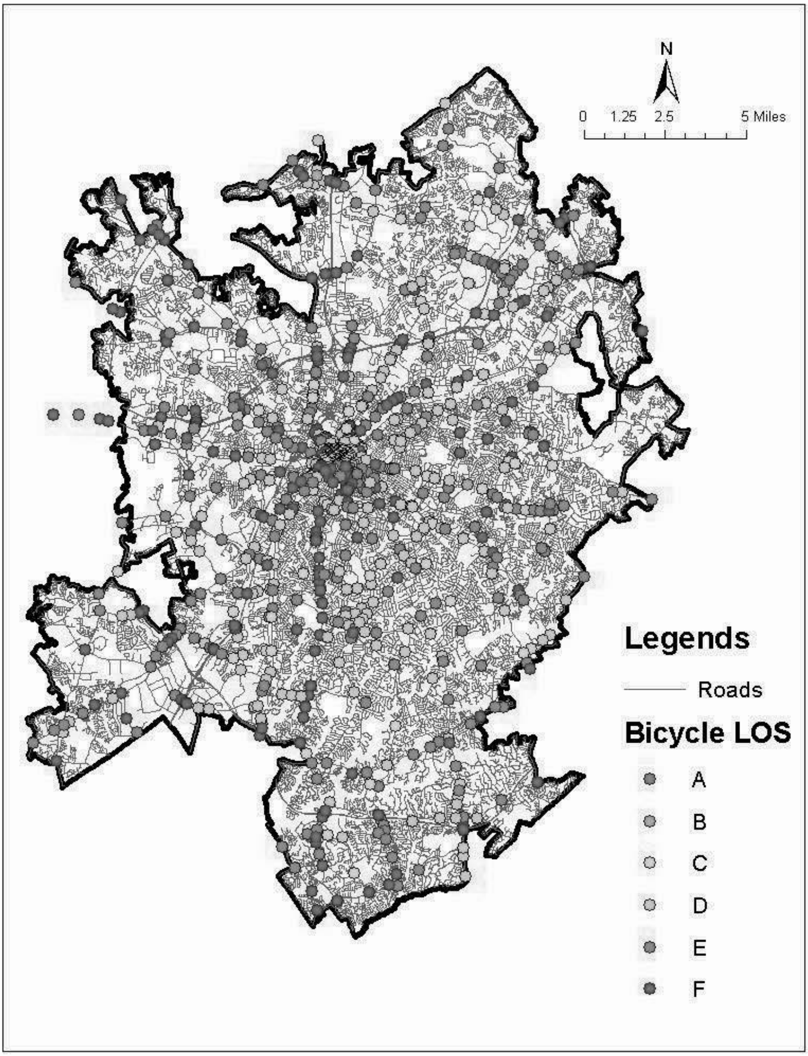

Figure 3. Spatial distribution of bicycle LOS at the selected signalized intersections in Charlotte, North Carolina.

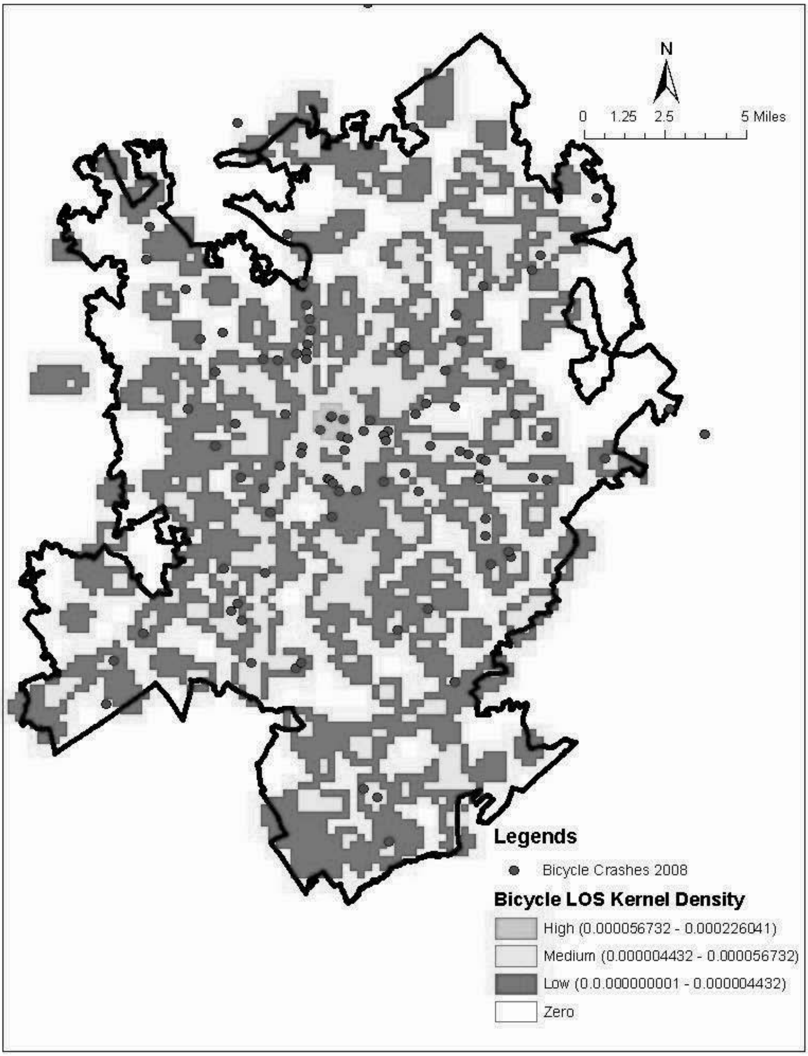

Figure 4. Spatial overlay of bicycle crashes on Kernel density of bicycle LOS at the selected signalized intersections in Charlotte, North Carolina.

Urban Transportation Networks to Support Sustainable Developments of New Communities in Egypt

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Abstract

Egypt is a country of contrast. Although it is the world's 30th largest country, with an area of approximately one million square kilometers, 97% of its population is concentrated along the Nile valley and delta, leaving approximately 96% of the country's area unpopulated. This has led to a concentration of business opportunities and services in and around major cities. Ultimately, migration has increased to these areas, limiting opportunities to develop other areas. The population is no longer able to grow and prosper within the old valley and needs to expand to a more population centers in a way that is sustainable. This need has motivated efforts towards developing new cities that have the potential to house and accommodate sustainable communities. This paper is a brief description of a planning effort to identify areas suitable for sustainable alternatives in different parts of Egypt. It also presents the basis for a national transportation network to support these sustainable developments. As part of this planning effort, college students, researchers, and young professionals from a variety of disciplines are asked to submit their ideas for sustainable developments as part of a design competition. The competition, entitled: "Sustainable Exit from the Valley", attracted more than 120 competitors and 42 different submissions. A panel of experts was used to evaluate and rank these proposed developments according to their sustainable economic potential and to develop a national transportation network that supports the proposed alternatives.

Introduction

Urban growth has been consuming the precious and limited agriculture land in the Nile Valley. The Nile Valley, which represents approximately 4% area of Egypt, is completely overcrowded. In the last two decades, there has been a push to move beyond the valley, but only to areas near or surrounding existing major cities. Several new neighborhoods were built near major cities occupying another 1%, leaving the remaining 95% of Egyptian land open for development. With the expected increase in population and the high demand for housing and jobs, "Sustainable Exit from the Valley" becomes not only a critical need, but a wise and logical choice for Egypt's future. Building an efficient urban transportation network is the benchmark for the success of the proposed sustainable developments. Defining the location of the new developments, the topography of the transportation network that serves them, which mode of transportation system is appropriate for the planned level of growth, and the basic resources needed to build sustainable communities are challenges that need to be fully addressed in the early stages of the planning process.

The Sustainable Exit from the Valley Initiative

The "Sustainable Exit from the Valley" initiative is a design competition that has been used as a tool to propose and define new urban growth in Egypt. The initiative is a collaborative effort between the British University in Egypt (BUE), its Center of Sustainability and Future Studies (CSFS), and a non-governmental organization (Mohamed Farid Khamis Foundation for community development). The completed initiative provides an opportunity to integrate new generations of students, researchers, and professional with governmental and non-governmental planning organizations. It has been developed to ensure that new community developments consider sustainability principles as a base for growth. Teams that participated in this competition have attempted to answer three main questions that define their vision for the new proposed developments. These questions are:

1. Where to go? - challenging the young minds of students, researchers, and young professionals to find alternatives spots for the growth.
2. How to go? - challenging the development of a sustainable urban transportation networks that are connecting the proposed development areas and link them with the valley.
3. Who are the decision makers? - stakeholders or the key players of the developments, investors for funding, government agencies for management, and new residences to live and work.

The answers to the above three questions are based on a list of sustainability principles. They are:

- Justifying "livability options" for the social reality.
- Providing green community and appropriate housing through housing pilot projects.
- Providing local renewable energy sources.
- Integrating sustainable water use, harvesting, and recycling.
- Offering opportunities for decentralization option for governmental management.

- Providing quality educational needs.
- Providing connection between the old valley and the new proposed modes for community sustainability, and
- Promoting media campaigns and leveraging opportunity and quality of life.

The "Sustainable Exit from the Valley" competition initiative resulted in 42 different project ideas from the participating 53 groups. A jury panel composed of educators and scholars from Egyptian and international universities, practitioners, consultants, and governmental officials covering relevant areas such as architecture, urban planning, environmental science, and different engineering disciplines reviewed, assessed, evaluated, and ranked the submitted projects according to the following criteria:

- creativity and innovation,
- sustainable housing designs with applicability of green architecture principles,
- economic growth and job opportunity potential,
- social liveability with certainty that social reality is the basis of population distribution ,
- energy alternatives for renewable energy resources,
- water desalination and re-use mechanisms,
- sustainable communities management alternatives,
- economic competitiveness,
- education opportunities, and
- future technology compliance

The proposed project and community development ideas were introduced and presented at a two-day conference. Each group also developed a web-based presentation that was available for those who could not attend the conference. Figure 1 presents the various project locations for the 42 proposals submitted as part of the competition initiative. The jury panel ranked the submissions based on the above listed criteria. Awards were given to the top 10 projects.

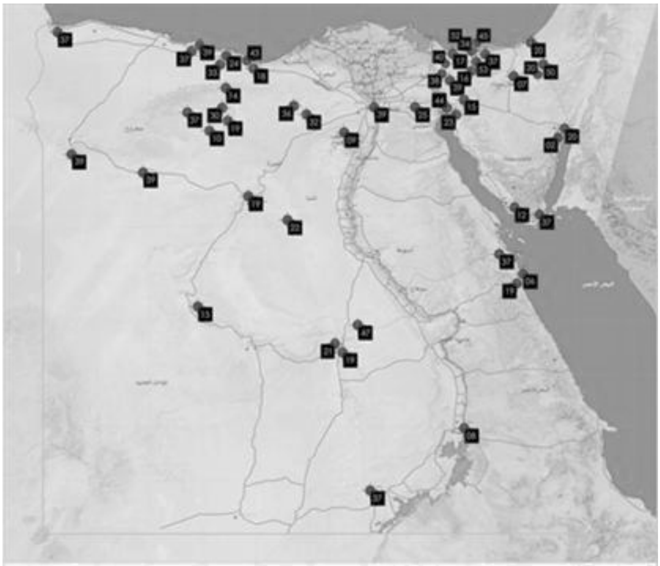

Figure 1 Location of the proposed 42 projects

Each proposed project was the result of considerable effort of groups of students, young professionals, and researchers that extended for hundreds of hours. The submissions quality was a testimony of the participants' creativity, knowledge, and thoroughness. Several iterations of the project process have resulted in a complete and mature project ready to be implemented in the field. Most of these submissions addressed the complex sustainability challenges each project faced and achieved the integrated goals they initially defined.

Defining Transportation Networks to Support Sustainable Development

As the evaluation process began, it became a variation in the depth and priorities existed among the 42 projects submitted. To define the transportation network needed to support these proposed sustainable developments, it was important to group them into different regional zones. Figure 2 presents the proposed 10 different regional zones that extend in different parts of Egypt. These zones and the different projects proposed within each zone are listed in Table 1.

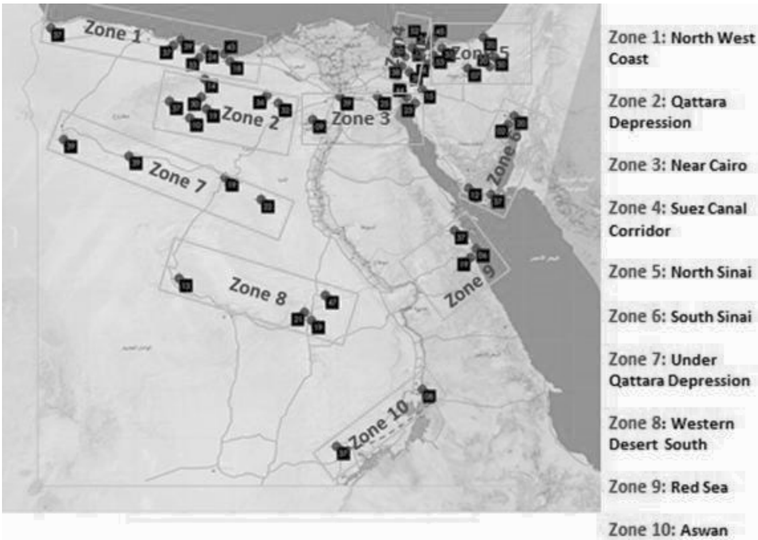

Figure 2 Proposed projects grouped into ten regional zones

Once these zones are identified, the requirements of the transportation needed to support these sustainable development regions are defined and the topography of the transportation networks for different modes are developed. These included a highway network, a railway network, aviation and airport network, and a marine network. The details of these networks are presented in Figure 3, Figure 4, Figure 5, and Figure 6, respectively.

In a recent effort by different governmental agencies, a master plan for 70 new development projects was established. This master plan (Figure 7) is characterized by varieties in typology and geographic distribution that supports both local and international investments within the main map for investments in urban development growth. These projects cover all sectors including agriculture, tourism, industrial, infrastructure, renewable energy, production and services, etc. The executive plan of these developments included 17 provinces. Seven of those projects share development among several provinces. Upon completion, the proposed development plan will provide 250,000 new job opportunities. The transportation networks, developed as result of the “Sustainable Exit from the Valley Initiative”, incorporated, when possible, different components of the proposed national strategic planning network. Such incorporation will ensure that the proposed transportation networks will be easily integrated into the proposed national network.

Table 1 Regional Zones and Associated Proposals

	Zone 1 North West Coast		Zone 2 Qattara Depression		Zone 3 Cairo		Zone 4 Suiz Canal		Zone 5 North Sinai		Zone 6 South Sinai		Zone 7 Under Qattara		Zone 8 West Desert - South		Zone 9 Red Sea		Zone 10 Aswan
18	Near Al-Alamein City	10	Qattara Depression	9	Above Lake Qarun	19	East of Ismailia - West Sinai	7	Hassana City - North Sinai		Taba - Nuweiba Road	19	El Bahria Oasis	13	Between Farafra & Kharga Oasis	6	Badaya City - Above Safaga	8	High Dam - Aswan
24	El Dabaa - North Coast	14	Qattara Depression	26	Cairo-Suez Road	23	North East Suez Gulf	15	North Sinai	2	El Qaa Plain - South Sinai	22	Farafra Oasis	19	El Kharga Oasis	19	South of Safaga - Red Sea	37	New Toshka City
33	North West Coast	19	Qattara Depression	32	Between Cairo and Fayoum Axis	38	East Suez Canal - North West Sinai	16	North Sinai	12	Sinai Eastern Border	39	Health care Cell - Siwa	21	El Kharga Oasis	37	New Sohag - Red Sea		
39	Tourist & Educational Cell -	30	Qattara Depression	39	Starting Cell - Cairo - New Cairo	39	Energy Cell - Sinai - Suez Canal	17	North Sinai - Bardawil Lake	20	Wadi El-Kayd - South Sinai			36	Western Desert - Development				
43	South of the Alexandria-Marsa Matrouh	37	Qattara Depression			44	End of Suez Canal	34	North Sinai - Bardawil Lake	37				47	Western Desert - Development Corridor				
		39	Agriculture Cell - Qattara			40	North Sinai	37	Canal - North Sinai										
								46	North Sinai - Bardawil Lake										
								50	Sinai Eastern [illegible]										
								53	North Sinai										

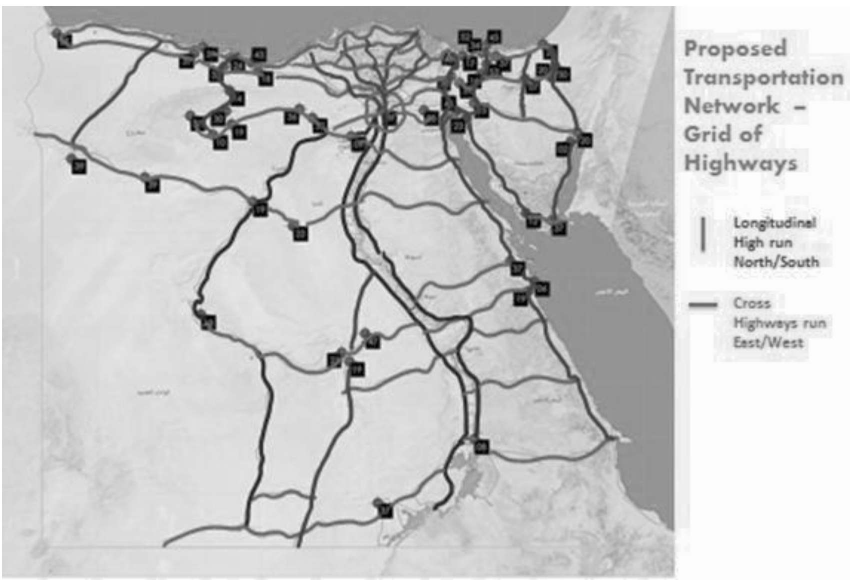

Figure 3 Proposed Highway Network to Support Sustiable Developments

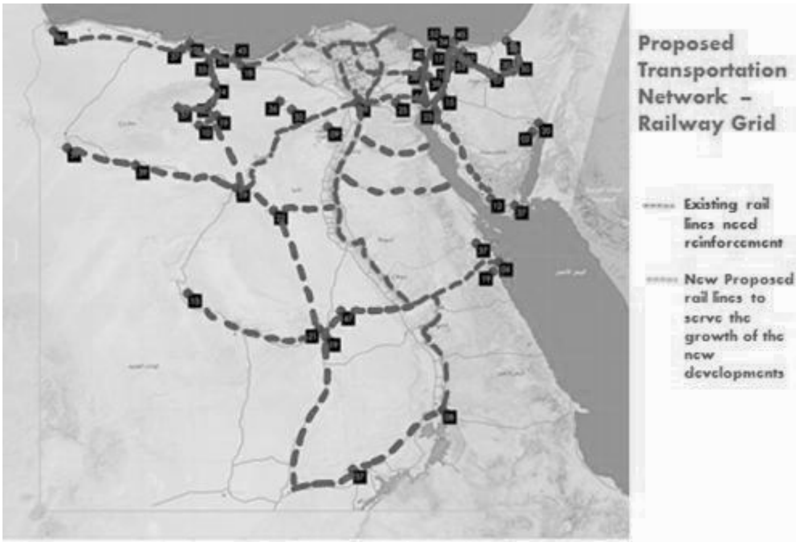

Figure 4 Proposed Railway Network to Support Sustiable Developments

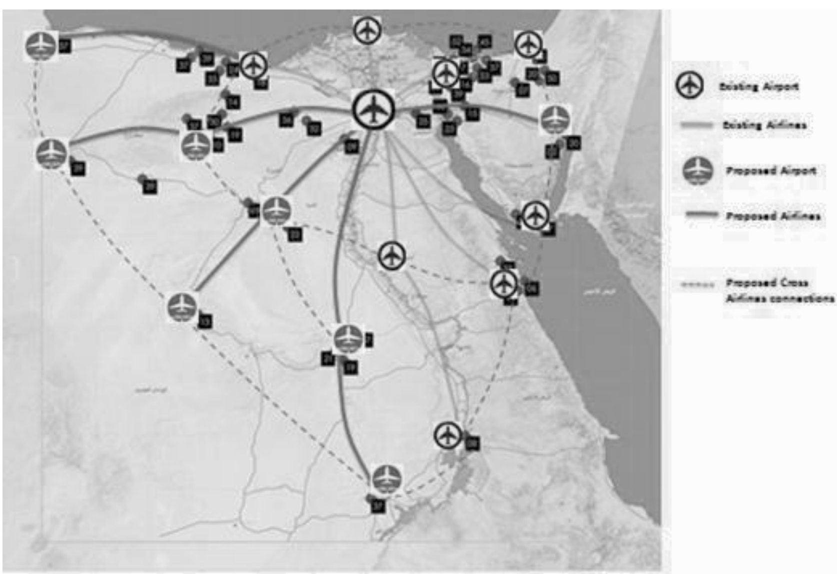

Figure 5 Proposed Aviation and Airport Network to Support Sustainable Developments

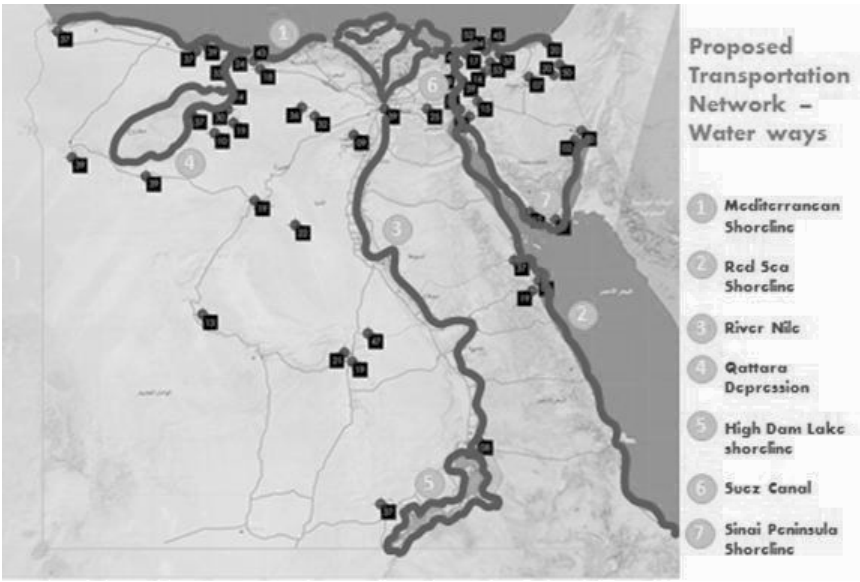

Figure 6 Proposed Marine Network to Support Sustainable Developments

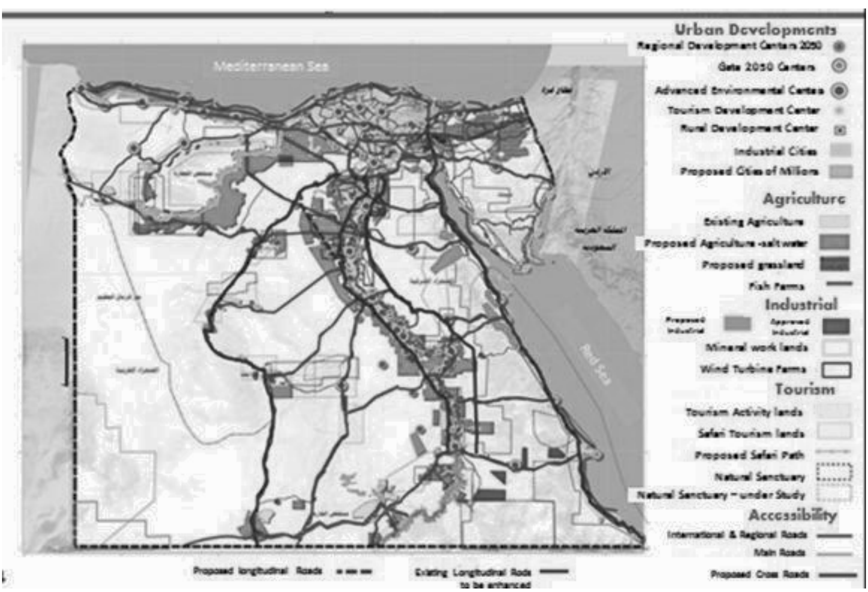

Figure 7 National Strategic Highway Network

Summary and Conclusions

This paper presented a community-wide planning effort aimed to define sustainable alternatives for future developments in different parts of Egypt. It also presents the architecture of a national transportation network to support these sustainable developments. As part of this planning effort, college students from different disciplines, researchers, and young professionals are asked to submit their ideas for sustainable developments outside the overcrowded Nile valley. The competition's initiative, entitled "Sustainable Exit from the Valley", attracted more than 120 competitors and resulted in 42 submissions with different project ideas. Expert panels are used to evaluate and rank these proposed developments according to their sustainable economic potential and to develop a national transportation network that supports proposed alternatives. The 42 project ideas are grouped into ten regional zones. The topography of highway, railway, aviation and airport, and marine transportation networks are developed to support the proposed sustainable development in the ten regions. The a proved transportation networks utilized different components of Egypt's national strategic highway network to ensure effective and integrated national transportation network operations. The proposed developments and the supporting transportation networks will facilitate a healthy growth in sustainable communities in Egypt away from the old valley providing new opportunities and saving critical agriculture land.

Sustainable Engineering Practices In A Digital Economy

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ABSTRACT

Traditional civil engineering practice methods are focused on the publishing of analog construction documents to support project delivery. Even with most internal processes being fully digital, most of the time and energy spent in engineering is consumed by the preparation of analog plans and specifications instead of the design itself. These documents then have to be reverse-engineered by digital-capable contractors for estimating, bidding, layout, and construction. A 2004 NIST report estimates that 40-60% of all engineering effort is consumed managing non-interoperable analog information. In order to produce a truly sustainable built environment engineers need to be able to simulate multiple design options within traditional budgets. This will require eliminating the cost of producing traditional analog documents and delivering the digital design information directly to contractors and other stakeholders. This paper will focus on the need for, and recent prototyping of, new practice philosophies that support engineering management and project delivery in a fully digital world.

Current situation

Almost all transportation engineering firms today produce digital data for their designs, mostly in the form of 2D files in either Microstation (.dgn) or Autocad (.dwg) format. These files represent the plan layout, in the real world project coordinate system, of each discipline of work: roadway, drainage, structure, electrical, communications, and so on. Some of the digital data represents other views, such as profile, elevation, cross sections, and highly complex digital data contains non-graphic data such as coordinate geometry, templates, and networks. This digital design data isn't new; it's been growing in use since the early 80's and reached critical mass in the early 90's

However, even with all of this digital data being created, the focus of the work is still on producing traditional deliverables in the form of plans (also referred to as drawings) where the format has changed very little since the blueprint was invented in the mid 1800's.

Traditional Plans Are Analog Information

Traditional plans or drawings are analog information printed by referencing the underlying digital information. The only means of interpreting them is by visual recognition (shape), scaling (approximate distance), or by reading a callout (text and numbers). They are a mimicry of what past technologies caused the format of communication to be. However, even though the technologies have changed, the mimicry of past form stays the same, in much the same manner as an electronic book mimics the look and feel of a traditional paper book.

This legacy format requires manual interpretation. With analog information, there's no way to ask either the paper, or even the electronic PDF file, to provide any information about the design so it can be constructed. The information has to be visually read and interpreted by a human being. This adherence to legacy formats often makes the cosmetic look and feel of the plans sheets as important as the information it contains. In any typical interim plans reviews, the majority of the comments will be on the cosmetics of the presentation, not the design.

What Has Changed Our Game?

Digital positioning and control technologies on the construction site have created new opportunities for the digital data that design firms are creating. If a contractor from fifteen years ago had been provided with a digital design file, they wouldn't have known what to do with it. Now many advanced contractors understand the digital data better than the engineers that created it in the first place.

Real Time Positioning – GPS and Robotic Total Station technology allows a single person with a rover to walk to any place on the project and not only get a high accuracy XYZ, but also Stations and Offsets if the design alignments are loaded.

Mobile Access To Digital Design Models – Positioning technology on rovers and equipment can compare the current computed location against stored 2D and 3D digital design models and tell the operator how far they are from the final design condition. Vertical distances up or down, horizontal distances in any direction, even angled distances through space. This feedback is as real time as a design engineer moving a cursor around in a design model.

Automated Machine Guidance (AMG) – Technology can adjust construction equipment without the intervention of the operator to place the work exactly where the design model specified. Not just confined to bulldozers and graders pushing dirt, AMG can control the placement of pavement, curb, pipe, stripe, markers, wicks, ducts, utilities, or anything else that needs to go in a specific place.

Construction Modeling - Advanced contractors are often modeling the project in a finer and more accurate granularity than the original design engineers. Contractors are not only modeling the final surface of the project, but unseen surfaces that are part of the construction process, the materials they're made of, when they're going to be built in the schedule, and how much they cost. These are purpose built models, supporting the task of actually building the job, rather than design models, which are often only used as a reference for printing traditional sheets.

High Construction Tempos – Innovative project delivery methods such as Design-Build, GMCG, and Concession are pushing construction schedules far faster than they have in the past. These fast paced projects demand a system of design information that can be changed at a moment's notice, as opposed to the legacy process of revising drawings, reissuing sheets, voiding out old sheets, and distributing new sheets to everyone. In some extreme cases parts of the project that are designed right after breakfast are being laid out and constructed right before dinner.

Technology-Savvy Contractors – Advanced contractors are often bigger users of technology than the design engineers. One of the things that might be driving this is that contractors aren't paid by the hour, so any automation that can replace labor usually pays for itself in short order. Engineers who are paid by the hour, or who are constrained to produce legacy deliverables in a legacy process, usually have less financial incentive to innovate.

The New Landscape

As more design firms participate in innovative delivery projects, more engineers are getting exposure to the fact that many advanced contractors can not only use, but even prefer, digital design data. In their traditional worldview the digital files were only for their internal use, and any anomalies in the files were filtered out once referenced into sheets and printed. Most engineers wouldn't anticipate that the contractor would have access to these files. But even in Design-Bid-Build, the contractors often get these files after the bid, provided by the facility owner who requested a CD of all the engineer's files before final payment of their fees.

Checking Designs For Errors - Clever contractors are known to take this digital design information, import it into their own construction modeling tools, and look for any conflicts, errors, or things that just don't fit, then prepare a stack of requests for information for the owner, who turns them over to the design engineer. Most design engineers are at a loss to understand how the contractors even noticed the problems so quickly when they are months or years away from building that part of the project.

Checking Plans For Errors - Even if the source design model files are correct, these technology-savvy contractors often use these files to quickly identify any errors in the traditional plans sheets. The contractor's tools can automatically (and correctly) label the XYZ, or stations, offsets, and elevations, of all critical points in the design files. These are compared to the published analog plans to highlight any callouts that appear incorrect, resulting in an additional flood of requests for information that often buys the contractor additional time with no penalties. Anecdotal evidence seems to suggest that 90% of the errors are in the sheet callouts and not in the original source files.

Digital Signing Of Designs - The conventional thinking of engineers is that only a physical document with a wet seal is a legal deliverable. However, most State practice rules have been updated in the last ten years allowing a digitally signed file to be just as legal and courtroom defendable as ink and mylar. In fact, the digital file might be more secure, because engineering seals of anyone can be created in CAD, and wet signatures can easily be forged. The digital seal would allow any user of the file to check it online and verify that the actual engineer who had the digital code, either in their office or on a personal thumbdrive, approved and locked the file.

What Are The Professional Problems?

Outdated Practice Methods – Civil engineering practice methods have evolved over the last 150 years, in what might be considered the golden age of civil engineering. Civil engineering students were required to learn all of the traditional methods of developing and communicating information, including isometric views, profiles, cross sections, plan views, elevation views, cut sections, borders, legends, north arrows, etc. There has been an expectation that engineers will meticulously fill out calculation sheets, calculation tables, and comment resolution tables. These practice methods are grounded in an analog world, and need to be updated to a digital world.

Obsolete Design Quality Management Plans - Design quality management has traditionally focused on two traditional tools: the Checkprint and the Checklist. The checkprint is an analog document control process that grew out of the need to keep tabs on the progress of increasingly complex plans. It relies on a system of multicolored pencils to highlight and communicate information on blueprints or diazoprints make from the original mylars, identifying who created it, who drafted it, who verified it, who backchecked it, and who approved it. The original purpose of the checkprint was to allow the design engineer of record, or any other stakeholders, to review the condition and progress of the developing construction documents, communicate changes to the drafter, and provide an audit trail for all changes, without the unnecessary touching of the original mylars, which will get stains and smudges if handled improperly. The checklist is a function of the fact that many items of information were often left off of the officially published plans, and served as a reminder to show each item to avoid omissions.

Document Focused Project Managers - Because of engineering training, and more importantly because of client requirements, the primary focus of design engineering is the production of traditional deliverables in the form of plans sheets. There are empirical and anecdotal estimates that 50% of all the time, labor, and money in the design engineering process goes into the production of the analog, cosmetically-focused documents. In many comment resolution meetings, most of the comments deal with the presentation of the design rather than the design itself.

Aversion To Sharing Digital Data – Because practice methods are outdated, and traditional project managers are out of touch with the technology, there is an aversion to sharing the digital data files because of the lack of knowledge about what's inside them. A significant amount of effort in the plans production process is consumed moving text around, lining it up, masking out certain areas, adjusting fonts , colors, line styles and weights, and fine tuning the visual appeal of patterns. This level of visual control of the deliverable is seen as the primary way of managing design risk. Unless the Engineer In Responsible Charge (EIRC) knows what's inside the digital data, there is always the fear that they'll be signing off on information they don't know about, didn't check, or even didn't supervise.

Standards Of Communicating Digital Information - There is a tribal standard in the engineering profession about what each item of analog, visual information means. Often this tribal standard is achieved by the "go-by", which is a set of plans that have been issued on a past project that serves as a guide for the structure, look, and feel of the new set. However, in digital data there is neither look nor feel. There's only the logical structure of the data. If a digital line is tagged as a 12" reinforced concrete pipe when the design intent was really a 24" corrugated steel pipe, then the contractor is going to order and install what the data specifies. While it's possible, and highly suggested, for a design engineer to carefully structure their design data based on specification or pay items, without a generally accepted standard then it's up to the judgment of the design engineer. If the descriptions are close an attentive contractor can figure them out, but it's certainly preferred if the design data is as carefully controlled and measure as contract pay item data.

Possible Solutions

Separation Of Design From Drafting - Since all design should be in the master design files and all drafting should be in the traditional sheet files, separating these two activities can not only help control their respective qualities, but also provide design firms with a more accurate measurement of how much time and money goes into one versus the other. The goal of separating the design from the drafting would be to produce design files with all of the information necessary to successfully build the project even in the absence of the analog plans sheets. If information is on the plans sheets that isn't in the design files, then one has to ask where the information came from in the first place.

Focus On Content, Not Style – Digital data is pure information. It doesn't have the styles of communication that we've seen in plans sheets for over a century. These plans sheets were modeled after maps, because a plans sheet is just a map of something that we haven't created yet. But digital content should be just enough information to get the job done, rather than additional information and graphics to seem pleasing to the eye and mind. By focusing on the content, the engineer has to determine the minimum amount of information needed to properly construct an element, and then provide only that and no more. Content could communicate position and size, but could also communicate materials, textures, surfaces, temperatures, and strength.

Talk To Contractors – Civil engineers are supposed to be part of a learned profession based on applied science. Part of professional responsibility is advancing the art of the practice, which means going out into the world to understand how it really works. If contractors are actively using this digital design data in ways the design engineers don't know or understand, then this lack of knowledge or understanding will cause increasing levels of problems until some crisis brings it to the forefront of the profession, forcing a solution. The civil engineering profession would benefit by solving these issues before they become major problems.

Understand The Technology – Digital design data by itself is useless on a construction project without some type of technology to exploit it. The technologies that make it work are a combination of positioning systems, data collection systems, and control systems. Both design and construction engineers need to learn the fundamentals of how these systems function including the coordinate systems, the data models, the ranges of errors and accuracies, and key things that might go wrong. This understanding will not only help improve design information, but transform construction engineering and inspection (CEI) from a labor and document intensive professional service into a technology and results intensive professional service.

What Does This Issue Have To Do With Sustainability?

One of the enemies of sustainability is waste. Waste can also be described as anything that consumes resources that adds no value.

The Japanese, in their quest for lean production, have developed more accurate terms for waste:

Muda: Uselessness
Mura: Unreliability
Muri: Excessiveness

How does these concepts of waste apply to engineering management in a digital economy?

Uselessness – Much of the analog information produced in our traditional project delivery processes could be considered useless. An example would be the thousands of error-ridden callouts that are placed on plans sheets to tell a contractor where things are to be constructed. Twenty years ago, these were necessary because the only way to communicate to a contractor was on paper. Today, however, information can be easily communicated to contractors digitally. This makes the analog information on a traditional plans sheet as useless as the buggy whip holder that was often left on early horseless carriages.

Unreliability – Traditional analog project delivery process often involve the same information being placed on multiple plans and specification sheets throughout the contract documents. However, as project elements are revised, some of this information is updated while the rest isn't. This results in the engineer consuming resources only to produce unreliable information. Empirical results from the field tend to indicate that 90% of the errors and omissions in a set of contract documents are in the plans sheets, not the underlying digital design files.

Excessiveness – Traditional project delivery methods are often an exercise in overkill. Every possible exculpatory statement is placed in the construction documents in an attempt to guard against litigation resulting in errors and omissions generated by that same overkill. This excessiveness takes time and money away from real engineering that could help make the project more sustainable. Empirical experience on actual projects has seen engineers who spend eight hours developing a design spend twice that amount of time filling out the forms, checklists, and checkprints that legacy contract requirements require to accompany the analog design deliverable.

If a major part of sustainability in civil engineering is eliminating anything in projects that consumes resources without resulting in value to our civilization, this focus should start with the engineering processes that creates the projects in the first place.

Summary

There are a few key concepts to remember in this transformation of the civil engineering profession from an analog world to a digital world.

Design Is Data – There's a traditional viewpoint that the documents represent the design, but the documents are merely the legacy media that communicates the information of the design in analog fashion. Marshall McLuhan's expression "the medium is the message" may ring true for entertainment, but not necessarily for engineering. The ultimate fixed work is still the same whether it was built with analog paper documents or digital data, although we assume that a project built with digital data should have fewer mistakes.

Design Is Only A Means To An End – The ultimate goal of civil engineering is fixed works that serve a useful purpose to society. Design is merely the process of deciding what that fixed work should be, and communicating it's requirements to the constructor. It may be true that in past decades we had professional draftsmen that could produce plans that were works of art. In fact there's even a commercial market that makes poster art from the plans of significant project like the Brooklyn Bridge or the Golden Gate Bridge. However, in our modern age we probably can't afford the time and expense to make our engineering communication a work of art. The art should be in the final project.

The Contractor Is The Customer Of The Design Data – While the client may be the customer of the engineer's services, the contractor is the customer of the data necessary to build the project. A design engineer should always consider what the needs of contractor's are in creating their design data, and take every reasonable means possible to make sure that data is immediately useful to the contractor without any additional review, processing or cleaning up.