CHAPTER 3

Traffic Engineering

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TRAFFIC ENGINEERING

3.1. Traffic Engineering Studies

The availability of highway transportation has provided several advantages that contribute to a high standard of living. However, several problems related to the highway mode of transportation exist. These problems include highway-related accidents, parking difficulties, congestion, and delay. To reduce the negative impact of highways, it is necessary to adequately collect information that describes the extent of the problems and identifies their locations. Such information is usually collected by organizing and conducting traffic surveys and studies.

3.1.1. Spot speed studies

Spot speed studies are conducted to estimate the distribution of speeds of vehicles in a stream of traffic at a particular location on a highway. A spot speed study is carried out by recording the speeds of a sample of vehicles at a specified location. Speed characteristics identified by such a study will be valid only for the traffic and environmental conditions that exist at the time of the study. Speed characteristics determined from a spot speed study may be used to;

- Establish speed zones,
- Determine whether complaints about speeding are valid,
- Establish passing and no-passing zones,
- Design geometric alignment, Analyze accident data,
- Evaluate the effects of physical improvements,
- Determine the effects of speed enforcement programs and speed control measures, to determine speed trends and so forth.

Locations for Spot Speed Studies

The locations for spot speed studies depend on the anticipated use of the results. For example, it may be for basic data collection or speed trend analyses. Any location may be used for the solution of a specific traffic engineering problem. When spot speed studies are being conducted, it is important that unbiased data be obtained. This requires that drivers be unaware that such a study is being conducted. Equipment used should therefore be concealed from the driver, and observers conducting the study should be inconspicuous.

Time of Day and Duration of Spot Speed Studies

The time of day for conducting a speed study depends on the purpose of the study. In general, when the purpose of the study is to establish posted speed limits, to observe speed trends, or to collect basic data, it is recommended that the study be conducted when traffic is free-flowing, usually during offpeak hours. However, when a speed study is conducted in response to citizen complaints, it is useful if the time period selected for the study reflects the nature of the complaints.

The duration of the study should be such that the minimum number of vehicle speeds required for statistical analysis is recorded. Typically, the duration is at least 1 hour and the sample size is at least 30 vehicles.

Definitions of values that are used to describe speed characteristics:

Average speed is the arithmetic mean of all observed vehicle speeds (which is the sum of all spot speeds divided by the number of recorded speeds). It is given as

$$\bar{u} = \frac{\sum f_i u_i}{\sum f_i} or; \bar{u} = \frac{\sum u_i}{N}$$

Where: $\bar{u}$ = arithmetic mean; f_i = number of observations in each speed group; u_i = mid value for the ith speed group; n = number of observed values

- **Median speed** is the speed at the middle value in a series of spot speeds that are arranged in ascending order. Fifty percent of the speed values will be greater than the median; 50 percent will be less than the median.
- **Modal speed** is the speed value that occurs most frequently in a sample of spot speeds.
- **The ith-percentile spot speed** is the spot speed value below which i percent of the vehicles travel; for example, 85th-percentile spot speed is the speed below which 85 percent of the vehicles travel and above which 15 percent of the vehicles travel.
- **Pace** is the range of speed- usually taken at 10-mph intervals- that has the greatest number of observations.
- **Standard deviation of speeds** is a measure of the spread of the individual speeds. It is estimated as $$S = \sqrt{\frac{\sum (u_j - \bar{u})^2}{N-1}}$$
  Where: S = standard deviation; $\bar{u}$ = arithmetic mean; u_j = jth observation; N = number of observations

However, speed data are frequently presented in classes where each class consists of all range of speeds. The standard deviation is computed for such cases as

$$S = \sqrt{\frac{\sum (f_i u_i^2 - (\sum f_i u_i)^2 / \sum f_i}{\sum f_i - 1}}$$

Where: u_i = Midvale of speed class i, f_i = frequency of speed class i

Sample Size for Spot Speed Studies

The calculated mean (or average) speed is used to represent the true mean value of all vehicle speeds at that location. The accuracy of this assumption depends on the number of vehicles in the sample. The larger the sample size, the greater the probability that the estimated mean is not significantly different from the true mean. It is therefore necessary to select a sample size that will give an estimated mean within acceptable error limits. Statistical procedures are used to determine this minimum sample size.

The minimum sample size depends on the precision level desired. The precision level is defined as the degree of confidence that the sampling error of a produced estimate will fall within a desired fixed range. Thus, for a precision level of 90-10, there is a 90 percent probability (confidence level) that the error of an estimate will not be greater than 10 percent of its true value. The confidence level is commonly given in terms of the level of significance (α), where α = (100 - confidence level). The commonly used confidence level for speed counts is 95 percent.

The properties of the normal distribution have been used to develop an equation relating the sample size to the number of standard variations corresponding to a particular confidence level, the limits of tolerable error, and the standard deviation.

The formula is $N = \left(\frac{Z\sigma}{d}\right)^2$ Where: N= minimum sample size; Z = number of standard deviations corresponding to the required confidence level 1.96 for 95 percent confidence level; α = standard deviation (mph); d = limit of acceptable error in the speed estimate (mph). The standard deviation can be estimated from previous data, or a small sample size can first be used.

Example 1

Methods for Conducting Spot Speed Studies

The methods used for conducting spot speed studies can generally be divided into two main categories: manual and automatic. Several automatic devices that can be used to obtain the instantaneous speeds of vehicles at a location on a highway are now available on the market. These automatic devices can be grouped into three main categories:

(1) Those that use road detectors,

(2) Those that use Doppler principle meters (radar type), and

(3) Those that use the principles of electronics.

Road Detectors

Road detectors can be classified into two general categories: pneumatic road tubes and induction loops. These devices can be used to collect data on speeds at the same time as volume data are being collected. When road detectors are used to measure speed, they should be laid such that the probability of a passing vehicle closing the connection of the meter during a speed measurement is reduced to a minimum. This is achieved by separating the road detectors by a distance of 3 to 15 ft. The advantage of the detector meters is that human errors are considerably reduced. The disadvantages are that (1) these devices tend to be rather expensive, and (2) when pneumatic tubes are used, they are rather conspicuous and may, therefore, affect driver behavior, resulting in a distortion of the speed distribution.

Doppler-Principle Meters

Doppler meters work on the principle that when a signal is transmitted onto a moving vehicle, the change in frequency between the transmitted signal and the reflected signal is proportional to the speed of the moving vehicle. The difference between the frequency of the transmitted signal and that of the reflected signal is measured by the equipment, and then converted to speed in mph. In setting up the equipment, care must be taken to reduce the angle between the direction of the moving vehicle and the line joining the center of the transmitter and the vehicle. The value of the speed recorded depends on that angle. If the angle is not zero, an error related to the cosine of that angle is introduced, resulting in a lower speed than that which would have been recorded if the angle had been zero. However, this error is not very large, because the cosines of small angles are not much less than 1.

The advantage of this method is that because pneumatic tubes are not used, if the equipment can be located at an inconspicuous position, the influence on driver behavior is considerably reduced.

Electronic-Principle Detectors

In this method, the presence of vehicles is detected through electronic means, and information on these vehicles is obtained, from which traffic characteristics such as speed, volume, queues, and headways are computed. The great advantage of this method over the use of road detectors is that it is not necessary to physically install loops or any other type of detector on the road. The most promising technology using electronics is video image processing, sometimes referred to as a machine-vision system. This system consists of an electronic camera overlooking a large section of the roadway and a microprocessor. The electronic camera receives the images from the road; the microprocessor determines the vehicle's presence or passage. This information is then used to determine the traffic characteristics in real time. One such system is the auto scope.

Example 2

3.1.2. Volume studies

Traffic volume studies are conducted to collect data on the number of vehicles and/or pedestrians that pass a point on a highway facility during a specified time period. This time period varies from as little as 15 min to as much as a year, depending on the anticipated use of the data. The data collected may also be put into subclasses which may include directional movement, occupancy rates, vehicle classification, and pedestrian age. Traffic volume studies are usually conducted when certain volume characteristics are needed, some of which are:

1. **Average Annual Daily Traffic (AADT)** is the average of 24-hr counts collected every day in the year. AADTs are used in several traffic and transportation analyses for
    a) Estimation of highway user revenues.
    b) Computation of accident rates in terms of accidents per 100 million vehicles per miles.
    c) Establishment of traffic volume trends.
    d) Evaluation of the economic feasibility of highway projects.
    e) Development of freeway and major arterial street systems.
    f) Development of improvement and maintenance programs.

2. **Average Daily Traffic (ADT)** is the average of 24-hour counts collected over a number of days greater than 1 but less than a year. ADTs may be used for;

   a. Planning of highway activities,
   b. Measurement of current demand,
   c. Evaluation of existing traffic flow and so forth.

3. **Peak Hour Volume (PHV)** is the maximum number of vehicles that pass a point on a highway during a period of 60 consecutive minutes. The peak hour volumes PHVs are used for,

   a. Functional classification of highways,
   b. Design of the geometric characteristics of a highway, for example, number of lanes, intersection signalization, or channelization,
   c. For capacity analysis,
   d. Development of programs related to traffic operations, for example street systems or traffic routing and Development of parking regulations and etc.

4. **Vehicle Classification (VC)** records Volume with respect to the type of vehicles, for example, passenger cars, two-axle trucks, or three-axle trucks. VC is used in

   a. Design of geometric characteristics, with particular reference to turning radii requirements, maximum grades, and lane widths, and so forth

   b. Capacity analyses, with respect to passenger-car equivalents of trucks

   c. Adjustment of traffic counts obtained by machines

   d. Structural design of highway pavements, bridges, and so forth

5. **Vehicle Miles of Travel (VMT)** is a measure of travel along a section of road. It is the product of the traffic volume (that is, average weekday volume or ADT) and the length of roadway in miles to which the volume is applicable. VMTs are used mainly as a base for allocating resources for maintenance and improvement of highways.

Methods of Conducting Volume Counts

Traffic volume counts are conducted using two basic methods: manual and automatic.

I. Manual Method

Manual counting involves one or more persons recording observed vehicles using a counter. The main disadvantages of the manual count method are that (1) it is labor-intensive and can therefore be expensive, (2) it is subject to the limitations of human factors, and (3) it cannot be used for long periods of counting.

II. Automatic Method

The automatic counting method involves the laying of surface detectors (such as pneumatic road tubes) or subsurface detectors (such as magnetic or electric contact devices) on the road. These detect the passing vehicle and transmit the information to a recorder, which is connected to the detector at the side of the road.

Traffic Volume Data Presentation

The data collected from traffic volume counts may be presented in one of several ways, depending on the type of count conducted and the primary use of the data. Some of the conventional data presentation techniques are:

- Traffic Flow Maps
- Intersection Summary Sheets
- Time-Based Distribution Charts
- Summary Tables

Traffic Volume Characteristics

A continuous count of traffic at a section of a road will show that traffic volume varies from hour to hour, from day to day, and from month to month. However, the regular observation of traffic volumes over the years has identified certain characteristics showing that although traffic volume at a section of a road varies from time to time this variation is repetitive and rhythmic. These characteristics of traffic volumes are taken in to consideration when traffic counts are being planned so that volumes collected at a particular time or place can be related to volumes collected at other times and places. Knowledge of these characteristics can also be used to estimate the accuracy of traffic counts.

Sample Size and Adjustment of Periodic Counts

The impracticality of collecting data continuously every day of the year at all counting stations makes it necessary to collect sample data from each class of highway and to estimate annual traffic volumes from periodic counts. This involves the determination of the minimum sample size (number of count stations) for a required level of accuracy and the determination of daily, monthly, and/or seasonal expansion factors for each class of highway.

Determination of Number of Count Stations

The minimum sample size depends on the precision level desired. The commonly used precision level for volume counts is 95-10. When the sample size is less than 30 and the selection of counting stations is random, a distribution known as the student's t distribution may be used to determine the sample size for each class of highway links. The student's t distribution is unbounded, with a mean of zero, and has a variance that depends on the scale parameter, commonly referred to as the degrees of freedom (ν). The degrees of freedom (ν) is a function of the sample size; $\nu = N - 1$ for the student's t distribution. The variance of the student's t distribution is $\nu/(\nu - 2)$, which indicates that as ν approaches infinity, the variance approaches 1.

Assuming that the sampling locations are randomly selected, the minimum sample number is given as

$$n = \frac{t^2_{\alpha/2,N-1}(S^2/d^2)}{1+(1/N)(t^2_{\alpha/2,N-1})(S^2/d^2)}$$

Where: n = minimum number of count locations required; t = value of the student's t distribution with (1 - α /2) confidence level (N - 1 degrees of freedom); N = total number of links (population) from which a sample is to be selected α = significance level; S = estimate of the spatial standard deviation of the link volumes; d= allowable range of error

To use the above equation, estimates of the mean and standard deviation of the link volumes are required. These estimates can be obtained by taking volume counts at a few links or by using known values for other, similar highways.

Example 3

Adjustment of Periodic Counts

Expansion factors, used to adjust periodic counts, are determined either from continuous count stations or from control count stations.

Expansion Factors from Continuous Count Stations- Hourly, daily, and monthly expansion factors can be determined using data obtained at continuous count stations.

Hourly expansion factors (HEFs) are determined by the formula

$$HEF = \frac{total..volume..for..24-hr..period}{volume..for..particular..hour}$$

These factors are used to expand counts of durations shorter than 24 hr to 24-hr volumes by multiplying the hourly volume for each hour during the count period by the HEF for that hour and finding the mean of these products.

Daily expansion factors (DEFs) are computed as

$$DEF = \frac{average.total..volume..for..the..week}{average.volume..for..particular..day}$$

These factors are used to determine weekly volumes from counts of 24-hr duration multiplying the 24-hr volume by the DEF.

Monthly expansion factors (MEFs) are computed as

$$MEF = \frac{AADT}{ADT..for..particular..month}$$

The AADT for a given year may be obtained from the ADT for a given month multiplying this volume by the MEF.

Example 4

3.1.3. Travel time and delay studies

A travel time study determines the amount of time required to travel from one point to another on a given route. In conducting such a study, information may also be collected on the locations, durations, and causes of delays. When this is done, the study is known as a travel time and delay study. Data obtained from travel time and delay studies give a good indication of the level of service on the study section. These data also aid the traffic engineer in identifying problem locations, which may require special attention in order to improve the overall flow of traffic on the route.

Applications of Travel Time and Delay Data

The data obtained from travel time and delay studies may be used in any one of the following traffic engineering tasks:

- Determination of the efficiency of a route with respect to its ability to carry traffic
- Identification of locations with relatively high delays and the causes for those delays
- Performance of before-and-after studies to evaluate the effectiveness of traffic operation improvements
- Determination of relative efficiency of a route by developing sufficiency ratings or congestion indices
- Determination of travel times on specific links for use in trip assignment models
- Compilation of travel time data that may be used in trend studies to evaluate the changes in efficiency and level of service with time
- Performance of economic studies in the evaluation of traffic operation alternatives that reduce travel time.

Definition of Terms Related to Time and Delay Studies

1. **Travel time** is the time taken by a vehicle to traverse a given section of a highway
2. **Running time** is the time a vehicle is actually in motion while traversing a given section of a highway.
3. **Delay** is the time lost by a vehicle due to causes beyond the control of the driver.
4. **Operational delay** is that part of the delay caused by the impedance of other traffic. This impedance can occur either as side friction, where the stream flow is interfered with by other traffic (for example, parking or un parking vehicles), or as internal friction, where the interference is within the traffic stream (for example, reduction in capacity of the highway).
5. **Stopped-time delay** is that part of the delay during which the vehicle is at rest

6. **Fixed delay** is that part of the delay caused by control devices such as traffic signals. This delay occurs regardless of the traffic volume or the impedance that may exist.

7. **Travel-time delay** is the difference between the actual travel time and the time that will be obtained by assuming that a vehicle traverses the study section at an average speed equal to that for an uncontested traffic flow on the section being studied.

Methods for Conducting Travel Time and Delay Studies

Several methods have been used to conduct travel time and delay studies. These methods can be grouped into two general categories:

(1) Those using a test vehicle and

(2) Those not requiring a test vehicle.

Methods Requiring a Test Vehicle

This category involves three possible techniques:

- Floating-car,
- Average-speed and
- Moving-vehicle techniques.

➢ **Floating - Car Technique**. In this method, the test car is driven by an observer along the test section so that the test car "floats" with the traffic. The driver of the test vehicle attempts to pass as many vehicles as those that pass his test vehicle. The time taken to traverse the study section is recorded. This is repeated, and the average time is as the travel time. The minimum number of test runs can be determined using values of the T-distribution. The equation is

$$N = \left(\frac{t_\alpha . \sigma}{d} \right)^2 \quad \text{-----3.1}$$

Where: N = sample size (minimum number of test runs), s = standard deviation (mph), d = limit of acceptable error in the speed estimate (mph), t_α = value of the student's t distribution with (1 - a/2) confidence level and (N - 1) degrees of freedom, a = significance level

The limit of acceptable error used depends on the purpose of the Study. The following limits are commonly used:

Before-and-after studies: ±1.0 to ±3.0 mph

Traffic operation, economic evaluations, and trend analyses: ±2.0 to ±4.0

Highway needs and transportation planning studies: ±3.0 to ±5.0 mph

- **Average - Speed Technique**. This technique involves driving the test car along the length of the test section at a speed that, in the opinion of the driver, is the average speed of traffic stream. The time required to traverse the test section is noted. The test run is repeated for the minimum number of times, determined from Eq. 3.1, and the avenge time is recorded as the travel time.

- **Moving - Vehicle Technique**. In this technique, the observer makes a round trip on a test section like the one shown in Fig 3., where it is assumed that the road runs east-west. The observer starts collecting the relevant data at section X-X, drives the car eastward to section Y-Y, and then turns the vehicle around and drives westward to section X-X again.

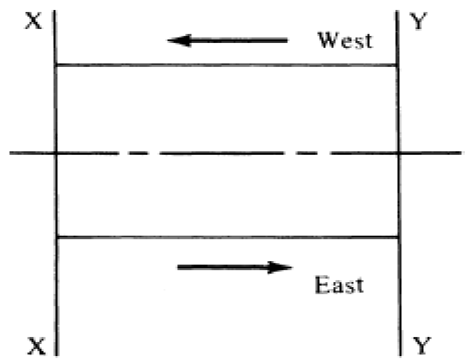


Figure 3 Test site for Moving –vehicle Method

The following data are collected as the test vehicle makes the round trip:

- The time it takes to travel from X-X to Y-Y (Te), in minutes
- The time it takes to travel from Y-Y to X-X (Tw), in minutes
- The number of vehicles traveling west in the opposite lane while the test car is traveling east (Ne)
- The number of vehicles that overtake the test car while it is traveling from Y-Y to X-X, that is, traveling in the westbound direction (Ow)
- The number of vehicles that the test car passes while it is traveling from Y-Y to X-X, that is, traveling in the westbound direction (Pw)

The volume (Vw) in the westbound direction can then be obtained from the expression

$$V_w = \frac{(N_e + O_w - P_w) * 60}{T_e + T_w} \text{-------3.2}$$

Where, (Ne+ Ow - Pw) is the number of vehicles traveling westward that cross the line X-X during the time (Te-Tw). Note that when the test vehicle starts at X-X, traveling eastward, all vehicles traveling westward should get to XX before the test vehicle, except those that are passed by the test vehicle when it is traveling westward. Similarly, all vehicles that pass the test vehicle when it is traveling westward will get to X-X before the test vehicle. The test vehicle will also get to X-X before all vehicles it passes while traveling westward. These vehicles have, however, been counted as part of Ne or Ow and should therefore be subtracted from the sum of Ne and Ow to determine the number of westbound vehicles that cross X-X during the time the test vehicle travels from X-X to Y-Y and back to X-X.

Similarly, the average travel time Tw in the westbound direction is obtained from

$$\frac{\bar{T}_w}{60} = \frac{T_w}{60} - \frac{O_w - P_w}{V_w}$$

$$\bar{T}_w = T_w - \frac{60*(O_w - P_w)}{V_w} \qquad \text{------3.3}$$

If the test car is traveling at the average speed of all vehicles, it will most likely pass the same number of vehicles as the number of vehicles that overtake it. Since it is probable that the test car will not be traveling at the average speed, the second term of Eq. 3.3 corrects for the difference between the number of vehicles that overtake the test car and the number of vehicles that are overtaken by the test car.

Example 5

Methods Not Requiring a Test Vehicle

This category includes the

- License-plate method and
- The interview method

➢ **License - Plate Observations.** The license-plate method requires that observers be positioned at the beginning and end of the test section. Observers can also be positioned at other locations if elapsed times to those locations are required. Each observer records the last three or four digits of the license plate of each car that passes, together with the time at which the car passes. The reduction of the data is accomplished in the office by matching the times of arrival at the beginning and end of the test section for each license plate recorded. The difference between these times is the traveling time of each vehicle. The average of these is the average traveling time on the test section. It has been suggested that a sample size of 50 matched license plates will give reasonably accurate results.

➢ **Interviews.** The interviewing method is carried out by obtaining information from people who drive on the study site regarding their travel times, their experience of delays, and so forth. This method facilitates the collection of a large amount of data in a relatively short time. However, it requires the cooperation of the people contacted, since the result depends entirely on the information given by them.

3.1.4. Parking studies

Types of Parking Facilities

Parking facilities can be divided into two main groups:

- On-street and
- Off-street.

➢ **On-Street Parking Facilities**

These are also known as curb facilities. Parking bays are provided alongside the curb on one or both sides of the street. These bays can be unrestricted parking facilities if the duration of parking is unlimited and parking is free, or they can be restricted parking facilities if parking is limited to specific times of the day for a maximum duration. Parking at restricted facilities may or may not be free. Restricted facilities may also be provided for specific purposes, such as to provide handicapped parking or as bus stops or loading bays.

➢ **Off-Street Parking Facilities**

These facilities may be privately or publicly owned; they include surface lots and garages. Self-parking garages require that drivers park their own automobiles; attendant-parking garages maintain personnel to park the automobiles.

Definitions of Parking Terms

1. **A space-hour** is a unit of parking that defines the use of a single parking space for a period of 1 hr.

2. **Parking volume** is the total number of vehicles that park in a study area during a specific length of time, usually a day.

3. **Parking accumulation** is the number of parked vehicles in a study area at any specified time. These data can be plotted as a curve of parking accumulation against time, which shows the variation of the parking accumulation during the day.

4. **The parking load** is the area under the accumulation curve between two specific times. It is usually given as the number of space-hours used during the specified period of time.

5. **Parking duration** is the length of time a vehicle is parked at a parking bay. When the parking duration is given as an average, it gives an indication of how frequently a parking space becomes available.

6. **Parking turnover** is the rate of use of a parking space. It is obtained by dividing the parking volume for a specified period by the number of parking spaces.

Methods of Parking Studies

A comprehensive parking study usually involves

(1) Inventory of existing parking facilities,
(2) Collection of data on parking accumulation, parking turnover, and parking duration,
(3) Identification of parking generators, and
(4) Collection of information on parking demand.
(5) Information on related factors, such as financial, legal, and administrative matters, may also be collected.

Analysis of Parking Data

Analysis of parking data includes summarizing, coding, and interpreting the data so that the relevant information required for decision-making can be obtained. The relevant information includes

- Number and duration for vehicles legally parked
- Number and duration for vehicles illegally parked
- Space-hours of demand for parking
- Supply of parking facilities.

The analysis required to obtain information on the first two items is straightforward; it usually involves simple arithmetical and statistical calculations. Data obtained from these items are then used to determine parking space-hours.

The space-hours of demand for parking are obtained from the expression

$$D = \sum_{i=1}^{N}(n_i t_i)$$

Where: D= space vehicle-hours demand for a specific period of time; N = number of classes of parking duration ranges; ti = mid parking duration of the i^{th} class; ni= number of vehicles parked for the ith duration range

The space-hours of supply are obtained from the expression

$$S = f\sum_{i=1}^{N}(t_i)$$

Where: S = practical number of space-hours of supply for a specific period of time; N = number of parking spaces available; ti = total length of time in hours when the ith space can be legally parked on during the specific period; f= efficiency factor

The efficiency factor is used to correct for time lost in each turnover. It is determined on the basis of the best performance a parking facility is expected to produce. Efficiency factors should therefore be determined for different types of parking facilities for example, surface lots, curb parking, and garages. Efficiency factors for curb parking, during highest demand, vary from 78 percent to 96 percent; for surface lots and garages, from 75 percent to 92 percent. Average values of f are 90 percent for curb parking, 80 percent for garages, and 85 percent for surface lots.

Example 6

3.2. Fundamental Principles of Traffic Flow

Traffic flow theory involves the development of mathematical relationships among the primary elements of a traffic stream: flow, density, and speed. These relationships help the traffic engineer in planning, designing, and evaluating the effectiveness of implementing traffic engineering measures on a highway system. Traffic flow theory is used in design to determine adequate lane lengths for storing left-turn vehicles on separate left-turn lanes, the average delay at intersections and freeway ramp merging areas, and changes in the level of freeway performance due to the installation of improved vehicular control devices on ramps. Another important application of traffic flow theory is simulation, where mathematical algorithms are used to study the complex interrelationships that exist among the elements of a traffic stream or network and to estimate the effect of changes in traffic flow on factors such as accidents, travel time, air pollution, and gasoline consumption.

3.2.1. Traffic flow elements

Let us first define the elements of traffic flow before discussing the relationships among them. Before we do that, though, we will describe the time-space diagram, which serves as a useful device for defining the elements of traffic flow.

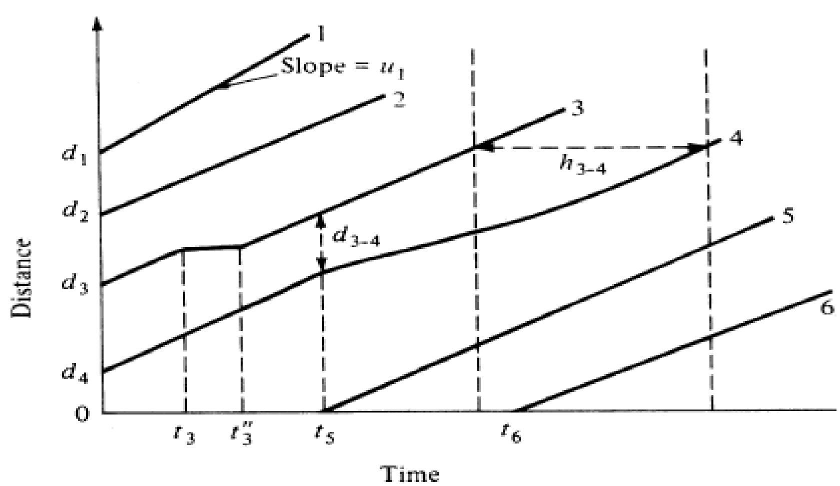


Figure 3.1 Time-space Diagram

The time-space diagram is a graph that describes the relationship between the location of vehicles in a traffic stream and the time as the vehicles progress along the highway. Figure 3.1 shows a time-space diagram for six vehicles, with distance plotted on the vertical axis and time on the horizontal axis, At time zero, vehicles 1, 2, 3, and 4 are at respective distances d1, d2, d3, and d4 from a reference point, whereas vehicles 5 and 6, cross the reference point later at times t5 and t6 respectively.

The primary elements of traffic

The primary elements of traffic flow are **flow**, **density**, and **speed**. Another element associated with density, is the **gap** or **headway** between two vehicles in traffic.

The definitions of these elements follow.

Flow (q) is the equivalent hourly rate at which vehicles pass a point on a highway during a time period less than 1 hr. It can be determined by

$$q = \frac{n * 3600}{T} vph$$

Where: n = the number of vehicles passing a point in the roadway in T sec; q = the equivalent hourly flow.

Density (k), sometimes referred to as **concentration**, is the number of vehicles traveling over a unit length of highway at an instant in time. The unit length is usually 1 mile thereby making vehicles per mile (vpm) the unit of density.

Speed (u) is the distance traveled by a vehicle during a unit of time. It can be expressed in miles per hour (mph), kilometers per hour (km/h), or feet per second (ft/sec). The speed of a vehicle at any time t is the slope of the time-space diagram for that vehicle at time t. Vehicles 1 and 2 in Figure 3.1, for example, are moving at a constant speed because the slopes of the associated graphs are constant. Vehicle 3 moves at a constant speed between time zero and time t3, then stops for the period t3 to t"3(the slope of the graph equals zero), and then accelerates and eventually moves at a constant speed.

There are two types of mean speeds: **time mean speed** and **space mean speed**.

Time mean speed ($\bar{u}_t$) is the arithmetic mean of the speeds of vehicles passing a point on a highway during an interval of time. The time mean speed is found by

$$\bar{u}_t = \frac{1}{n}\sum_{i=1}^{n} u_i$$

Where: n =number of vehicles passing a point on the highway; ui = speed of the ith vehicle (ft/sec)

Space mean speed ($\bar{u}_s$) is the harmonic mean of the speeds of vehicles passing a point in a highway during an interval of time. It is obtained by dividing the total distance traveled by two or more vehicles on a section of highway by the total time required by these vehicles to travel that distance. This is the speed that is involved in flow-density relationships. The space mean speed is found by

$$\bar{u}_t = \frac{n}{\sum_{i=1}^{n}(1/u_i)} = \frac{nL}{\sum_{i=1}^{n} t_i}$$

Where: $\bar{u}_s$ = space mean speed (ft/sec); n = number of vehicles; ti = the time it takes the ith vehicle to travel across a section of highway (see); Ui =speed of the ith vehicle (ft/sec); L = length of section of highway (ft)

Time headway (h) is the difference between the time the front of a vehicle arrives at a point on the highway and the time the front of the next vehicle arrives at that same point. Time headway is usually expressed in seconds. For example, in the time-space diagram (Figure 6.1), the time headway between vehicles 3 and 4 at d1 is h3-4.

Space headway (d) is the distance between the front of a vehicle and the front of the following vehicle. It is usually expressed in feet. The space headway between vehicles 3 and 4 at time t5 is d3-4 (see Figure 6.1).

Example 7 & 8

3.2.2. Flow-density relationships

The general equation relating flow, density, and space mean speed is given as

- Flow = (density) x (space mean speed)

$$q = k * \bar{u}_s \text{ --------------3.5}$$

Each of the variables in Eq. 6.5 also depends on several other factors, including the characteristics of the roadway, the characteristics of the vehicle, the characteristics of the driver, and environmental factors such as the weather.

Other relationships that exist among the traffic flow variables are given below.

- Space mean speed = (flow) x (space headway)

$$\bar{u}_s = q * \bar{d}$$

Where: $\bar{d}$ = (1/ k) = average space headway

- Density = (flow) x (travel time for unit distance)

$$k = q * \bar{t}$$

Where: $\bar{t}$ is the average time for unit distance.

Average space headway = (space mean speed) x (average time headway)

$$\bar{d} = \bar{u}_s * \bar{h}$$

Average time headway = (average travel time for unit distance) x (average space headway)

$$\bar{h} = \bar{t} * \bar{d}$$

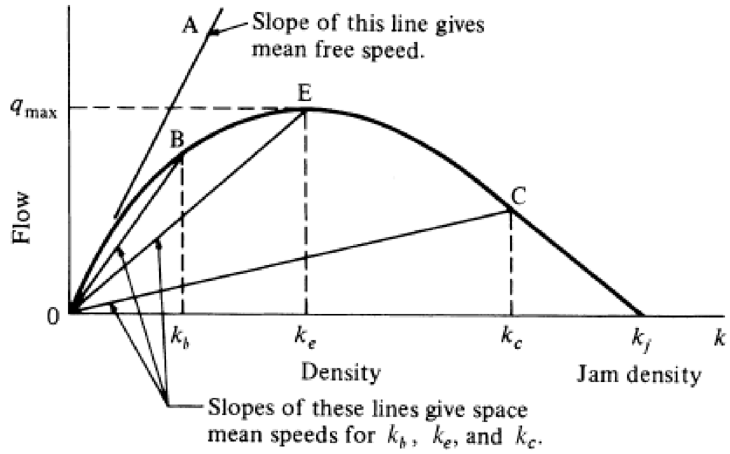
3.2.3. Fundamental diagram of traffic flow

The relationship between the density (vpm) and the corresponding flow of traffic on a highway generally is referred to as the fundamental diagram of traffic flow. The fol1owing theory has been postulated with respect to the shape of the curve depicting this relationship.

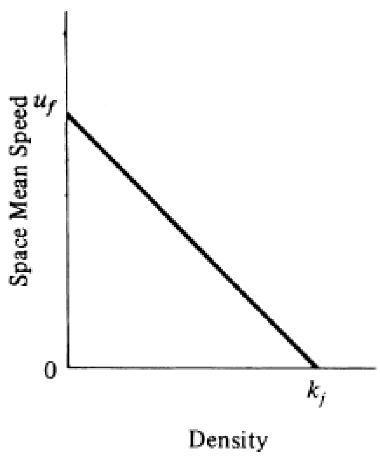
1. When the density on the highway is zero, the flow is also zero because there are no vehicles on the highway.
2. As the density increases, the flow also increases.
3. However, when the density reaches its maximum, generally referred to as the jam density (kj), the flow must be zero because vehicles will tend to line up end to end.
4. It follows that as density increases from zero, the flow will also initially increase from zero to a maximum value. Further continuous increase in density will result in continuous reduction of the flow, which will eventually be zero when the density is equal to the jam density. The shape of the curve therefore takes the form in Figure 6.3a.

A similar argument can be postulated for the general relationship between the space mean speed and the f1ow. When the flow is very low, there is little interaction between individual vehicles. Drivers are therefore free to travel at the maximum possible speed. The absolute maximum speed is obtained as the flow tends to zero, and it is known as the mean free speed (Uf). Continuous increase in flow will result in a continuous decrease in speed. A point will be reached, however, when further addition of vehicles will result in the reduction of the actual number of vehicles that pass a point on the highway (that is, reduction of flow). This result in congestion, and eventually both the speed and the flow become zero. Figure 6.3c shows this general relationship. Figure 6.3b shows the direct relationship between speed and density.

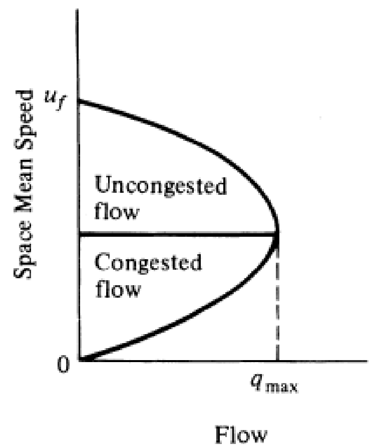
From Eq. 6.5, we know that space mean speed is flow divided by density, which makes the slopes of lines OB, OC, and OE in Figure 6.3a represents the space mean speeds at densities kb, kc, and ke, respectively. The slope of line OA is the speed as the density tends to zero and little interaction exists between vehicles. The slope of this line is therefore the mean free speed (Uf); it is the maximum speed that can be attained on the highway. The slope of line OE is the space mean speed for maximum flow. This maximum flow is the capacity of the highway. Thus it can be seen that it is desirable for highways to operate at densities not greater than that required for maximum flow.



(a) Flow versus density



(b) Space mean speed versus density



(c) Space mean speed versus volume

3.2.4 Mathematical relationships describing traffic flow

Mathematical relationships describing traffic flow can be classified into two general Categories - macroscopic and microscopic- depending on the approach used in the development of these relationships. The macroscopic approach considers flow density relationships, whereas the microscopic approach considers spacing between and speed of individual vehicles.

Macroscopic Approach

The macroscopic approach considers traffic streams and develops algorithms that relate the flow to the density and space mean speeds. The two most commonly used macroscopic models are the Green shields and Greenberg models.

Green shields Model. Green shields carried out one of the earliest recorded works, in which he studied the relationship between speed and density. He hypothesized that a linear relationship existed between speed and density, which he expressed as

$$\bar{u}_s = u_f - \frac{u_f}{k_j} * k \text{ --3.11}$$

Corresponding relationships for flow and density and for flow and speed can be developed. Since $q = \bar{u}_s k$ substituting $q/\bar{u}_s$, for k in Eq. 3.11 gives

$$\bar{u}_s{}^2 = u_f . \bar{u}_s - \frac{u_f}{k_j} * q \text{ --3.12}$$

Also substituting q/k for $\bar{u}_s$, in Eq. 6.11 gives

$$q = u_f . k - \frac{u_f}{k_j} * k^2 \text{ --3.13}$$

Equations 6.12 and 6.13 indicate that if a linear relationship in the form of Eq. 6.11 is assumed for speed and density, then parabolic relationships are obtained between flow and density and between flow and speed. The shape of the curve shown in Figure 6.3a will therefore be a parabola. Also, Eqs. 6.12 & 6.13 can be used to determine the corresponding speed and the corresponding density for maximum flow.

Consider Eq. 6.12.

$$\bar{u}_s{}^2 = u_f . \bar{u}_s - \frac{u_f}{k_j} * q$$

Differentiating q with respect to $\bar{u}_s$ we obtain

$$2\bar{u}_s = u_f - \frac{u_f}{k_j} \frac{dq}{du_s}$$

That is,

$$\frac{dq}{d\bar{u}_s} = u_f \frac{k_j}{u_f} - 2\bar{u}_s \frac{k_j}{u_f} = k_j - 2\bar{u}_s \frac{k_j}{u_f}$$

For maximum flow,

$$\frac{dq}{d\bar{u}_s} = 0 \;=>\; k_j = 2\bar{u}_s \frac{k_j}{u_f} \;=>\; u_o = \frac{u_f}{2} \text{ --3.14}$$

Thus, the space mean speed u_o, at which the volume is maximum, is equal to half the free mean speed.

Consider Eg. 3.13.

$$q = u_f.k - \frac{u_f}{k_j} * k^2$$

Differentiating q with respect to k, we obtain

$$\frac{dq}{dk} = u_f - 2k\frac{u_f}{k_j}$$

For maximum flow,

$$\frac{dq}{dk} = 0 \;=>\; u_f = 2k\frac{u_f}{k_j} \;=>\; k_o = \frac{k_j}{2} \text{ ---3.15}$$

Thus, at the maximum flow, the density k. is half the jam density. The maximum flow for the Greenshields relationship can therefore be obtained from Eqs. 3.14, and 3.15, as shown in Eq. 3.16.

$$q_{\max} = \frac{k_j u_f}{4} \text{ --3.16}$$

Greenberg Model. Several researchers have used the analogy of fluid flow to develop macroscopic relationships for traffic flow. One of the major contributions using the fluid-flow analogy was developed by Greenberg in the form

$$\bar{u}_s = c\ln\frac{k_j}{k} \text{ --3.17}$$

$$q = ck\ln\frac{k_j}{k} \text{ --3.18}$$

Differentiating q with respect to k, we obtain

$$\frac{dq}{dk} = c\ln\frac{k_j}{k} - c$$

For maximum flow, $\frac{dq}{dk} = 0\,, \ln\frac{k_j}{k} = 1$

Giving $\ln k_j = 1 + \ln k_o$ --3.19

That is, $\ln\frac{k_j}{k_o} = 1$ and Substituting 1 for $\ln\frac{k_j}{k_o}$ in eq 3.17 gives $u_o = c$

Thus, the value of c is the speed at maximum flow.

Model Application

Use of these macroscopic models depends on whether they satisfy the boundary criteria of the fundamental diagram of traffic flow at the region that describes the traffic conditions. For example, the Green shields model satisfies the boundary conditions when the density k is approaching zero as well as when the density is approaching the jam density kj. The Greenshields model therefore can be used for light or dense traffic. The Greenberg model, on the other hand, satisfies the boundary conditions when the density is approaching the jam density, but it does not satisfy the boundary conditions when k is approaching zero. The Greenberg model is therefore useful only for dense traffic conditions.

Calibration of Macroscopic Traffic Flow Models-

The traffic models discussed thus far can be used to determine specific characteristics such as the speed and density at which maximum flow occurs and the jam density of a facility. This usually involves collecting appropriate data on the particular facility of interest and fitting the data points obtained to a suitable model. The most common method of approach is regression analysis. This is done by minimizing the squares of the differences between the observed and the expected values of a dependent variable. When the dependent variable is linearly related to the independent variable, the process is known as linear regression analysis, and when the relationship is with two or more independent variables, the process is known as multiple linear regression analysis.

If a dependent variable y and an independent variable x are related by an estimated regression function, then

$y = a + bx$ --3.20

The constants a and b could be determined from

$$a = \frac{1}{n}\sum_{i=1}^{n} y_i - \frac{b}{n}\sum_{i=1}^{n} x_i = \bar{y} - b\bar{x} \qquad \text{-----3.21}$$

And

$$b = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2} \qquad \text{-----3.22}$$

Where: n = number of sets of observations; xi = ith observation for x; yi = ith observation for y

A measure commonly used to determine the suitability of an estimated regression function is the coefficient of determination (or square of the estimated correlation coefficient) R^2, which is given by

$$R^2 = \frac{\sum_{i=1}^{n}(Y_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \text{---}3.23$$

Where: Yi is the value of the dependent variable as computed from the regression equations.

The closer R^2 is to 1, the better the regression fit.

Example 8

3.2.5. Shock waves in traffic streams

The fundamental diagram of traffic flow for two adjacent sections of a highway with different capacities (maximum flows) is shown in Figure 3.2. This figure describes the phenomenon of backups and queuing on a highway due to a sudden reduction of the capacity of the highway (known as a bottle neck condition). The sudden reduction in capacity could be due to accidents, reduction in the number of lanes, restricted bridge sizes, work zones, a signal turning red, and so forth, creating a situation where the capacity on the highway suddenly changes from C1 to a lower value of C2, with a corresponding change in optimum density from k_o^a to a value of k_o^b.

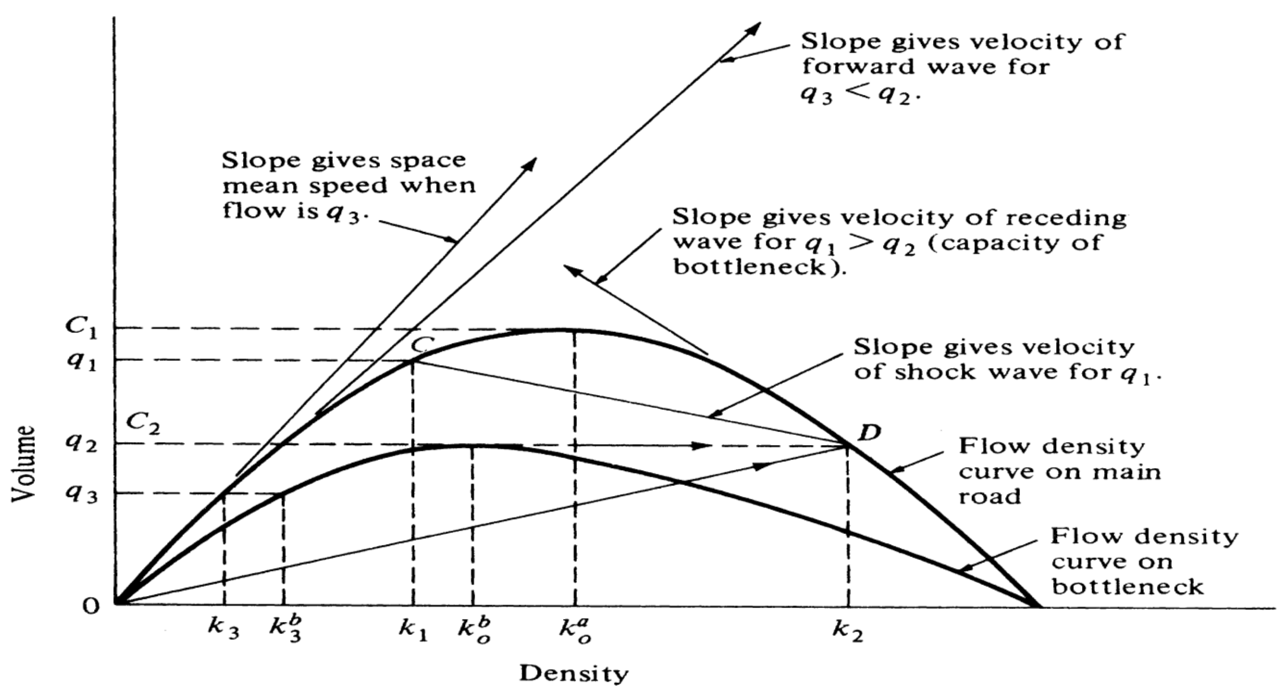


Figure 3.2 Kinematic and Shock Wave Measurements Related to Flow-Density Curve

When such a condition exists and the normal flow and density on the highway are relatively large, the speeds of the vehicles will have to be reduced while passing the bottleneck. The point at which the speed reduction takes place can be approximately noted by the turning on of the brake lights of the vehicles. An observer will see that this point moves upstream as traffic continues to approach the vicinity of the bottleneck, indicating an upstream movement of the point at which flow and density change. This phenomenon is usually referred to as a shockwave in the traffic stream.

Let us consider two different densities of traffic, k1 and k 2, along a straight highway as shown in Figure 3.3, where k 1 > k 2. Let us also assume that these densities are separated by the line w, representing the shock wave moving at a speed U_w. If the line w moves in the direction of the arrow (that is, in the direction of the traffic flow), U_w is positive.

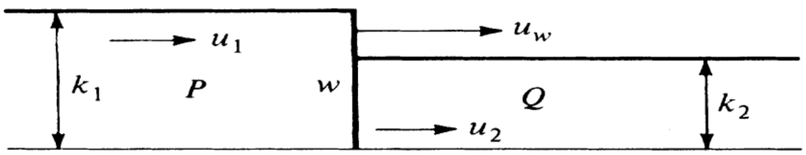


Fig.3.3 Movement of Shockwave Due to Change in Densities

With U_1 equal to the space mean speed of vehicles in the area with density k_l (section P), the speed of the vehicle in this area relative to the line **w** is

$$u_{r1} = (u_1 - u_w)$$

The number of vehicles crossing line **w** from area P during a time period t is

$$N_1 = u_{r1} k_1 t$$

Similarly, the speed of vehicles in the area with density k_2 (section Q) relative to w is

$$u_{r2} = (u_2 - u_w)$$

And the number of vehicles crossing line w during a time period t is

$$N_2 = u_{r2} k_2 t$$

Since the net change is zero

$$N_1 = N_2$$

$$(u_1 - u_w) k_1 t = (u_2 - u_w) k_2 t$$

$$u_2 k_2 - u_1 k_1 = u_w (k_2 - k_1) \text{ ---3.24}$$

If the flow rates in sections P and Q are q_l and q_2, respectively, then

$q_2 = u_2 k_2, q_1 = u_1 k_1$

Substituting q_1 and q_2 for k_1u_1 and k_2u_2 in Eg. 3.24 gives

$q_2 - q_1 = u_w(k_2 - k_1)$

That is,

$$u_w = \frac{q_2 - q_1}{k_2 - k_1} = \omega_{12}$$

Which is also the slope of the line CD shown in Figure 3.2 above This indicates that the velocity of the shock wave created by a sudden change of density from kl to k2 on a traffic stream is the slope of the chord joining the points associated with kl and k2 on the volume density curve for that traffic stream.

Shock Waves and Queue Lengths Due to a Red Phase at a Signalized Intersection (Frontal stationary shock wave)

Figure 3.4 also shows the traffic conditions that exist at an approach of a signalized intersection when the signal indication is green then changes to red at the end of the green phase (start of the red phase) and changes to green again at the end of the red phase (start of the green phase). When the signal indication is green, the flow is normal as shown in section 1. When the signals change to red at time t1, two new conditions are formed immediately. Flow from this approach is stopped creating section 2, immediately downstream of the stop line with a density of zero and flow of zero. At the same time, all vehicles immediately upstream of the stop line are stationary, forming section 3, where the flow is zero and the density is the jam density. These results in the formation of the frontal stationary shock wave with velocity ω_{23} and the backward forming shock wave with velocity ω_{13}. At the end of the red phase at time t2 when the signal indication changes to green again, the flow rate at the stop line changes from zero to the saturation flow rate. This results in the forward moving shock wave ω24. The queue length at this time—that is at the end of the red phase—is represented by the line RM. Also at this time, the backward recovery shock wave with velocity of ω_{34} is formed that releases the queue as it moves upstream of the stop line. The intersection of the backward forming and backward recovery shock waves at point T and time t3 indicates the position where the queue is completely dissipated with the maximum queue length being represented by the line ST. The backward forming and backward recovery shock waves also terminate at time t3 and a new forward moving shock wave with velocity ω_{14} is formed. When the forward moving shock wave crosses the stop line, at time t4, the flow changes at the stop line from the saturated flow rate to the original flow rate in section 1 and this continues until time t5 when the signals change again to red.

And the length of the queue at the end of the red signal $\boxed{r * \omega_{13}}$, r is the length of red signal indication. Refer fig 3.4

$$ST = \frac{r\omega_{13}\omega_{34}}{\omega_{34} - \omega_{13}},$$ ST maximum queue length.

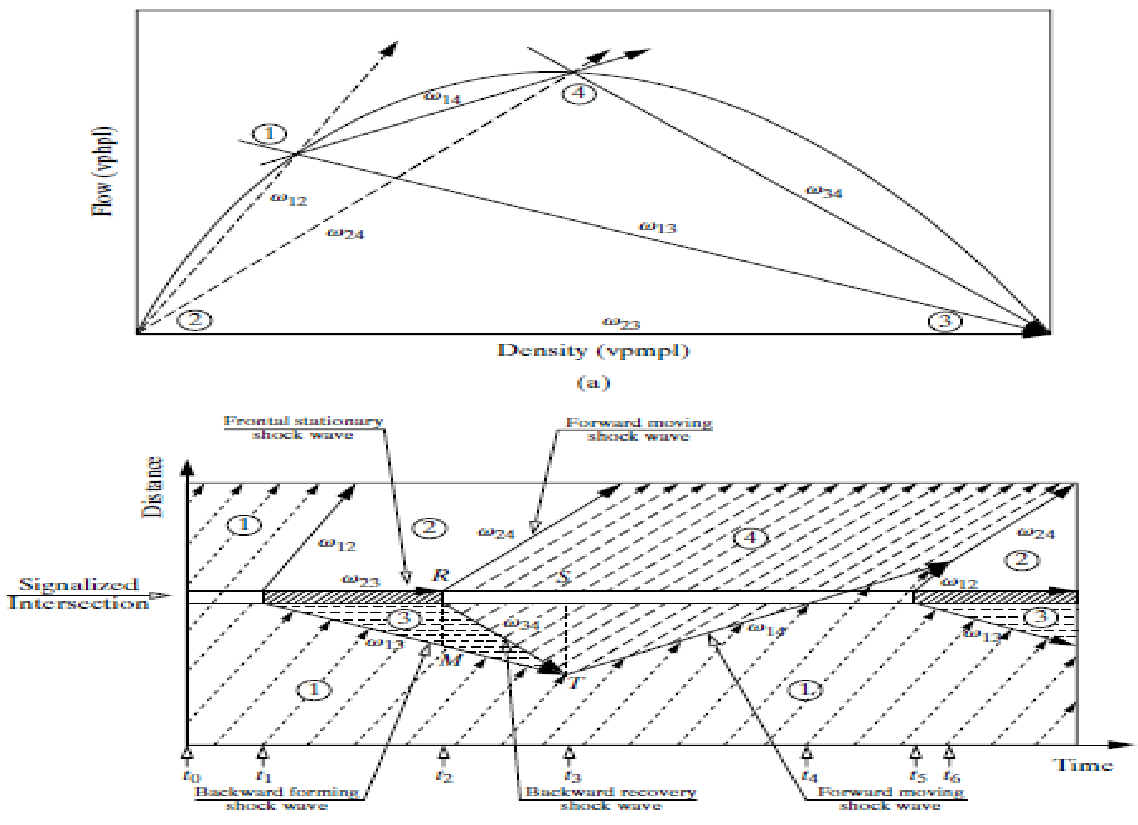


Fig 3.4 Shock wave at signalized intersection

Shock Waves and Queue Lengths Due to Temporary Speed Reduction at a Section of Highway

Let us now consider the situation where the normal speed on a highway is temporarily reduced at a section of a highway where the flow is relatively high but lower than its capacity. For example, consider a truck that enters a two-lane highway at time t1 and traveling at a much lower speed than the speed of the vehicles driving behind it. The truck travels for some time on the highway and eventually leaves the highway at time t2. If the traffic condition is such that the vehicles cannot pass the truck, the shock waves that will be formed are shown in Figure 3.5. The traffic conditions prior to the truck entering the highway at time t1 is depicted as section 1. At time t1, vehicles immediately behind the truck will reduce their speed to that of the truck. This results in an increased density immediately behind the truck resulting in traffic condition 2. The moving shock wave with a velocity of ω12 is formed. Also, because vehicles ahead of the truck will continue to travel at their original speed, a section on the highway just downstream of the truck will have no vehicles thereby creating traffic condition 3. This also results in the formation of the forward moving shock waves with velocities of ω13, and ω32. At time t2 when the truck leaves the highway, the flow will be increased to the capacity of the highway with traffic condition 4. This results in the formation of a backward moving shock wave velocity v24 and a forward moving shock wave with velocity ω34. At time t3, shock waves with velocities ω12 and ω24 coincide resulting in a new forward moving shock wave with a velocity ω41. It should be noted that the actual traffic conditions 2 and 4 depend on the original traffic condition 1 and the speed of the truck.

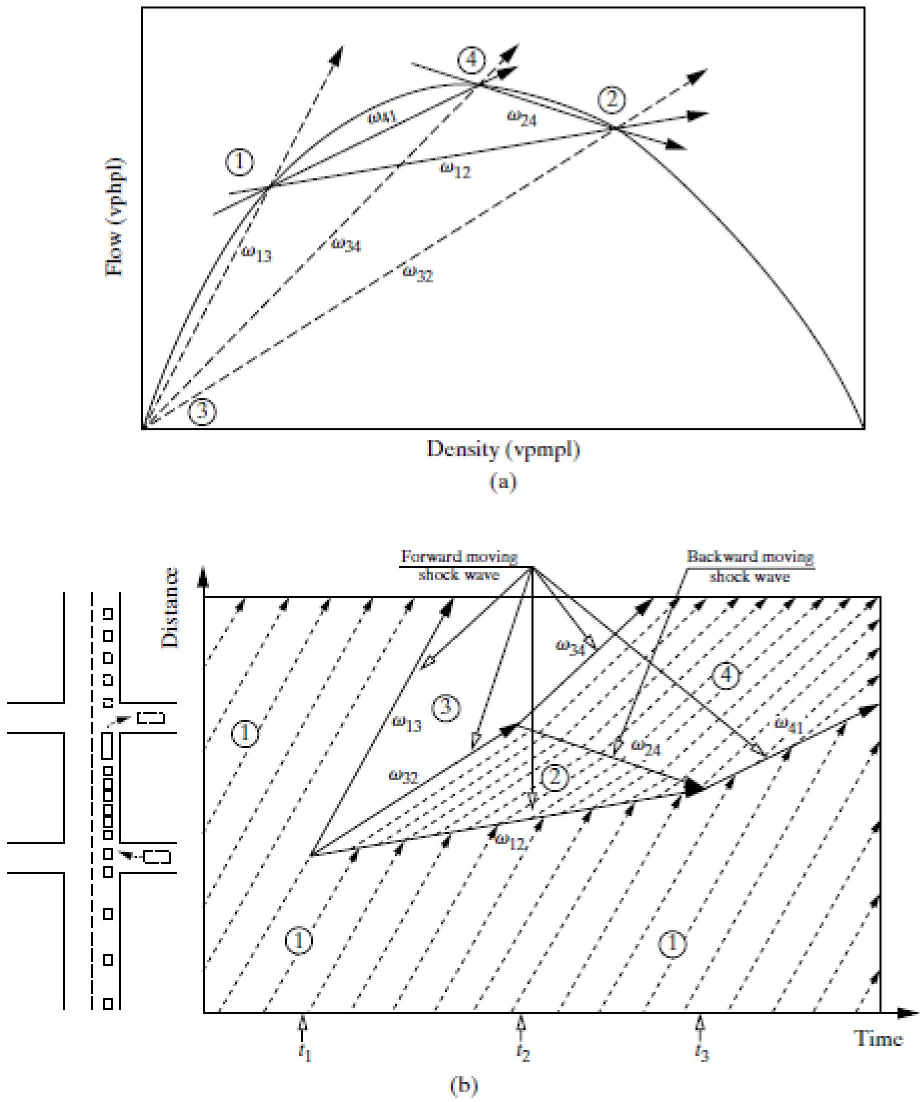


Figure 6.12 Shock Wave Created By Slow Traffic

Example 9 &10

References

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