Freeway Analysis Manual: Parts 1 and 2

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PARTS 1 AND 2 OF

FREEWAY ANALYSIS MANUAL

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PART 1  FREEWAY ANALYSIS FUNDAMENTALS

CHAPTER 1.1  INTRODUCTION

This Freeway Analysis Manual is intended for those who are responsible for understanding, analyzing, and evaluating the operations of freeways for planning, design, and operational improvements of such facilities. Freeway analysis requires a creative person, knowledgeable in freeway analysis fundamentals, having good traffic data, and selecting appropriate analytical tools.

The first part of this Manual attempts to cover the fundamentals of freeway analysis using a demand-supply analytical framework. Special attention is given to estimating capacity and origin-destination demands. A detailed example application of the demand-supply analytical framework is provided for a typical freeway situation. This part of the Manual concludes with a description of special situations that may be encountered and ways in which they can be analyzed.

The second part of this Manual attempts to cover the study design and required traffic data for analyzing a freeway. This portion of the Manual begins with guidelines for establishing spatial and temporal limits of the freeway study area, the selection of appropriate analytical tool(s), and the identification of critical issues to be considered. Specific data requirements for freeway analysis are identified and described which include supply, demand, control, and performance data.

The third part of this Manual attempts to provide detailed guidance in the use and application of a macroscopic deterministic simulation model which is currently being used in a number of Caltrans districts for freeway analysis. This model is the FREQ model and an overview and a history of the model is provided. The chapters in this part of the Manual include inputting data, checking and calibrating the model, and applying the model in a wide variety of investigations.

The fourth and last part of this Manual provides a real-life application of the FREQ model to a 25-mile eastbound segment of the I-580 Freeway during the afternoon five-hour peak period in the Pleasanton, Dublin, and Livermore area. The application is developed in a step-by-step process beginning with the definition of study boundaries and the collection of model input data and performance data required for calibration. The step-by-step process continues with the calibration and validation effort, an investigation of implementing ramp metering in combination with adding selected auxiliary lane(s), an investigation of alternative added HOV freeway lane designs, and a set of future scenario improvement investigations.

This manual is based upon the experience of the two authors in working with Caltrans staff over the past 30 years in teaching workshops, providing technical assistance, developing freeway analytical tools, and undertaking research. The authors would like to recognize the support and encouragement provided by the Manual’s Caltrans Advisory Group.
CHAPTER 1.2 SUPPLY-DEMAND ANALYTICAL FRAMEWORK

The fundamentals of freeway analysis can be described in a supply-demand analytical framework that is depicted graphically in Illustration 1.2.1.

The horizontal scale of the illustration is distance with traffic moving from left to right. Special care is required in selecting the upstream and downstream spatial study section boundaries (see Chapter 2.3 for more details). Once the upstream and downstream boundaries are selected, the study section is divided into subsections with subsection boundaries being established at any location where there is a change in demand (on-ramps and off-ramps) and/or a change in capacity (i.e., lane drops/ads, significant changes in grade, etc.). The length and number of subsections will vary between study sections but the number of subsections will normally range from one to three subsections per mile.

The vertical scale of the illustration is time with time moving from top to bottom. Special care is required in selecting the beginning and ending temporal study time duration limits (see Chapter 2.3 for more details). Once the beginning and ending time limits are selected, the study duration time is divided into equal time intervals. The most common time interval used for most freeway analysis projects is 15 minutes because of the availability of 15-minute traffic counts and the desire to record the status of freeway congestion at 15-minute time intervals. Some studies have used shorter time intervals (i.e., 5-minutes when traffic count data is available and frequent status of freeway congestion is desired) and longer time intervals (i.e., one-hour when only one-hour traffic count data is available and less frequent status of freeway congestion is required). The normal length of the study duration time varies between 3 and 6 hours (12 to 24 15-minute time intervals) depending upon the duration of congestion on the study section.

The result of establishing subsection boundaries and time intervals is a series of individual cells as shown in Illustration 1.2.1. The number of cells is equal to the product of the number of subsections and number of time intervals. In this illustration there are 48 cells. The identification of these cells is very important because the freeway will be analyzed on an individual cell basis and if needed, modified due to interactions between cells. The analysis proceeds from furthest upstream subsection to furthest downstream subsection starting in the first time interval and then continuing from one time interval to the next until all time intervals have been analyzed. The analogy of a typist on a typewriter exemplifies the process: beginning in the upper left hand margin (first subsection in first time interval), moving horizontally to the right until the right margin is reached (last subsection in first time interval), then carriage return to the next line (next time interval), repeating moving from left margin to right margin, and continuing the process until the full page of typing is completed.

A capacity and demand estimate are needed for each cell in the freeway analysis demand-supply diagram. Each will be briefly described in the next two paragraphs but chapters later will be devote to each of them (Chapter 1.3 on estimating capacity and Chapter 1.4 on estimating origin-destination demands).
Referring to Illustration 1.2.1, there are six subsections in this study section and the capacity of each subsection in each of the eight time intervals is needed. The capacity values may be thought of as ‘flowing up through the diagram’. Only freeway weaving sections (such as subsections SS3-SS4) and a few special cases (see Chapter 1.6) may having changes in capacity over time due to changing weaving flows. Otherwise the capacity of a subsection will not change between time intervals. The result is a ‘$C_{it}$’ value for each cell in the demand-supply diagram.

Referring to Illustration 1.2.1, there are eight time intervals in this study duration time and the demand of each subsection in each of the six subsections is needed. The demand values may be thought of as ‘flowing across the diagram’. There will be changes in demands between every pair of subsections in all time slices except those where there is no on-ramp or off-ramp between them (i.e., lane drop subsection boundaries such as shown between subsections 3 and 4). The result is a ‘$D_{it}$’ value for each cell in the demand-supply diagram.

A word about the use of the term ‘demand’ rather than ‘volume’ or ‘flow’ may need an explanation. Demand is a demand rate that depicts the quantity of traffic that would like to travel over a subsection in a particular time interval. Volume or flow is a flow rate that depicts the quantity of traffic that can travel over a subsection in a particular time interval. In the event of complete free-flow conditions, the demand rates are exactly the same as the flow rates since all of the traffic wishing to use the subsection in a particular time interval can be served. However, in congested-flow conditions, demand rates will be different from flow rates, and therefore demand rates rather than flow rates are needed as input to the freeway analysis procedures. It is also important to note the introduction of the term ‘rate’ being used. For example, if the demand for travel in a subsection in a particular 15-minute time interval is 1000 vehicles, the demand rate is expressed as 4000 vehicles per hour rate over the 15-minute time interval. Hourly rates are normally used within the analytical tools since capacity values are expressed as hourly rates.

So now, each cell in the Illustration 1.2.1 has a demand estimate ‘$D_{it}$’ and a capacity estimate ‘$C_{it}$’ and they are expressed as hourly rates regardless of the length of the time interval. The key question in beginning to analyze a particular cell is “Is the $D_{it}$ value equal to or less than the $C_{it}$ value”? If the answer is yes, then this particular cell is not a bottleneck (does not cause congestion since it can handle its demand) and it has the ability of passing its demand from its upstream boundary to its downstream boundary under free-flow conditions. If the answer is no, then this particular cell is a bottleneck and it will influence upstream subsection(s), downstream subsection(s), and later time interval(s). When this occurs, additional steps in the analytical process will be required. As we proceed with the analysis using Illustration 1.2.1, we will answer the question above as ‘yes’ until the cell$_{33}$ (time interval 3 in subsection 3 is reached).

1.2.1 Analyzing Non-Bottleneck Subsections

The analysis begins with the cell in the upper left-hand corner (cell$_{11}$) of Illustration 1.2.1. The question stated in the previous paragraph is asked and the answer is yes; the
demand \((D_{11})\) is equal to or less than its capacity \((C_{11})\). Since demand is less that capacity then the volume \((V_{11})\) in the subsection will be equal to the demand \((D_{11})\). The volume-to-capacity ratio \((V_{11}/C_{11})\) can be calculated and it will be equal to or less than 1.0. Knowing the volume-to-capacity ratio, the speed can be estimated using one of the relationships depicted in Illustration 1.2.2. Once speed and volume are estimated for a cell, then density, percent occupancy, travel time, travel distance, fuel consumption, vehicle emissions, and many other performance measures can be estimated. Computerized methods for estimating these various performance measures are included in the simulation model described in Part 3 of this Manual. Some details about Illustration 1.2.2 are given in the next paragraph.

The vertical and horizontal scales of Illustration 1.2.2 are estimated average subsection speed (mph) and volume-to-capacity ratio respectively. There are two sets of curves shown; the upper curves and the lower curves. The use of the lower curves will be discussed later when congested-flow conditions are encountered. The upper curves are used for free-flow conditions and the lower curves are used for congested-flow conditions. Since the volume-to-capacity ratio is equal to or less than 1.0 in this cell and since at present no downstream bottlenecks have been analyzed which result in congestion extending into this cell, then the upper curves will be used to estimate subsection average speed in this initial cell. Upper curves used for analyzing free-flow conditions are shown for free-flow speeds of 50 to 75 mph. Free-flow speed can be estimated in the field by observing average freeway speeds when the freeway is operating at volume-to-capacity ratios less than 0.5 during periods of time similar to those being studied. Volume-to-capacity ratios less than 0.5 have little influence on freeway speeds however freeway speeds decrease as volume-to-capacity ratios closer to 1.0 are reached. Speeds at bottlenecks (volume-to-capacity ratios of 1.0) are usually found to be between the high 40’s to the low 50’s mph. For example on a freeway subsection having a free-flow speed of 65 mph and having an estimated volume-to-capacity ratio of 0.9, the expected average speed on the subsection would be 59 mph.

Proceeding further with the analysis following Illustration 1.2.1, cell\(_{12}\) (the cell in the first time interval for subsection 2) will be analyzed and again the question is asked “Is the \(D_{it}\) value equal to or less than the \(C_{it}\) value”? Again like for cell\(_{11}\), the answer is ‘yes’ and procedures followed for cell\(_{11}\) are followed for cell\(_{12}\). The analysis is continued for the remaining subsections in the first time interval and as long as the answer to the question is always ‘yes’ for each subsection, the analysis continues until the last subsection in the first time interval is analyzed.

With the analogy of the typist with the carriage return, the analysis continues by investigating the first cell in the second time interval (cell\(_{21}\)). Assume again that the answer to the question is always ‘yes’ for each subsection in the second time interval, the procedure used for all cells up to this point is repeated. Then the analysis is continued into the next time interval and the procedures are continued to be repeated until a cell (cell\(_{34}\)) is encountered where the answer to the question “Is the \(D_{it}\) value equal to or less than the \(C_{it}\) value” is ‘no’. The first bottleneck is encountered and additional analytical steps are required because the bottleneck in cell\(_{34}\) affects upstream subsection(s),
downstream subsection(s), and later time interval(s). A total of four steps need to be undertaken when analyzing bottleneck subsections and each will be discussed in the following section.

1.2.2 Analyzing Bottleneck Subsections

The first step is to analyze the bottleneck subsection itself. Since the demand for the bottleneck is greater than its capacity in cell 34, the flow in the bottleneck subsection can not be equal to demand but to the limiting capacity. Hence, the volume in cell 34 is equal to capacity and the volume-to-capacity ratio will be 1.0. Using Illustration 1.2.2 and the free-flow speed curve of 65 mph, a volume-to-capacity ratio of 1.0 results in an estimated speed of 53 mph. From the volume and speed information, other freeway performance measures can be estimated.

The second step is to modify the previously estimated speed and other performance measures of the upstream subsection(s) in this time interval. Since demand exceeds capacity in cell 34, the excess demand \((D_{34}-C_{34})\) in cell 34 will be stored in upstream subsection(s) resulting in higher densities and lower speeds in the upstream subsections. A shock wave analytical procedure can be engaged that will first determine the velocity of the upstream-moving shock wave and then the extent of the congestion in the upstream subsection(s) at the end of the time interval. The shock wave velocity can be calculated as the ratio of the change in flow divided by the change in density between the upstream and downstream bottleneck subsections. For example assume that a three-lane subsection is connected to a two-lane subsection (lane-drop location):

- Demand wishing to enter the bottleneck subsection = 4500 vph
- Capacity of the bottleneck subsection = 4000 vph
- Density in the upstream subsection = 80 vpmpl x 4 lanes = 320 vpm
- Density in the bottleneck subsection = 50 vpmpl x 3lanes = 150 vpm

Then the change in flow would be 500, the change in density would be 170 vpm, and the upstream-moving shock wave velocity would be 2.94 mph. If 15-minute time intervals were used, then the congested area would extend 0.735 miles (3880 feet) upstream of the bottleneck subsection by the end of the 15-minute time interval. If the capacity of the four-lane upstream subsection is 6000 vph and its volume is 4500 vph, the resulting volume-to-capacity ratio would be 0.75. Since the upstream subsection is congested the lower curves of Illustration 1.2.2 would be used, and the estimated speed in the congested portion of the upstream subsection(s) would be between 8 and 19 mph depending upon what lower curve is selected. The various lower curves are identified by their speeds at a volume-to-capacity ratio 1.0 and vary between 20 and 50 mph. Experience with California freeways suggest that the 40 mph curve may be the most typical, and hence the estimated speed would be about 16 mph. Knowing the volume and speed in the congested portion of the upstream subsection(s), other performance measures can be estimated. Understanding shock wave analysis and successfully applying shock wave analysis to real-world problems are complex and require extensive analysis. The reader may wish to refer to other references for a more in-depth description of shock wave
The third step is to modify the estimated demands for downstream subsections due to the bottleneck subsection. Following the example just given, the demand for the bottleneck subsection was 4500 vph while its capacity was only 4000 vph. As a result of the bottleneck, a rate of 500 vph will not be able to reach the downstream subsection(s). Hence the previously calculated downstream subsection demands need to be reduced. For subsections immediately downstream of the bottleneck subsection with no off-ramps between them, the reduced demand is 500 vph. For subsections downstream of the bottleneck subsection with off-ramps between them, the reduced demand will be less than 500 vph since some of the vehicles stored in the upstream congested portion will have destination for the off-ramp(s). This can be a complicated calculation procedure and computerized methods have been developed to handle such situations. One such method is included in the simulation model described in the third part of this Manual.

The fourth and final step is the transfer of the unsatisfied demand at the bottleneck subsection (cell\(_{34}\)) to the next time interval. This transfer involves a demand rate of 500 vph rate or 125 vehicles since 15-minute time intervals were used. A new freeway origin is added at the upstream end of the bottleneck subsection coupled with the appropriate distribution of this unsatisfied demand to downstream freeway destinations. This too can be a complicated calculation procedure and a computerized method for handling this demand transfer process is included in the simulation model described in the third part of this Manual.

1.2.3 Continue Analyzing Subsections

Once cell\(_{34}\) and it’s upstream, downstream, and next time interval effects are analyzed following the procedures described in the previous section of this chapter, the analysis continues in the third time interval and the fifth subsection (cell\(_{35}\)). For example purposes, it is assumed that no further bottlenecks are identified in the third time interval so analysis continues into the fourth time interval. The first three subsections in time interval four are identified as non-bottlenecks. Thus all of these cells are analyzed following the procedures described previously in section 1.2.1 of this chapter.

In the fourth time interval subsection 4 (cell\(_{44}\)) is identified as a bottleneck and the procedures described previously in section 1.2.2 of this chapter are followed.

This process is continued until all subsections in all time intervals are analyzed.

1.2.4 Summary

The results for the spatial and temporal boundaries of the study investigation should be carefully reviewed to insure that the boundaries are adequate for a thorough analysis of the selected study site.
The results for the first and last time intervals should be carefully reviewed for they are the temporal boundaries for the investigation. If bottlenecks are identified in the first and/or last time intervals, serious consideration should be given to starting the study investigation earlier in time and/or extending the study investigation later in time.

The results for the first and last subsections should be carefully reviewed for they are the spatial boundaries for the investigation. If bottlenecks are identified in the first and/or last subsections, serious consideration should be given to extending the study section upstream and/or downstream. The importance of the temporal and spatial boundaries for a study investigation will be covered in greater detail in Chapter 2.3.

The objective of this chapter has been to provide an overview of the detailed analysis required for evaluating a study section particularly one that is congested. Many special situations can be encountered that will require additional consideration and analysis, and have not been considered in this chapter. For example in this discussion no mention is made of the possibility of on-ramp demands exceeding their capacities causing queues on on-ramps and modifying the traffic demand that can reach the freeway. No mention is made of off-ramp demands exceeding their capacities causing queues to form on the freeway upstream of off-ramps. There are many other special situations that will add complexity to the analysis. Attempts have been made to identify many of these special considerations and attention will be given to them in Chapter 1.6.
Illustration 1.2.1  Freeway Analysis Demand-Supply Diagram

<table>
<thead>
<tr>
<th>TIME</th>
<th>SS1</th>
<th>SS2</th>
<th>SS3</th>
<th>SS4</th>
<th>SS5</th>
<th>SS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>TS2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TS3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>D_{it} ≤ C_{it}?</td>
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<tr>
<td>TS4</td>
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<td>TS8</td>
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</tr>
</tbody>
</table>

DISTANCE

Illustration 1.2.1  Freeway Analysis Demand-Supply Diagram
Illustration 1.2.2  Speed Versus Volume/Capacity Ratio Curves
CHAPTER 1.3 ESTIMATING FREEWAY CAPACITY

The capacity of the various elements of a freeway facility must be estimated in order to undertake a quantitative freeway analysis study. The required accuracy of the capacity estimate depends on how close the traffic demand is to the capacity of the freeway element being studied. The suggested approach is to initially estimate the capacities of the various freeway elements in an approximate manner and then refine the estimates as needed depending on how close the traffic demand is to the capacity.

The purpose of this chapter is to provide the user with default capacity estimates that should be considered in the initial analysis. These capacity estimates can later be refined based on personal experience, by use of the HCM2000 and other such techniques, and/or by field studies at locations where traffic demands approaches or exceeds their capacities.

The 2000 Highway Capacity Manual (HCM2000) published by the Transportation Research Board (TRB) in the year 2000 is considered to be the national standard for estimating freeway capacity. It should be consulted for in-depth procedures particularly involving situations where the traffic demand approaches the capacity of the freeway element being investigated. Note that the HCM2000 uses units of passenger car units not vehicles. In order to improve the capacity estimates, field studies should be undertaken at freeway elements where the traffic demand exceeds their capacities.

There are four types of freeway subsections from a capacity perspective, each requiring a specific procedure for estimating their capacities. They include basic subsections, on-ramp subsections, off-ramp subsections, and weaving subsections. The remaining sections in this chapter will be devoted to each of these four types of freeway subsections and to a summary at the end.

1.3.1 Freeway Basic Subsections

Freeway basic subsections are subsections located along the freeway study section away from the influence of on-ramps and off-ramps. Such sections are considered not to be under the influence if they are 2000 or more feet away from on-ramps and off-ramps. The suggested capacity of basic freeway subsections that are essentially level (less than 2% upgrades), straight (less than 3 degree curves), and carrying a low percentage of truck traffic (2 to 5%) is in the range of 2000 to 2400 vehicles per hour per lane with an expected value of 2200 vehicles per hour per lane.

1.3.2 Freeway On-Ramp Subsections

A freeway on-ramp subsection is one in which an on-ramp occurs at the beginning of a subsection. Capacity estimates are needed at various locations along the on-ramp (on-ramp entrance, on-ramp proper, and freeway merge area) and for the freeway subsection itself. Attention is given in this chapter only to right-side on-ramps and some discussions of left-side on-ramps are included later in Chapter 1.6.
The entrance to the on-ramp may have a limiting capacity due to the adjacent intersection or freeway connector. If it does not have a limiting capacity, then no queuing will occur at the entrance to the on-ramp and the capacity of the on-ramp proper will govern. If it does have a limiting capacity, then queuing will occur at the entrance to the ramp and the maximum flow that can enter the on-ramp proper will be limited to the entrance capacity. This situation may require additional study and there is some discussion on this topic later in Chapter 1.6.

The capacity analyses of the on-ramp proper and the on-ramp merge area are best analyzed together since the element that has the lowest capacity will determine whether congestion occurs. The upper-most left-side diagram in Illustration 1.3.1 depicts the most common on-ramp and merge area design with a single lane on-ramp merging into the freeway without an added freeway lane. The capacity of the single lane on-ramp will be on the order of 1500 vph while the capacity for ramp vehicles at the merge area depends on the number of freeway vehicles in the shoulder lane just upstream of the on-ramp merge area. Assuming that the shoulder lane capacity just downstream of the on-ramp merge area is 2400 vph, at least one-half of this capacity can be allocated to the on-ramp vehicles because of the cooperative merging between on-ramp and freeway vehicles. In the event the upstream shoulder lane carries less than 1200 vph, then the on-ramp merge capacity would be increased accordingly. Hence, the normal range for the on-ramp merge capacity is on the order of 1200 to 1500 vph. Therefore considering both the on-ramp proper capacity and the on-ramp merge capacity, the capacity limit will normally vary between 1200 and 1500 vph.

Other on-ramp proper and on-ramp merge area designs are often encountered. For example, a single lane on-ramp with an added freeway lane at the on-ramp merge will have a capacity on the order of 2000 vph (see second left-side diagram of Illustration 1.3.1). Another design would consist of two lanes on the on-ramp proper and a single lane added to the freeway that would have a capacity of about 4000 vph on the on-ramp proper and a capacity of 3000 vph in the on-ramp merge area (see third left-side diagram of Illustration 1.3.1). Another example would be a two lane freeway connector on-ramp where two lanes are added on the freeway that would have a capacity of at least 4000 vph.

The freeway capacity of the on-ramp subsection is also required and can be estimated using the basic freeway subsection procedures described in the previous section 1.3.1. In the event the on-ramp subsection becomes a bottleneck or if some adjacent downstream subsection becomes a bottleneck, the congestion may affect the on-ramp merge area and possibly the on-ramp itself. More about this in Chapter 1.6.

**1.3.3 Freeway Off-Ramp Subsections**

A freeway off-ramp subsection is one in which an off-ramp occurs at the end of a subsection. Capacity estimates are needed for the freeway subsection itself and at various locations along the off-ramp (freeway diverge area, off-ramp proper, and off-ramp exit).
Attention is given in this chapter only to right-side off-ramps and some discussion of left-side off-ramps is included later in Chapter 1.6.

The freeway capacity of the off-ramp subsection is required and can be estimated using the basic freeway subsection procedures described in the previous section 1.3.1. In the event any portion of the off-ramp is capacity limited and causes congestion to extend into the freeway, the performance of the freeway off-ramp subsection will be affected and further analysis will be required. This is discussed later in Chapter 1.6.

The capacity analyses of the off-ramp diverge area and the off-ramp proper are best analyzed together since the element that has the lowest capacity will determine whether congestion occurs. The upper-most right-side diagram in Illustration 1.3.1 depicts the most common off-ramp diverge area and off-ramp design with a single lane off-ramp diverging from the freeway without a lane being dropped at the off-ramp diverge area. The capacity of the single lane off-ramp will be on the order of 1500 vph while the capacity for ramp vehicles at the diverge area depends on the number of freeway vehicles in the shoulder lane just upstream of the off-ramp diverge area. Assuming that the capacity of the shoulder lane just upstream of the off-ramp merge area is 2400 vph provided there is no congestion in the diverge area, at least one-half of this capacity can be allocated to the off-ramp vehicles because of the cooperative movements between off-ramp and freeway vehicles. Hence, the normal range for the off-ramp diverge area is on the order of 1200 to 1500 vph. Therefore considering both the off-ramp proper capacity and the off-ramp merge capacity, the capacity limit will vary between about 1200 and 1500 vph. However if congestion occurs in the diverge area due to downstream freeway subsection bottleneck(s), the capacity of the off-ramp diverge area will be less and will require additional study. This situation is discussed later in Chapter 1.6.

Other off-ramp proper and off-ramp diverge area designs are often encountered. For example, a single lane off-ramp with a lane drop at the off-ramp diverge area will have a capacity on the order of 2000 vph (see second right-side diagram of Illustration 1.3.1). Another design would consist of two lanes on the off-ramp proper and a single lane dropped at the diverge off-ramp area which would result in a capacity of about 3000 vph in the diverge area and 4000 vph on the off-ramp (see third right-side diagram of Illustration 1.3.1). Another example would be a two lane freeway connector off-ramp where two lanes are dropped at the diverge area that would have a capacity of at least 4000 vph.

The off-ramp exit may have a limiting capacity due to the adjacent downstream intersection or freeway connector. If it does not have a limiting capacity, then no queuing (except intermittent queues due to a signal) will occur at the exit to the off-ramp and the capacity of the off-ramp itself will govern. If it does have a limiting capacity, then queuing will occur at the off-ramp exit and the maximum flow that can exit the off-ramp will be limited to the exit capacity. This is likely to cause queuing on the off-ramp
that may extend back into the freeway. This situation may require additional study and there is some discussion on this topic later in Chapter 1.6.

1.3.4 Freeway Weaving Subsections

The estimation of capacities and the demand-capacity analyses of the various components of freeway weaving subsections can be the most complex type of freeway subsection to be analyzed. Further, insignificant research is available today and most recently developed methodologies have been questioned. In the event the estimated demand for a weaving section is close to or greater than its estimated capacity, it is very important that field measurements of maximum flow in the weaving subsection be observed in the field. The weaving subsection method presented for estimating capacity should be considered as being approximate.

The lower diagram in Illustration 1.3.1 depicts a typical simple freeway weaving section. Another popular design would be to add an auxiliary lane between the on-ramp and the off-ramp. Many other freeway weaving subsection configurations exist such as weaving sections with left-side on- and off-ramps and compound weaving sections in which more than a single on-ramp and a single off-ramp are coupled to form a more complex weaving section. These other weaving subsection configurations are discussed later in Chapter 1.6.

Only the typical simple weaving section shown in Illustration 1.3.1 will be discussed in this section of this chapter. A simple weaving subsection is one in which a right-side on-ramp is followed by a right-side off-ramp and the distance between ramps is less than 8000 feet. Depending on the amount of weaving traffic and the distance between ramps, the capacity of this subsection may be less than a basic freeway subsection. The procedures require analyzing a weaving subsection as a:

- basic subsection (using procedures presented earlier in section 1.3.1);
- on-ramp subsection (using procedures presented earlier in section 1.3.2);
- off-ramp subsection (using procedures presented earlier in section 1.3.3); and
- weaving subsection (using procedures that will be presented in this section 1.3.4).

There are at least eight locations within the weaving subsection where capacity estimates are needed and demand-capacity analysis performed. They include three locations involving the on-ramp (see section 1.3.2), three locations involving the off-ramp (see section 1.3.3), and two capacity estimates of the weaving subsection itself; first as a basic subsection and then as a weaving subsection to determine whether weaving reduces the basic subsection estimated capacity. Any location that becomes a bottleneck will result in the need for further analyses.

One method for estimating capacity of a weaving subsection is to use the following equation:
\[ C_w = C_b - (k-1) W_s \]

Where

- \( C_w \) = weaving subsection capacity in vph
- \( C_b \) = basic subsection capacity in vph
- \( k \) = weaving factor
- \( W_s \) = smaller of the two weaving movements

Illustration 1.3.2 presents a graphical method for estimating the weaving factor (K). There is a sketch at the bottom of this illustration that depicts the four movements at a simple weaving subsection as being:

- \( V_{01} \) freeway-to-freeway movement in vph
- \( V_{02} \) on-ramp-to-off-ramp movement in vph
- \( V_{w1} \) freeway-to-off-ramp movement in vph
- \( V_{w2} \) on-ramp-to-freeway movement in vph

The ‘\( W_s \)’ term in the earlier equation is the smaller of the two weaving movements (\( V_{w1} \) or \( V_{w2} \)). The ‘\( k \)’ term in the earlier equation can be determined from Illustration 1.3.2 by entering the length of the weaving section (feet) on the horizontal scale and the sum of the two weaving movements (\( V_{w1} + V_{w2} \)) on the vertical scale. One of three results may occur:

- If the point representing the weaving subsection falls below the curve designated as \( k=1 \), then \( k=1 \) in the equation, there is no reduction in capacity due to weaving, and the weaving subsection capacity is equal to the basic subsection capacity;

- If the point representing the weaving subsection lies above the curve designated as \( k=3 \), then the methodology predicts an infeasible solution which indicates extremely poor operations even under modest demand levels; or

- If the point representing the weaving subsection lies between the \( k=1 \) curve and the \( k=3 \) curve, then the \( k \) value can be determined, entered into the equation, and the weaving subsection capacity can be estimated.

For example, if the length of the weaving subsection is 4000 feet, \( k \) factors of 1.0, 2.0, and 3.0 would be estimated based on total weaving traffic of 1500 vph, 2000 vph, and 4000 vph respectively.

Application of this methodology over the past 10 to 20 years to actual California freeways and field studies has indicated that the reduced capacity due to weaving (the second term in the equation) is significantly smaller today then when the methodology was originally developed. The reasons given for this is that the performance of vehicles has improved and that drivers have more experience and can more effectively traveling
through weaving subsections today. A crude estimate is that the second term should be reduced by a factor of about 0.5 to better represent the effect of weaving under today’s traffic. A major NCHRP research study is expected to begin soon on estimating capacity and predicted performance of weaving subsections, and will likely be completed in 2005 or 2006.

1.3.5 Summary

While accurate estimation of capacity may not be so critical when traffic demands are much less that predicted capacities, they are extremely critical when traffic demands are predicted to be greater than estimated capacities. In such cases, small errors in capacity estimates of 5% to 10% will seriously affect predicted traffic performance. While methods presented in this chapter for predicting capacity may lie within this 5% to 10% range for simply situations, they may not meet these requirements for more complicated situations such as for weaving subsections. The best estimate of capacity for a particular subsection of existing freeway that is a bottleneck can always be obtained through field measurements. Counting traffic at these locations for relatively short periods of time (15 to 30 minutes) when there is no congestion backing into the subsection from downstream and there is congestion upstream of the subsection will provide the best estimate of capacity. Particularly whenever predicted demands exceed corresponding capacities, field observations should be undertaken. Some refinements in the capacity estimation procedures presented in this chapter can likely be improved from more sophisticated procedures such as they contained in the Highway Capacity Manual (HCM2000).
<table>
<thead>
<tr>
<th>1500</th>
<th>1200 +</th>
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<tbody>
<tr>
<td>1200 +</td>
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<td>4000</td>
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</tbody>
</table>

\[ C_w = C_b - (k-1) W_s \]

Illustration 1.3.1 Freeway Ramp and Weaving Configurations
Illustration 1.3.2  Determining k-Factor as Function of Weaving Lengths and Movements
CHAPTER 1.4 ESTIMATING FREEWAY ORIGIN-DESTINATION DEMANDS

The demands for travel on the various elements of a freeway facility must be estimated in order to undertake a quantitative freeway analysis study. Note that demands not volumes are needed as input to the freeway analysis process, that origin-destination demand tables are required not demand estimates at specific locations, and that traffic count errors must be corrected in estimating demands. These requirements will become more clear as the process for estimating freeway origin-destination demand tables is described in this chapter.

Demand is expressed as a demand rate that depicts the quantity of traffic that would like to travel over a portion of the freeway in a particular time interval. Volume or flow is a flow rate that depicts the quantity of traffic that can travel over a portion of the freeway in a particular time interval. In the event of complete free-flow conditions, the demand rates are exactly the same as the flow rates since all of the traffic wishing to use a portion of the freeway in a particular time interval can be served. However, in congested-flow conditions, demand rates will be different from flow rates, and therefore demand rates rather than flow rates are needed as input to the freeway analysis procedures. As described earlier in Chapter 1.2, it is also important to note that the term ‘rate’ is used. For example, if the demand for travel on a particular portion of the freeway in a particular 15-minute time interval is 1000 vehicles, the demand rate is expressed as 4000 vehicles per hour over the 15-minute time interval. Hourly rates are normally used within the analytical tools since capacity values are expressed and are known as hourly rates (i.e., the capacity of a typical freeway lane would be expressed as being 2200 vehicles per lane per hour not as 550 vehicles per lane in 15 minutes). It should be noted that individual freeway origin-destination demand tables are needed for each time slice; hence there would be a set of such demand tables for a particular freeway investigation; the number of which would be equal to the number of time intervals.

The process for developing freeway origin-destination demand tables begins with traffic counts taken in a prescribe manner at each entrance and exit to the freeway including the freeway mainline input and the freeway mainline output. Then checks are made of the entrance and exit traffic counts, corrected for possible errors, and then converted to entrance and exit demands. The final step is to transform the entrance and exit demands into freeway origin-destination tables through logical and mathematical programming techniques. The remaining portions of this chapter will describe these three principal steps in deriving freeway demand origin-destination tables and conclude with a summary section.

1.4.1 Obtaining Freeway Entrance and Exit Counts

The required input to this process of deriving freeway origin-destination tables begins with field-measured counts at each freeway entrance and exit in each time interval taken in a prescribed manner. The terms ‘origin’ and ‘entrance’ are used interchangeably and
the number of origins in a freeway study section will be equal to the number of on-ramps plus the freeway mainline input. The terms ‘destination’ and ‘exit’ are used interchangeably and the number of destinations in a freeway study section will be equal to the number of off-ramps plus the freeway mainline output.

Special care is needed in the field-measurement of entrance counts to insure that these counts expressed as flow rates can be assumed to be equal to their demand rates. This can be accomplished by selecting a specific location at each freeway entrance (freeway mainline input and at each on-ramp) where queues (congestion) does not occur. Under this situation the needed demand information expressed as demand rates can be assumed to be equal to the obtained counts expressed as flow rates since all of the traffic which wishes to enter the freeway can in fact enter the freeway system.

Special care is also required in the field-measurement of exit counts. This can be accomplished by selecting a specific location at each freeway exit (at each off-ramp and at the freeway mainline output) where queues (congestion) do not occur. While these counts do not represent demands if freeway congestion occurs, they can be used as a starting point for estimating destination (exit) demand rates.

At least two situations may arise that may add complications to obtaining these freeway entrance and exit counts. Some investigations may use planning models to provide traffic counts rather than direct field measurement of traffic counts. This is particular true if the freeway does not currently exist or if the freeway study investigation is for some period of time in the future. Another situation may arise if it is not possible to obtain entrance and exit counts at locations where queues (congestion) do not occur. This should not be a problem at the freeway mainline input nor at the freeway mainline output location since the spatial boundaries of the study site has been selected to insure no congestion occurs in either the upstream nor downstream subsections in any time interval. The requirement of no queues at exit count locations is not too crucial (except to insure accurate counts) but the requirement at entrance count locations is crucial so that such counts are identical to demands. In these cases the traffic counts obtained need to be modified by adding (subtracting) the change in the number of vehicles in the queue upstream of the count location in each time interval.

Before describing the process in the following sections, it would be desirable to present a template for the evolving freeway origin-destination (O-D) table. This O-D template for the freeway shown in Illustration 1.2.1 is contained in Illustration 1.4.1. There are three origins (the freeway mainline origin and two on-ramps) and three destinations (two off-ramps and the freeway mainline destination). Therefore the O-D tabular template consists of three rows (one row for each origin) and three columns (one column for each destination). The information available at the end of this first task are row and column sums of traffic counts as shown in Illustration 1.4.1. Note that there will be a set of such tables and for the example given in Illustration 1.2.1, there will be eight such tables; one for each time interval.
Illustration 1.4.1 Sample O-D Tabular Template of Traffic Counts

The need for modifying traffic counts in order to estimate demands becomes apparent in this sample table. The sum of the origin counts (4000+800+400) is 5200 vph while the sum of the destination counts (200+600+4200) is 5000 vph.

There are two possible reasons for these two sums **not to be exactly** equal for traffic counts. Either there is an error(s) in the traffic counts or in this case freeway congestion which reduces the number of vehicles (200 vph) that can not reach the freeway exits because they are being stored on the freeway study section. To assist in determining the accuracy of the traffic counts, a scale factor should be calculated for each time interval. The time interval scale factor is the ratio of the sum of the origins divided by the sum of the destinations. The resulting scale factors (vertical scale) should be plotted against time intervals (horizontal scale).

The expected shape of these plotted points over a typical peak period might exhibit the following pattern.

- In the early time intervals before congestion occurs, the scale factor would be expected to be about 1.00 (no vehicles being stored or de-stored on the freeway) and should not be greater than 1.05 or less than 0.95. If the computed scale factors are not within this range, the traffic counts are highly susceptible and should be thoroughly checked.
- As congestion begins to occur on the freeway (vehicles being stored on the freeway) the expected scale factor values would increase to perhaps 1.05 but generally should lie between 1.00 and 1.10. Otherwise the traffic counts should be checked.
- At the peak of congestion where the number of stored vehicles on the freeway begins to be stable, the scale factors should begin to approach 1.00 and should lie between 0.95 and 1.05. Otherwise the traffic counts should be checked.
- As congestion begins to recede, the number of stored vehicles will decrease and the scale factor should begin to approach 0.95 and should lie between 0.90 and 1.00. Otherwise the traffic counts should be checked.
- In the later time intervals when freeway congestion is over, the scale factor should begin to approach 1.00 and should lie between 0.95 and 1.05. Otherwise the traffic counts should be checked.
1.4.2 Converting Freeway Counts to Demands

It is assumed that upon continuing to the next step in the demand estimation process that the traffic counts have been checked, corrected as needed, and accepted based on the criteria given in the previous section.

Since the counts taken at the freeway entrances (origins) were input counts taken at locations where congestion does not occur, these counts can be considered as origin demands and no correction is needed. Thus the importance of accurate origin counts are obvious.

Since the counts taken at the freeway exits (destinations) represent the number of vehicles that can reach the freeway exit not necessarily the number of vehicles that would like to reach the freeway exit, they do not necessarily represent destination demands.

Since the accuracy of the traffic counts was acceptable in the last step of this process, the scale factor variation is assumed to be due exclusively to the freeway congestion pattern.

Theoretically, the sum of the destination demands should be equal to sum of the origin demands. If the origin counts are accepted as the origin demands, and if the sum of the destination counts is not equal to the origin demands, the destination counts need to be corrected to represent destination demands. This is accomplished by multiplying each destination by the scale factor. This implies that during periods of increased storage of vehicles on the freeway, the scale factor will be greater than 1.00 and the destination counts will be increased to represent destination demands. During periods of decreased storage of vehicles on the freeway, the scale factor will be less than 1.00 and the destination counts will be decreased to represent destination demands. Applying the computed scale factor of 1.04 (5200/5000), the traffic count template shown earlier in Illustration 1.4.1 is converted to the demand template shown in Illustration 1.4.2.

<table>
<thead>
<tr>
<th>ORG/DEST</th>
<th>DEST D01</th>
<th>DEST D02</th>
<th>DEST D03</th>
<th>ORIGIN SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O01</td>
<td></td>
<td></td>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>O02</td>
<td></td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>O03</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>DEST SUM</td>
<td>208</td>
<td>624</td>
<td>4368</td>
<td>5200</td>
</tr>
</tbody>
</table>

Illustration 1.4.2 Sample O-D Tabular Template of Traffic Demands

Further analysis of the freeway congestion pattern can result in means of improving the adjustment to destination counts. For example if all of the congestion in this time interval lies downstream of destination 02, then adjustments should only be made to destination 03.
1.4.3 Deriving Freeway Origin-Destination Demand Tables

The final step is to complete the cell entries in Illustration 1.4.2 that will represent expected demand rates for individual origin-to-destination movements. Referring to the previous Illustration 1.2.1, certain origin-to-destination movements are not possible since some destination locations are upstream of some origin locations. A zero value can be entered in such cells of the demand O-D table as shown in Illustration 1.4.3.

<table>
<thead>
<tr>
<th>ORG/DEST</th>
<th>DEST D01</th>
<th>DEST D02</th>
<th>DEST D03</th>
<th>ORIGIN SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>O01</td>
<td></td>
<td></td>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>O02</td>
<td>0</td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>O03</td>
<td>0</td>
<td>0</td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>DEST SUM</td>
<td>208</td>
<td>624</td>
<td>4368</td>
<td>5200</td>
</tr>
</tbody>
</table>

Illustration 1.4.3 First Partially Completed O-D Template of Traffic Demands

Since the sum of the cell values both in rows and in columns must be equal to the row or column sum, so called ‘corner’ cells can now be estimated (see Illustration 1.4.4).

<table>
<thead>
<tr>
<th>ORG/DEST</th>
<th>DEST D01</th>
<th>DEST D02</th>
<th>DEST D03</th>
<th>ORIGIN SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>O01</td>
<td>208</td>
<td></td>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>O02</td>
<td>0</td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>O03</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>DEST SUM</td>
<td>208</td>
<td>624</td>
<td>4368</td>
<td>5200</td>
</tr>
</tbody>
</table>

Illustration 1.4.4 Second Partially Completed O-D Template of Traffic Demands

In this example, there now remains four cells without specified values. However since we know that the sum of the individual cells in each row and column must be equal to the row and column sums, four equations can be written that include the four unknown cell values as follows.

- \((O01-D02) + (O02-D02) = 624\)
- \((O01-D03) + (O02-D03) - 400 = 4368\)
- \((O01-D02) + (O01-D03) - 208 = 4000\)
- \((O02-D02) + (O02-D03) = 800\)

There are several possible ways to estimate the four remaining cell values. At one end of the spectrum would be simply a trial-and-error solution approach while at the other end of the spectrum would be some form of a mathematical programming formulation. The first way could be very time consuming and could result in considerable estimation errors. The second method is very elegant but the solution may not be possible.
depending on the number of unknowns and the number of equations that can be formulated.

Another way of estimating the four remaining cell values would be on a proportional basis that will be described here. This method, called a proportional method, allocates the demands between cells based on the proportion of traffic demands entering or exiting at that location. For example, consider the cell value for origin-to-destination movements (O01-D02) and (O01-D03). The sum of these two cell values must be equal to (4000 – 208) or 3792 vph. Since the destination demand for D02 is 624 vph and the destination demand for D03 is 4368 vph, the proportion and number of the 3792 vehicles exiting at D02 and D03 would be:

- Proportion at D02 = \( \frac{624}{624+4368} \) = 0.125
- Proportion at D03 = \( \frac{4368}{624+4368} \) = 0.875
- Demand exiting D02 = (0.125)(3792) = 474 vph
- Demand exiting D03 = (0.875)(3792) = 3318 vph

Entering these demand cell values and insuring that the sum of the individuals cells in both the rows and columns equal to the indicated sum, all demand cells can now be estimated as shown in Illustration 1.4.5.

<table>
<thead>
<tr>
<th>ORG/DEST</th>
<th>DEST D01</th>
<th>DEST D02</th>
<th>DEST D03</th>
<th>ORIGIN SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>O01</td>
<td>208</td>
<td>474</td>
<td>3318</td>
<td>4000</td>
</tr>
<tr>
<td>O02</td>
<td>0</td>
<td>150</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>O03</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>DEST SUM</td>
<td>208</td>
<td>624</td>
<td>4368</td>
<td>5200</td>
</tr>
</tbody>
</table>

**Illustration 1.4.5 Final O-D Template of Traffic Demands**

**1.4.4 Summary**

It is important to remember that the values shown in Illustration 1.4.5 are the expected number of vehicles (demands expressed in vph) that wish to travel between a specific origin and a specific destination. Also recall that there will be a set of such tables; one for each time interval.

The reason why this synthetic technique is presented is because it is assumed that an origin-destination study is not available which will provide such information. It should also be clear that only row and column demand rates are needed to estimate subsection demands along the freeway by simply adding entrance demands and subtracting exit demands. However origin-destination movements are required if diversion from the freeway to parallel arterial(s) in the freeway corridor such as with ramp metering are to be modeled.
Estimating O-D tables for linear freeways is reasonably straightforward. However estimating O-D tables for freeways corridors is very complex and will be briefly described later in Chapter 1.6.

The main key for successful application of this process is to start with good traffic count data. Particular emphasis on good traffic data will continually be given to this issue in Part 2 of this Manual.
CHAPTER 1.5 EXAMPLE PROBLEM

A very simple example problem will be simulated manually in a step-by-step process using the techniques presented in earlier chapters. By using a very simple example problem it is thought that the fundamentals of supply-demand analysis can be clearly seen in a reasonable period of time. This problem only contains three subsections and five time intervals for a total of 15 cells to be analyzed. Queueing analysis techniques could also be applied in such simple situations. More complicated freeway investigations will almost always be encountered and computerized simulation models are likely to be used in such situations. One such computerized simulation model is described in considerable detail in Part 3 of this Manual.

The problem statement for this example problem is to complete a demand-supply diagram for the following three subsection, five time interval freeway study section. The analysis is to be performed in a step-by-step format with intermediate results being presented. The objective is to provide predicted traffic performance measures for each cell in the demand-supply diagram. The following input data is provided:

- The three consecutive subsections from upstream to downstream are each two-miles long and have three lanes, two lanes, and three lanes respectively. There are no on- or off-ramps in the freeway study section. All subsections are assumed to have freeway lane capacities of 2000 vphpl.

- The entering 15-minute traffic demand rates in the consecutive five time intervals are 3000, 4000, 5000, 4000, and 3000 vph respectively.

Illustration 1.5.1 contains the freeway analysis demand-supply diagram for the example problem similar in format to the earlier Illustration 1.2.1. The D/C ratios, V, V/C ratios, and estimated speeds are entered in each of the 15 cells as analysis proceeds. Note that there are double entries in subsection 1 because later it will become clear that the flow situations at the upstream and downstream portions of this subsection are different.

1.5.1 Analysis of First Time Interval

In the first time interval, the demand/capacity ratios for the three subsections are 0.50, 0.75, and 0.50 respectively. This indicates that the entire freeway study section in the first time interval is operating under free-flow conditions and that flows in each of the three subsections will be exactly the same as the inputted demands. Hence, the volume/capacity ratios will be the same as demand/capacity ratios and their values are included in Illustration 1.5.1. Knowing the V/C ratios for the three subsections, Illustration 1.2.2 can be used to estimate subsection speeds that are found to be 65, 64, and 65 mph respectively.
1.5.2 Analysis of Second Time Interval

In the second time interval, the demand/capacity ratios for the three subsections are 0.67, 1.00, and 0.67 respectively. This indicates that the entire freeway study section in the second time interval is operating under free-flow conditions and that the flows in each of the three subsections will be exactly the same as the inputted demands. However note that the V/C ratio in subsection 2 is 1.00 and therefore operating right at capacity. A further increase in demands will cause it to become a bottleneck. Again as in first time interval, the volume/capacity ratios will be the same as demand/capacity ratios and their values are included in Illustration 1.5.1. Knowing the V/C ratios for the three subsections, Illustration 1.2.2 can be used to estimate subsection speeds that are found to be 65, 53, and 65 mph respectively.

1.5.3 Analysis of Third Time Interval

Starting in the third time interval the analysis becomes more complicated as a bottleneck occurs in the second subsection. More details will be given in the next few steps because of the iterative process required because of the bottleneck in the second subsection. The initial analysis of the first subsection is straightforward with a D/C ratio of 0.83, an expected flow rate of 5000 vph, a V/C ratio of 0.83, and an estimated subsection average speed of 63 mph. Moving ahead to the second subsection, the D/C ratio is 1.25 that indicates that the second subsection is a bottleneck. Therefore the volume in subsection 2 is equal to its capacity not its demand, the V/C ratio is 1.00, and the estimated speed is 53 mph. Three additional analytical steps are required because subsection 2 is a bottleneck: modify upstream conditions, modify downstream demand, and transfer unsatisfied demand to the next time interval.

Since only a volume of 4000 vph can enter the upstream end of subsection 2, the volume in the downstream end of subsection 1 is limited to 4000 vph and there will be congestion in the downstream end of subsection 1. The V/C ratio will be 0.67 and will be denoted as –0.67 since this is a congested area. Illustration 1.2.2 indicates that when the V/C ratio is –0.67 (the minus indicates the lower curves should be used). If the 40 mph lower curve is used, the estimated speed is 12 mph. Subsection 1 will be not congested at its upstream portion but will be congested at its downstream portion and a shock wave analysis is required to separate this cell into an uncongested portion and a congested portion. The congestion will begin at the downstream end of subsection 1 at the beginning of time interval 3 and will grow in length to the end of time interval 3. What is needed is to determine how long is the queue (congestion) at the end of time interval 3. Shock wave analysis is undertaken to determine the rate at which congestion moves upstream and then the length of the queue (congestion) is determined as a function of the shock wave velocity and the duration of the time interval (15 minutes in this case). The shock wave equation is:
\[
W = \frac{(V_1 - V_2)}{(D_1 - D_2)}
\]

W is the shock wave velocity in mph

V1 is the flow rate in the upstream portion in vph

V2 is the flow rate in the downstream portion in vph

D1 is the roadway density in the upstream portion in vpm

D2 is the roadway density in the downstream portion in vpm

V1 is equal to 5000 vph and V2 is equal to 4000 vph. D1 is equal to 5000 divided by 63 which is 79.4 vpm while D2 is equal to 4000/12 which is 333.3 vpm. Note the density values are for the total three-lane subsection not on a per lane basis. Substituting the values for V1, V2, D1, and D2 into the above equation, the shock wave is estimated to have a backward moving speed of 3.9 mph. After 15 minutes, the length of the congested area would extend upstream a distance of 0.98 miles. Since the length of subsection 1 is two miles long, subsection 1 will be congested over slightly less than one-half of its length after 15 minutes (the end of time interval 3). If the length of the congestion exceeded the length of subsection 1, then an additional upstream subsection would need to be analyzed since congestion would extend into it. So in conclusion, about one-fourth of cell 31 would be congested (the lower right-hand portion) and the remainder of the cell would be uncongested. The weighting the estimated speeds of the two portions of cell 31 based on area of the cell not in congestion and the area of the cell in congestion, the estimated cell 31 speed would be about 51 mph (63X0.76 + 12X0.24).

The next step is to modify the demand for cell 33 which is downstream of the bottleneck in subsection 3-2. The original demand for cell 33 was 5000 vph but (5000 vph – 4000 vph) are stored upstream of subsection 2 and can not reach subsection 3. Therefore the reduced demand for subsection 3 is 4000 vph not 5000 vph which changes the D/C ratio from 0.83 to 0.67. With a volume of 4000 vph in subsection 3, the V/C ratio becomes 0.67 and the estimated speed is 65 mph.

The final step is to transfer the unsatisfied demand (5000 vph – 4000 vph) at the upstream end of cell 32 to the same location in cell 42 (next time interval). This completes the analysis and the prediction of traffic performance in the third time interval.

1.5.4 Analysis of Fourth Time Interval

The analysis continues to be a little complicated because of the bottleneck in second subsection. The demand in cell 41 is 4000 vph and the maximum volume that can enter cell 42 is 4000 vph so the upstream boundary of congestion will remain at the same location throughout the fourth time interval. The upstream portion of subsection 1 will have a V/C ratio of 0.67 resulting in an estimated speed of 65 mph. The downstream portion of subsection 1 will have a V/C ratio of –0.67 with an estimated speed of 12 mph.
The origin demand in cell 42 was 4000 vph but 1000 vph were transferred to this time interval at the upstream end of subsection for a total demand of 5000 vph. This increases the D/C ratio from 1.00 to 1.25 which is greater than 1.00 and the volume is equal to capacity, the V/C ratio in subsection 2 is 1.00, and the estimated speed is 53 mph. Since the demand is 5000 vph and only 4000 vph can be served then 1000 vph are again transferred to the next time interval.

Since the volume in subsection 2 is 4000 vph, the volume in subsection 3 will be 4000 vph. Since the D/C ratio is less than 1.00, the volume will be 4000 vph, the V/C ratio in subsection 3 is 0.67, and the estimated speed is 65 mph. This completes the analysis and the prediction of traffic performance in the fourth time interval.

1.5.5 Analysis of Fifth Time Interval

The analysis continues to the fifth and final time interval. The demand in cell 51 is 3000 vph. The upstream end of subsection 2 will have a V/C ratio of 0.5 with a resulting estimated speed of 65 mph. Since subsection 2 continues to be a bottleneck, the flow in downstream portion of subsection 1 will be 4000 vph, the V/C ratio will be –0.67, and the estimated speed will be 12 mph.

The demand for subsection 2 is equal to 4000 vph (3000 vph for the original fifth time interval and 1000 vph being transferred from the last time interval. Since the capacity of subsection 2 is 4000 vph it will continue to operate as a bottleneck until the end of the fifth time interval but the demand will be satisfied by the end of the fifth time interval and congestion will be over by the end of this time interval. The volume in subsection 2 will be 4000 vph, the V/C ratio will be 1.00, and the estimated speed will be 53 mph.

Since the volume in subsection 2 is 4000 vph, the volume in subsection 3 will be 4000 vph. Therefore the V/C ratio in subsection 3 will be 0.67 and the estimated speed will be 65 mph.

1.5.6 Summary

The demand-supply analysis of subsections unaffected by any bottleneck is a straightforward process in which volumes and volume/capacities are equal to demands and demand/capacities, and estimated speed is a function of the volume/capacity ratio. Subsections are independent of one another and can be analyzed in any order. Unfortunately, freeway investigations of greatest interest almost always involves one or more subsection bottlenecks.

If an investigation includes bottleneck subsections, a specific sequence of cells in the supply-demand diagram must be analyzed and an additional four step process is required whenever demand exceeds capacity in a subsection. These four steps are: analysis the subsection as a bottleneck, store the excess demands upstream of the bottleneck and recompute upstream traffic performance, reduce the demands of subsections downstream
of the bottleneck, and transfer the excess demand at the bottleneck to the next time interval.

The process becomes very intense and complicated when two or more bottlenecks interact with one another and causes many iterations of analyses. In such cases a computerized simulation model is required. One such simulation model is described in some detail in Part 3 of this Manual.
<table>
<thead>
<tr>
<th>Demand</th>
<th>Subsec 1 Cap = 6000 vph</th>
<th>Subsec 2 Cap = 4000 vph</th>
<th>Subsec 3 Cap = 6000 vph</th>
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<td>D/C= 0.50</td>
<td>D/C= 0.75</td>
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<td>V = 3000</td>
<td>V= 3000</td>
<td>V= 3000</td>
</tr>
<tr>
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<td>V/C= 0.50</td>
<td>V/C= 0.75</td>
<td>V/C= 0.50</td>
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<tr>
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<td>SP = 65</td>
<td>SP= 64</td>
<td>SP= 65</td>
</tr>
<tr>
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<td>D/C= 0.67</td>
<td>D/C= 1.00</td>
</tr>
<tr>
<td>V = 4000</td>
<td>V = 4000</td>
<td>V= 4000</td>
<td>V= 4000</td>
</tr>
<tr>
<td>V/C= 0.67</td>
<td>V/C= 0.67</td>
<td>V/C= 1.00</td>
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</tr>
<tr>
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<td>D/C= 0.83</td>
<td>D/C= 1.25</td>
</tr>
<tr>
<td>V = 5000</td>
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<td>V= 4000</td>
<td>V= 4000</td>
</tr>
<tr>
<td>V/C= 0.83</td>
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Illustration 1.5.1  Freeway Analysis Demand-Supply Diagram for Example Problem
CHAPTER 1.6 SPECIAL CONSIDERATIONS

There are many situations encountered in freeway analysis projects that require special considerations. The previous chapters are primarily directed to typical situations in terms of freeway design, capacity analysis, demand estimation, environmental circumstances, and traffic analysis. The intent of this chapter is to identify many of the special situations that may be encountered in freeway analysis. It is beyond the scope of this manual to attempt to identify all of them or to provide detailed description of them.

The Transportation Research Board over the years has published Highway Capacity Manuals from 1950 to 2000. The HCM2000 addresses many types of transportation facilities and chapters directed to freeway facilities include the following:

- Chapter 22 Freeway Facilities
- Chapter 23 Basic Freeway Segments
- Chapter 24 Freeway Weaving
- Chapter 25 Ramps and Ramp Junctions

The earlier chapters of this Manual and the Highway Capacity Manual both begin with the analysis of basic or typical conditions and then adjust for special situations. The freeway analysis user is encouraged to refer to these particular chapters in the HCM2000 for more comprehensive coverage and for more in-depth analysis of special situations.

1.6.1 Special Freeway Design Situations

Modern day design standards have been established and most of the current freeway system has either been built to these standards or modified to more closely conform to these standards. However the freeway analyst will sometimes encounter design features that vary from these standards or are unique and additional analysis is required to estimate the reduction in capacity and traffic performance.

On the freeway itself, these standards or guidelines include such elements as design speeds, lane widths, shoulder widths, lateral clearance, horizontal alignment, and vertical alignment. Minimum lane widths of 12 feet, minimum right-shoulder lateral clearance of 6 feet, minimum median lateral clearance of 2 feet, level terrain with grades no greater than 2 percent, horizontal alignment that does not affect the free-flow speed, commuter driver population, and free-flow speeds on the order of 70 mph are generally considered as typical or basic. Other design elements that may be of concern are left-side on- and off-ramps, lane-drop areas, bridge or tunnel facilities, long steep upgrades, and special lane operations (i.e., HOV lanes, truck lanes, climbing lanes, etc.).

Lower design standards will have an effect on capacity and operating speeds. Chapter 23 of the HCM2000 should be consulted for estimating the effect of these substandard design elements for basic freeway subsections.
In addition to special design situations that may occur on basic freeway subsections, special design situations may occur in freeway weaving subsections. Only right-side simple weaving sections with single lane on-ramps and off-ramps were covered previously in Chapter 1.3 of this Manual. Note that the capacity of weaving subsections may vary over time depending on the intensity of the weaving flows. There are numerous variations of weaving sections; left-side weaving sections, combined left-side and right-side weaving sections, compound weaving sections, added auxiliary lane(s) in the all or part of the weaving section, multiple lane on-ramps and/or off-ramps. The most recent comprehensive coverage for analyzing weaving sections is contained in Chapter 24 of the HCM2000.

Finally another type of special design situation that may occur on the freeway is in on- and off-ramp subsections. The three potential weak points at on-ramps are at the ramp entrance, on the ramp proper, and in the freeway merge area. The capacity relationship just upstream of the ramp entrance and on the ramp is very important depending whether either capacity is lower than the estimated ramp demand. If the capacity at either location is less than the estimated ramp demand, the traffic that can enter the ramp will be reduced. In one case the on-ramp will be staved of traffic while on the other hand, a queue will form at the entrance to the ramp and will back into the area upstream of the on-ramp.

The three potential weak points at off-ramps are at the freeway diverge area, on the off-ramp proper, and at the ramp exit. The design features of on-ramps and off-ramps should be carefully evaluated and design deficiencies identified. The capacity relationship upstream of the ramp exit and downstream of the ramp exit is very important depending whether either capacity is lower than the estimated ramp demand. If the capacity at either location is less than the estimated ramp demand, the traffic that can leave the ramp will be reduced. In one case a queue will form on the freeway just upstream of the off-ramp while on the other hand, a queue will form on the ramp and potentially could cause the queue to back into the freeway.

The most recent comprehensive coverage for analyzing on-ramp and off-ramp subsections is contained in Chapter 25 of the HCM2000.

**1.6.2 Special Capacity Analysis Situations**

Deficient design features mentioned in the previous paragraphs result in reduced capacity. Reduced capacity will lower the traffic performance, may cause locations to become bottlenecks, and/or may increase the level of congestion. Additional capacity analysis of these special situations is required at such locations where the traffic demand approaches or exceeds the capacity.

The HCM2000 devotes chapters 23, 24, and 25 to the capacity analysis of basic, weaving, and ramp subsections covering both typical designs and deficient or alternative design features. Particularly for deficient design features, the user is encouraged to give
attention to the methodologies for estimating capacities under these special situations covered in these three chapters of the HCM2000.

1.6.3 Special Demand Estimation Situations

Procedures for developing O-D demand table estimates were covered in the previous Chapter 1.4. These procedures are considered adequate for linear freeway study sections. Keep in mind that the origins and destinations consist of freeway entrances and exits, and all trips use portions of one directional facility.

However methodologies for creating O-D demand table estimates for freeway corridors is a much more complicated process and is still being developed. Origins and destinations are considered as geographic zones and there are many route possibilities between various origins and destinations. The two general methods used include the application of regional planning models and mathematical programming procedures based on traffic counts. Regional planning models have been developed and are continuously being updated in most urban areas. These models generally include O-D trip generation based on land use and route assignment based on freeway corridor traffic performance. While they are extremely helpful for regional planning they have limitations for operational freeway analysis. These limitations include the study time intervals and the accuracy of the results.

Regional planning models are often developed for 24-hour periods, peak periods, or one-hour time intervals. Operational freeway analysis studies generally use 15-minute time intervals and at most, one-hour time intervals. While the accuracy of these models may be sufficient for planning purposes, operational studies require greater accuracy. For example, in the evaluation of ramp metering strategies, incorrectly estimating the flow at an individual on-ramp in a 15-minute time interval by 10% or by 100 or so vehicles may likely cause a undesirable ramp metering plan being developed (and possibly implemented).

The other approach used for developing freeway corridor O-D demand table estimates is based on mathematical programming procedures based on traffic counts. Time interval traffic counts are obtained at as many freeway corridor segments as possible and the freeway corridor is divided into O-D geography area nodes. The mathematical programming procedure attempts to generate O-D trips and assign them to routes within the freeway corridor in manner that will result in the closest comparison between field-measured traffic counts and predicted counts. Research continues in this development effort and the user may wish to consult references for more detailed coverage.

1.6.4 Special Environmental Situations

There are many environmental situations that affect traffic demands and capacities that may be of short-term or long-term consequences. These include weather impacts and the occurrence of incidents, maintenance and reconstruction activities, and many others. For
example drivers who commute regularly and are familiar with a particular freeway as opposed to unfamiliar drivers can result in higher capacities and better traffic performance. The HCM2000 devotes a portion of its Chapter 22 to these situations and their effects on capacity and users are encouraged to consult these materials.

Weather impacts include rain, snow, and fog. More subtle situations may be encountered such as headlight glare, blinding sunlight and shadows, etc. Many incidents of varying types occur along the freeway such as vehicle breakdowns, accidents, and many others such as rubbernecking (drivers who are distracted by such incidents). As the freeway system becomes older there is an increased need for maintenance and reconstruction activities. Even if these activities are not going on, the appearance of such activities by the presence of signs, cones, equipment will likely affect the capacity and traffic performance of the freeway.

1.6.5 Special Freeway Analysis Situations

Special freeway analysis situations may occur when the congestion due to a downstream bottleneck extends upstream into on-ramp or off-ramp subsections and directly affects the on-ramp or off-ramp operations. The interactions between freeway subsections along the freeway have been covered earlier in Chapters 1.2 and 1.5 but the impacts in the vicinity of on-ramps and off-ramps were not covered in such detail.

Consider an off-ramp that has been impacted by congestion due to a downstream bottleneck. The maximum flow in the shoulder lane just upstream of the off-ramp is no longer equal to the capacity of that lane but to the maximum flow that can pass downstream of the off-ramp in the shoulder lane. Hence the number of vehicles that can reach the off-ramp may be reduced depending upon how the through traffic distributes itself between the freeway lanes and the quantity of traffic that is destined to the off-ramp. If the number of vehicles that can reach the off-ramp is less than the number that wants to exit at the off-ramp, a queue will form in the shoulder lane of the freeway just upstream of the off-ramp. If the queue continues to grow, other freeway lanes will be affected. Thus a new upstream bottleneck is formed due to the downstream bottleneck that had not been a bottleneck before.

Consider an on-ramp that has been impacted by congestion due to a downstream bottleneck. The maximum flow in the shoulder lane just downstream of the on-ramp is no longer equal to the capacity of that lane but to the maximum flow that can pass downstream of the on-ramp in the shoulder lane. Hence the number of vehicles that can enter the freeway from the on-ramp and the number of vehicles on the freeway shoulder lane upstream of the on-ramp may be reduced. This reduction depends upon how the through traffic distributes itself between the freeway lanes and the quantity of traffic that is attempting to enter on the on-ramp. If the number of vehicles on the freeway in the shoulder lane that can reach the on-ramp merge area is less than the number that wants to enter the on-ramp merge area, a queue will form in the shoulder lane of the freeway just upstream of the on-ramp. If the number of on-ramp vehicles that can enter the on-ramp merge area is less than the number that wants to enter the on-ramp merge area, a queue
will form on the on-ramp. Under such situations, queues may form in the shoulder lane and/or the on-ramp.

1.6.6 Summary

Performing freeway analysis on high-standard freeways without situations requiring special considerations is difficult. Situations requiring special considerations as identified in this chapter add complexity to the freeway analysis. While the analytical framework covered in Chapter 1.2 is robust and can handle most special situations, the identification of these special situations and quantifying their effects requires the modification of the input to the analytical framework.

Special situations covered in this chapter include those related to design features, capacity estimation, demand estimation, environmental situations, and freeway analysis complexities. The HCM2000 is the most comprehensive and in-depth reference available which cover many of these special situations. Particular reference should be given to Chapters 22, 23, 24, and 25 in the HCM2000.
PART 2 STUDY DESIGN AND DATA COLLECTION

CHAPTER 2.1 INTRODUCTION

The second part of this Manual attempts to cover the study design and required data for analyzing a freeway. Issues related to study design are covered in the next four chapters and issues related to data requirements and collection are covered in the final five chapters. As a rule-of-thumb, a well-developed study design and the collection of a comprehensive data set will require about one-third of the effort needed to complete the entire freeway analysis study. It is common to underestimate the time and resources needed to perform these two initial tasks so special attention needs to be directed to these efforts.

The freeway analysis study must be carefully designed in order to meet the requirements of the study in an effective and efficient manner. Poorly designed studies are likely not to meet their study objectives and/or will cost significantly more than well-design studies. Later steps in the freeway analysis study should not be initiated until the study design is completed and approved by all concerned parties.

The study design issues begin in Chapter 2.2 and include discussion of assembling available data, methods for identifying freeway operational problems, and their possible improvement alternatives. The next step in the study design is to establish appropriate spatial and temporal study boundaries for the study area that is covered in Chapter 2.3. Once the freeway operational problems have been identified, sets of possible improvement alternatives proposed, and study boundaries are established, the appropriate analytical tool(s) need to be selected. The discussion of alternative analytical tool(s) is covered in Chapter 2.4. The final chapter dealing with additional study design issues is Chapter 2.5 in which coverage is given to identifying criteria issues to be addressed in the study design.

An accurate database is essential for freeway analysis and often is required to be very comprehensive. Without an accurate database comprehensive enough to meet the study requirements, the freeway analysis study can not be successfully completed. There is little value in proceeding with the study unless time and resources are sufficient to meet these requirements and a data collection plan is implemented. The old familiar axiom “Garbage In, Garbage Out” is so true and so often ignored.

The final five chapters of this second part of the Manual are directed to data requirements and data collection methods. Chapter 2.6 provides an overview for developing a data collection plan. The input data that is required and is to be collected consist of supply, demand, and control data. Supply data is facility component-oriented and details for each facility component is required as input to the freeway analysis study and is discussed in Chapter 2.7. Demand data consist of origin-destination tables for each time interval and is discussed in Chapter 2.8. Control data includes all control features in the freeway study area and is covered in Chapter 2.9. The final chapter, Chapter 2.10, contains discussions of traffic performance data requirements and collection. Traffic performance
data are required in calibrating and validating the analytical tool(s) that are applied to the study area.
CHAPTER 2.2 IDENTIFYING PROBLEMS AND POSSIBLE SOLUTIONS

The first step in the study design for freeway analysis is to assemble available data, to identify the freeway problem(s) to be addressed, and to describe possible solutions to be considered. The freeway problems to be addressed in this Manual are those in which the traffic demand exceeds the available capacity for some portion of the freeway over some period of time. It can include both recurring and non-recurring congestion. Possible solutions include reducing the traffic demand, increasing the freeway capacity, and improving operations through freeway control. All three of these measures are likely to be required in some combination in most applications.

2.2.1 Assemble Available Data

In preparation for the study design and data collection phases, all available data for the selected study site within the study duration should be assembled and reviewed. For example, freeway and ramp lane configurations maps and plan/profile diagrams will be very helpful in defining the supply-side data. Previous freeway entrance and exit traffic counts can be used later in comparison with the new data being collected. Records of freeway control features such as ramp metering rates, HOV lane specifications, speed limits, and truck restrictions can serve as a beginning point for new control data being collected. Traffic performance measures such as tach runs and traffic detector data can be used later to check the new data being collected. Procedures should be developed to obtain traffic incident data and weather information. Other data such as available vehicle compositions and vehicle occupancy distributions will be found useful. These previous data sources support but do not substitute for the data collection effort unless a previous data source is considered to represent such data during the data collection phase. However the review of all available data will be extremely helpful in this study design phase.

2.2.2 Identifying Freeway Problem(s)

Recurring and non-recurring congestion is encountered whenever the freeway traffic demand exceeds its available capacity for some period of time at some location along the freeway and its associated ramps and connectors. Such locations referred to as primary bottlenecks or bottlenecks, include on-ramps, freeway subsections, and off-ramps. Bottleneck locations can be singular or multiple, and multiple bottlenecks are likely to occur at different times. The resulting congestion caused by multiple bottlenecks may be isolated or interacting. Interacting multiple bottlenecks are more difficult to identify and their solutions are likely to be more complex.

Primary bottlenecks can be identified in the field by observing traffic flow conditions upstream and downstream of the bottleneck. Hidden bottlenecks may also exist along a freeway but can not be identified in the field but only later through freeway analysis. Hidden bottlenecks exist at locations where the freeway traffic demand exceeds its available capacity but the total freeway traffic demand can not reach the hidden
bottleneck location due to upstream or downstream primary bottleneck(s). The existence and impacts of hidden bottlenecks must be included in freeway analysis studies.

One practical way of beginning to identify bottlenecks is to make a tach run along the directional freeway during the congested period and continuously observe the speedometer. As the trip begins speeds in excess of 55 to 60 mph are observed that would indicate free-flow conditions. As the trip continues brake lights can be seen ahead and gradually the speedometer reading decreases (sometimes very rapidly) to speeds of 40 mph or less. This indicates that the upstream congested area has been reached and speeds in the congested area of 10 to 25 mph are common. These low speeds identify the congested area but it is extremely important to recognize that freeway subsections in the congested area are not the problem but are the effect of the problem. As the trip continues it is important to continue reading the speedometer. When the speeds begin to increase to 40 to 50 mph, the vehicle is entering the bottleneck area and this location is the cause of the upstream congestion. For a single non-interacting bottleneck, speeds will continue to increase to 55 mph or more and traffic conditions will return to free-flow conditions. Complicated freeway study sections with multiple interacting bottlenecks will be more difficult to observe in the field and more systematic and thorough procedures will be required.

The best way to identify problems due to freeway bottlenecks is to obtain an initial data set over space and time of traffic performance measures such as speed, percent occupancy, or density. The traffic performance measure(s) is displayed in the form of a contour map. The anticipated freeway study section is displayed along the horizontal axis of the contour map (with traffic going from left to right) and the anticipated freeway study duration time is displayed along the vertical axis (with time going down the contour map). The freeway study section is divided into subsections and the freeway study duration time is divided into equal-length time intervals. Subsection boundaries occur at every location along the length of the freeway study section in which there is a change in traffic demand and/or capacity (i.e., every on-ramp and off-ramp as well as at locations with capacity changes). Common time intervals are 15-minutes although shorter or longer time intervals may be used depending upon the precision required to represent the existing traffic conditions.

The contour map is divided into cells with each cell have a length of one subsection and a time duration of one time interval. The number of cells in the contour map is the product of the number of subsections multiplied by the number of time intervals. A speed, percent occupancy, or density value is entered in each cell based on field measurements. Speeds can be obtained from tach runs or detectors while percent occupancy or density can be obtained from detectors. For illustrative purposes, a contour map based on field-measured speed will be demonstrated. Percent occupancy and density contour maps could also be used if such data is available. The differences are that ‘valleys’ in speed contour maps represent congestion while congestion is represented by ‘hills’ in percent occupancy and density contour maps; and of course threshold values are different.
An example of a speed contour map for a directional freeway having two bottlenecks is presented in Illustration 2.2.1. Two contour lines for speed (40 and 55 mph) are selected to separate the spatial-temporal area of the contour map into three freeway performance levels: free-flow conditions, transitional-flow conditions, and congested-flow conditions. Areas of the contour map in which speeds are observed to be greater than 55 mph represent free-flow conditions (white), areas in which the observed speeds are between 40 and 55 mph represent transitional-flow conditions (light gray), and areas in which the observed speeds are less than 40 mph represent congested-flow conditions (dark gray).

The shape of the congested-flow portion of the contour map clearly indicates that there are two bottlenecks. The upstream bottleneck is located in subsection 7 and the duration of upstream congestion occurs from time slice 2 through time slice 6 for a total of five time intervals. With 15-minute time slices, the duration would be one hour and fifteen minutes. The congestion extends upstream through subsection 4 for a distance of 0.73 miles. The downstream bottleneck is located in subsection 14 and the duration of its upstream congestion occurs from time slice 3 through time slice 10 for a total of seven time intervals (one hour and forty-five minutes). The congestion extends upstream through subsection 11 for a distance of 0.83 miles. Note that the congestion due to the downstream bottleneck does not extend upstream to the upstream bottleneck.

A triangular-shaped congested-flow area is typical for an isolated freeway bottleneck with the blunt end of the area downstream and the point upstream. This pattern is caused by demand exceeding capacity starting in the first congested time interval and continuing until the upstream demand becomes less than the capacity of the bottleneck. At this point in time, the length of the upstream congestion reaches its maximum value. Thereafter, as upstream demand continues to be less than the capacity of the bottleneck, the length of the queue decreases until all excess demand in the congested area is served and passes through the bottleneck. The size of the congested area is indicative of the seriousness of the problem and the level of solution required.

Illustration 2.2.1 also suggests that there are two potential hidden bottlenecks. One hidden bottleneck is in subsection 9 and the other in subsection 16. It is unlikely that the hidden bottlenecks would have been identified in the field since they do not cause congestion. However the potential hidden bottleneck are shown as being in a transitional-flow area and operating very close to its capacity. The importance of identifying hidden bottlenecks is that if the capacity of the upstream bottlenecks are increased even slightly, they will released more traffic to the downstream hidden bottleneck, and the hidden bottleneck will become an actual bottleneck. Keep in mind that hidden bottlenecks can also occur upstream of a bottleneck in the current identified congested area.

The objective of this first step in the study design is to identify the bottleneck location(s) and obtain some appreciation of the magnitude of the problem. These results and the traffic performance contour map will be essential as the study design tasks continue into identifying possible solutions, establishing study boundaries, selecting analysis technique(s), and in the identification of critical issues.
2.2.3 Possible Solutions

Solutions to freeway problems in which traffic demands exceed available capacity must consider one of three sets of actions (or their combinations): increase capacity, reduce demand, and improve operations through traffic control. First attention should be directed to primary bottlenecks followed by hidden bottlenecks. The location of all bottleneck(s) needs to be carefully identified and some appreciation of the magnitude of the problem recognized before proceeding with identifying possible solutions.

Historically the solution approach has been to increase the capacity at the bottleneck location(s). This is the most direct approach and leads to the most immediate improvements in freeway operations. It is particularly true in situations where the magnitude of the bottleneck problem is severe and other locations along the freeway are operating well under capacity flow conditions. The situation most frequently encountered is at simple or multiple weaving sections where traffic demand increases due to the upstream on-ramps and sufficient capacity is not available downstream of the on-ramp. Adding an auxiliary lane from the on-ramp to some off-ramp downstream where demand is reduced is a possible solution. This may be referred to as a procedure for ‘balancing’ the capacity along the freeway with the existing traffic demand.

In situations where many serious bottlenecks occur and most subsections along the freeway are operating at or near capacity, adding a continuous through freeway lane may be a candidate solution. There has been some resistance to this approach because of the concern that adding more capacity results in encouraging future growth in traffic demand.

A possible solution for situations in which the previously adding of a through freeway lane was considered, is adding a high-occupancy (HOV) lane. This solution approach offers some short-term benefits particularly in terms of passenger-flow, and has the potential long-term benefits of encouraging multiple-vehicle usage and reserving capacity into the future for such vehicles.

A problem that is sometimes encountered with added HOV lanes is that the usage in the HOV lane is much less than its lane capacity due to the selected minimum occupancy restriction. This results in the under-utilization of the added lane and potential adverse reactions by non-HOV vehicles in the mixed-flow lanes. A recently developed solution has been to convert the HOV lane to a HOV/HOT lane in which vehicles that do not qualify as a HOV vehicle can nevertheless use the HOV lane by paying a toll. In theory, the established toll level would be frequently adjusted to assure that the HOV/HOT lane would always operate under free-flow conditions.

Another group of possible solutions for freeway congestion deals with reducing the freeway traffic demand at bottlenecks. There are four ways to reduce freeway traffic demand: spatial response, temporal response, modal response, and total response.

Spatial response deals with spreading excess freeway demand to other alternate routes such as to frontage roads and parallel arterials. In order for this to happen, there must be incentives (or disincentives) to cause this spatial response to occur. One incentive would
be to improve travel on the alternate routes by improved geometric and controlled means. Another potential incentive would be to provide real-time travel information. Disincentives would be to increase the access time to the freeway by introducing ramp metering and/or by charging tolls.

Temporal response deals with spreading the excess freeway demand to uncongested freeway time periods before and after the peak traffic period. In order for this to happen there must be incentives (or disincentives) to cause this temporal response to occur. Incentives might take the form of informational systems that alert drivers when travel time is less in earlier and later time periods and to employment-based incentives. Disincentives might take the form of ramp metering or by charging tolls.

Modal response deals with encouraging multiple occupancy vehicle travel and reducing low occupancy vehicle travel. Implementing on-freeway HOV lanes and/or HOV bypass lanes at ramp meters are examples of incentives to cause modal response to carpool vehicles. Incentives also include supporting vanpool programs and improved transit service. Disincentives include allocating added freeway lanes to HOV vehicles only and excluding low occupancy vehicles from HOV bypass lanes at ramp meters.

Total response is the most difficult method of reducing freeway traffic demand and requires a broad set of actions such as re-structuring land use, increasing cost of travel in peak periods (such as by adding tolls), encouraging the reduction in the number of trips by combining trips, and fuel cost increases.

Another group of possible solutions for eliminating or reducing freeway congestion deals with improving operations through freeway control. Freeway control can take many forms and often overlap with capacity increase and demand reduction solutions. Ramp metering, both normal ramp metering and priority ramp metering are prime candidates. Other types of control include lane use control (HOV lanes, truck lanes, and other types of lane designations), speed control, advance dynamic signing, and incident management.

A summary of possible solutions to eliminate or reduce freeway congestion is provided in Illustration 2.2.2.
Illustration 2.2.1 Identifying Isolated and Hidden Bottlenecks from Speed Contour Map

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### Increased Capacity Approaches
- Adding short lanes
  - Merge areas
  - Weaving sections
  - Diverge areas
- Adding lanes
  - Added mixed-flow lanes
    - Adding HOV lanes
  - Adding HOV/HOT lanes

### Reduced Demand Approaches
- Spreading demand over space
  - Improve alternate routes
  - Provide real-time travel information
  - Introduce ramp metering
  - Peak period freeway tolls
- Spreading demand over time
  - Provide real-time travel information
  - Employment-based incentives
  - Introduce ramp metering
  - Peak period freeway tolls
- Spreading demand over mode
  - Introduce on-freeway HOV lanes
  - Introduce ramp metering with HOV bypass lanes
  - Support vanpool programs
  - Improve transit service and reduce fares
- Reducing total demand
  - Land use restructuring
  - Peak period freeway tolls
  - Increase fuel costs
  - Combining trips

### Control Approaches
- Ramp metering
  - Normal ramp metering
  - Priority ramp metering
- Lane use restrictions
  - HOV lanes
  - Truck lanes
  - Other designated lane use restrictions
- Speed control and advanced information
- Incident management

**Illustration 2.2.2 Possible Solution Approaches**
CHAPTER 2.3 ESTABLISHING STUDY BOUNDARIES

Having identified the location of the freeway problem(s) and gained some insights into the magnitude of the problem and possible solutions, the next step in the study design phase is to establish study boundaries. The study boundaries are spatial and temporal. There is an optimum balance between having the study boundaries too limited or too extensive. Tight study boundaries generally reduce the cost of the freeway analysis study but if too limiting, will not permit the study of the full impact of the improvement plan. Study boundaries too broadly chosen will permit the study of the full impact of the improvement plan, but will likely increase the cost of the freeway analysis study significantly. The key is to select the most limiting boundaries but with the assurance that the full impact of the improvement plans will be assessed including the ‘no-build’ alternative.

The spatial and temporal study boundaries must be selected considering all freeway analysis situations that will be investigated. Normally the most demanding requirement is to investigate the ‘no-build’ situation in some future year. Another consideration is whether the study is to be a freeway-only study or a freeway corridor study. The only spatial consideration in a freeway-only study is the length of the freeway and associated ramps to be studied. For freeway corridor studies the spatial considerations are much more critical in terms of how large the corridor should be in terms of the number of parallel and crossing arterials. Freeway corridor studies require on the order of 10 or times as much effort as freeway-only studies. For example, freeway corridor studies require supply-side information for all arterials and the freeway, control-side information for intersection signals as well as ramp metering signals, and requiring network-based origin-destination tables for each time interval. Studies of freeway corridors will be discussed further in the later chapter, Chapter 2.5 when critical issues are discussed. The remaining portion of this section will be devoted to directional freeway-only studies.

For directional freeway-only studies, the study boundary issues are spatial (where does the freeway study section begin and end) and temporal (when does the study time duration begin and end). It is better to initially extend spatial and temporal boundaries beyond the minimum requirements for the added cost is not too significant and adding additional data at a later date if found necessary, is expensive and time consuming.

2.3.1 Establishing Spatial Boundaries

The beginning or upstream end of the study section and the ending or downstream end of the study section should be selected to capture all congestion that will occur along the freeway for the no-build situation in the furthest future year investigation. Congestion should not extend upstream beyond the upstream end of the study section nor should a bottleneck occur downstream of the study section that causes congestion to occur within the study section boundary.

The added cost of initially deciding to extend the study section upstream or downstream is not too expensive and adding it later will be expensive and will delay the study. The
earlier illustration, Illustration 2.2.1, depicts spatial study boundaries that are adequate for the situations shown. However if a future year scenario is to be included in the analysis that increases the demand and thus causes congestion to extend upstream of the upstream study section boundary, the full performance assessment of this scenario will not be captured and comparisons with other scenarios will not be correct. Also one should be sure that there is not a downstream bottleneck (primary or hidden) that will cause congestion to backup into the study section when future demand growth scenarios are investigated.

2.3.2 Establishing Temporal Boundaries

The study duration beginning time and ending time should be selected to capture all congestion that will occur along the freeway for the no-build situation in the furthest future year investigation. Congestion should not occur before the study duration beginning time nor extend beyond the study duration ending time. The cost of extending the study duration time is relatively minor (particularly if detectors are available) and so adding an extra half-hour or so at the beginning and at the end of the study duration time is very prudent. Adding time intervals later in the analysis is expensive and time consuming.

The earlier illustration, Illustration 2.2.1, depicts temporal study boundaries that are adequate for the situations shown. However if a future year scenario is to be included in the analysis that increases the demand and thus causes congestion to occur before or after the study duration time, the full performance assessment of this scenario will not be captured and comparisons with other scenarios will not be correct.

2.3.3 Summary

Selecting spatial and temporal boundaries for the freeway analysis study is an important task and if selected correctly, can result in an effective and efficient study that meets its objectives. It is better to extend the boundaries beyond the expected requirements at the beginning of the study than to attempt to increase the boundaries at a later time in the study. A major decision is to whether to undertake a freeway-only study or a freeway corridor study. A freeway corridor study will require a much greater effort in each step of the study but may be needed to meet the requirements of the study. This is issue is discussed further in a later chapter, Chapter 2.5 along with other critical issues.
CHAPTER 2.4 IDENTIFY ANALYSIS TECHNIQUES

Different freeway analysis studies require different analytical techniques ranging from pencil and paper procedures to large-scale network microscopic stochastic simulation models. Selecting a more complicated analytical technique than needed for the study at hand results in unnecessary expenditure of resources and time. Selecting a less complicated analytical technique than needed for the study at hand results in either not meeting the objectives of the study or additional resources and time to redo the analysis with a higher level analytical technique. If an error is made in selecting the correct analytical technique, it is better to start with a simpler technique and then have to upgrade the analysis if necessary to a higher-level technique. Experience has also led a number of investigators to select a two-level approach with analytical techniques. That is, using a simpler technique to serve as a problem learning and filtering technique, and then moving up to a higher-level technique for the more detailed investigation.

The following sections of this chapter will describe various analytical techniques that are available with particular emphasis on the types of problems they are intended to address. The selection of the appropriate analytical technique is a critical issue and documentation of candidate techniques or models should be carefully reviewed before final selection.

2.4.1 Pencil and Paper Procedures

The power of pencil and paper approaches for some simple freeway analysis studies should not be overlooked. It obviously must be a simple problem in terms of scope and geography area, and depends on the creativity and knowledge of the investigator. It usually results in qualitative decisions rather than quantitative ones such as answer the questions “will it work and/or will it provide an improvement”. It has frequently been used as a first-level learning situation that would lead to greater in-depth study analysis. Reliance would be placed on the use of manuals and other references as well as experience in handling other similar analyses.

Examples are too numerous to identify but might include estimating the increase demand that a current near-capacity subsection could handle before congestion occurs to local qualitative evaluations of alternative designed merging and diverging areas. The analysis is generally localized (not concerned about upstream or downstream impacts) and either directed to under-saturated flow situations or to only one time interval of over-saturated flow conditions.

2.4.2 Macroscopic Flow Relationships

Traffic flow relationships have been developed over the years and permit the estimation of a wide-variety of traffic performance measures at the macroscopic and deterministic level. The emphasis is on the characteristics of groups of vehicle being concerned with only the average statistics and for under-saturated flow levels. Without adding complexity, macroscopic flow relationships can be used particularly to analyze under-saturated flow situations. The Highway Capacity Manual (HCM2000) and other
references provide macroscopic flow relationships such as the effect of traffic flow on speed. These relationships can be used for example to estimate speeds and density as a function of flow. Often default capacity estimates or available field-measured relationships for similar locations are required. The HCM provides methodologies for estimating capacities.

An example would be to estimate the level of service of a freeway subsection as a function of number lanes available given an expected flow demand.

2.4.3 Queuing Analysis

Queuing analysis techniques are well suited for simple single-point queuing situations in which the physical length of the queue is not required. They can be at the microscopic stochastic level for under-saturated flow conditions or at the macroscopic deterministic level for over-saturated flow conditions.

Equations are available in most queuing theory textbooks for estimating various queuing characteristics as a function of the demand and capacity at a point in a system when under-saturated flow conditions occur. Some type of microscopic flow description is assumed for the arriving and departing traffic. Predicted characteristics might include average delays and number of queued vehicles in stochastic terms. An example of their use includes estimating delays and number of queued vehicles at toll facilities as a function of mean arrival times and mean service times.

Queuing analysis techniques at the macroscopic deterministic level can be used to study over-saturated flow conditions at single point locations. Traffic-oriented queuing analysis textbooks and references are available that describe such applications. They normally encompass multiple time intervals with the unserved demand in one time interval being transferred to the next time interval. These techniques can provide delay information as well as estimates of the number of vehicles in the queue over time. However they do not provide queue length information. These techniques can become applicable to more complicated situations such as analyzing the effect of changes in demand and/or capacity over time and often require computer programs for effective applications. An example was a study of the effect of incident service time and type of incident on traffic delay.

2.4.4 Linear Freeway Models

Both macroscopic and microscopic simulation models are available for analyzing linear freeways under both under-saturated and over-saturated flow conditions. Macroscopic models are deterministic models that deal with groups of vehicles. Investigations using macroscopic models require much less effort in terms of data, calibration, and application but provide only single deterministic predicted performance measures for groups of vehicles for a specific set of inputs. Microscopic models are stochastic models that deal with individual vehicles. Investigations using microscopic models require more effort but provide detailed vehicle-by-vehicle assessment and associated animation.
There are at least four macroscopic deterministic models that are available for undertaking directional linear freeway studies. They include the FREFLO, FREQ, HCM, and (District 11) models. The FREFLO model was introduced in the 1970’s and later incorporated into the FHWA’s suite of computerized models. The FREQ model was introduced in the late 1960’s and has been continuously updated with support from Caltrans, FHWA, and Texas Department of Transportation. The HCM2000 includes chapter 22 that describes its macroscopic deterministic methodology that has been computerized (FREVAL). District 11 several years ago used a deterministic macroscopic model but its current status is unknown.

There are a number of microscopic stochastic models that are available for undertaking directional linear freeway studies. The models used in the United States include the AIMSUM, CORSIM, MITSIM, PARAMICS, and VISSIM models. The CORSIM model was developed and currently supported by FHWA and has been frequently used in the United States. The AIMSUM, PARAMICS, AND VISSIM models are more recently developed models developed by the private sector and are available for licensing from them. The MITSIM model was developed by an academic institution.

Macroscopic deterministic models have the advantage of modeling long freeway study sections, requiring less input data, being easier to calibrate, providing multi-colored traffic performance contour maps, and having very short computer run times. Microscopic stochastic models have the advantage of simulating the trajectories of individual vehicles on a per-lane basis and are ideally suited for complicated merging, diverging, and weaving study sections. Microscopic models can also provide animated graphics. Important issues to consider in selecting a particular model in addition to the comments earlier in this paragraph are the availability of detailed manuals, available training workshops, and prompt in-depth technical support.

2.4.5 Freeway Corridor Models

Microscopic models identified earlier (AIMSUM, CORSIM, MITSIM, PARAMICS, AND VISSIM) can be used as freeway corridor models. The only macroscopic model with limited capabilities to handle freeway corridor modeling is the FREQ model. The microscopic models are very powerful tools in terms of the details that they can provide, their multi-modal features, and the geographic areas that they can simulate.

Advancing the analysis level from a linear freeway to a freeway corridor is not a trivial step and should be considered only if the needs of the study require it. Each step in the simulation process will be more demanding in terms of resources and time. Designing the study, collecting the data, calibrating the model, and applying the model will require greater resources and more experienced users. On the other hand if portions of the freeway corridor have strong interactions on other portions such as implementing strategies that result in the re-distribution of traffic demands between the freeway and alternate routes, a freeway corridor model approach is essential.
Except for the application of the FREQ model to simulate linear freeways and freeway corridors, this Manual does not discuss the use of microscopic model to simulate freeway corridors further. The reader is directed to the list of references located at the end of the manual for guidance in learning about other models.
CHAPTER 2.5 IDENTIFY CRITICAL ISSUES

There are many critical issues to be considered in the study design for a freeway analysis project depending upon the scope and objectives of the study. A few of these critical issues are identified and described in the following portions of this chapter.

The requirements of the project may call for the quantification of the impacts upon energy consumption and vehicle emissions. If this is the case, the analysis technique selected and the collection of input data will be affected. Not all analytical techniques provide such estimations. Energy consumption and vehicle emission prediction procedures require more in-depth information about the vehicle fleet traveling within the study area and fairly accurate speed trajectories over space and time. The vehicle fleet needs to be specified and quantified into sub-vehicle classes depending upon energy and emission characteristics. Speed profiles need to be accurately predicted over time and space. Vehicle fleet compositions change over time and weather conditions affect fuel consumption and vehicle emissions.

The requirements of the project may call for investigations dealing with special treatment for subgroups of vehicles such as truck lanes and a variety of preferential treatment strategies for high occupancy vehicles. The study design should identify such investigations and the data collection that is required in the analysis. For example, in considering truck lanes, the composition of vehicles from a performance perspective and the vertical and horizontal alignment of the freeway need to be carefully determined. For preferential treatment investigations, the composition of vehicles from an occupancy perspective for multi-time interval origin-destination tables is needed. The analysis technique needs to include the behavioral characteristics of modeling the use of the HOV lane(s) and the potential mode shift.

The requirements of the project may require investigating strategies that result in demand modifications that in turn will affect the traffic performance within the study area. Demand modifications were mentioned earlier in Chapter 2.2 and include spatial, temporal, modal, and total responses. If demand modifications are a critical issue, analytical procedures need to be selected that handle such situations. Another dimension to demand modifications is predicting demand changes into the future. For short-term projections, growth factors are often used. For longer-term estimations, planning models are sometimes employed to provide information about future demand patterns and intensities. A common problem is that these models often overestimate future demands because the input level of traffic performance in the planning models has been over-estimated. A later check is to compare the planning input level of traffic performance with the predicted level of performance from the analytical procedure.

The decision whether the freeway analysis will be directed to a linear freeway or a freeway corridor is an extremely important decision. A decision to embark upon a freeway corridor study should be carefully considered in light of the significant resource and time commitments. Even if the decision is made to undertake a freeway corridor
study, it may be prudent to first undertake the analysis of the linear freeway portion of the freeway.

Special studies may be required if capacity operational modifications are being considered. Most-likely candidates for capacity modifications are in the vicinity of freeway interchanges, complicated weaving sections, and unusual horizontal and vertical alignment sections. Careful estimation of revised capacities at these locations as well as adjacent upstream and downstream sections are needed. Most-likely candidates for operational modifications deal with ramp metering. Special studies are required of the ramp design configuration such as to available ramp queue storage, availability of additional lanes for multi-lane metering or added HOV lane.

Finally, each governmental agency responsible for freeways has design standards and policies that must be adhered to in the identification and design of improvement alternatives to be investigated. Such improvement plans should be documented and reviewed by supervisors with experience in working with standards and policies.
Developing a data collection plan follows the freeway analysis project’s study design. Careful attention to the study design is required in terms of the identified problems, possible solutions, study boundaries, selected analysis techniques, and identified critical issues. The requirement for an accurate and comprehensive data set cannot be overemphasized. Data collection is a major activity requiring considerable advanced planning, significant allocation of personnel and equipment resources, and careful field supervision and conduct.

The comprehensive data set includes the following five data sub-sets: supply-side, demand-side, control-side, and traffic performance. This data set needs to be collected simultaneously over the same period of time; a minimum of three days of data within the study boundaries (space and time) are needed. Data should usually be collected Tuesday through Thursday during a week not related to any holiday or special events. The week should be carefully selected since the initial analysis will be performed using this data set. Each of the four data sub-sets will be described and discussed in some detail in the following five chapters.

In preparation for the data collection phase, all available data for the selected study site within the study duration should be reviewed again. For example, freeway and ramp lane configurations maps and plan/profile diagrams will be very helpful in defining the supply-side data. Previous freeway entrance and exit traffic counts can be used later in comparison with the new data being collected. Records of freeway control features such as ramp metering rates, HOV lane specifications, speed limits, and truck restrictions can serve as a beginning point for new control data being collected. Traffic performance measures such as tach runs and traffic detector data can be used later to check the new data being collected. Procedures should be developed to obtain traffic incident data and weather information. Other data such as available vehicle compositions and vehicle occupancy distributions will be found useful. These previous data sources support but do not substitute for the data collection effort unless a previous data source is considered to represent such data during the data collection phase.
CHAPTER 2.7 SUPPLY-SIDE DATA

This chapter will describe and discuss the supply-side data to be obtained during the data collection effort. The supply-side data includes all physical dimensions of the directional freeway and associated ramps included within the study area. It is essential that all such data represent the existing conditions during the time of the data collection effort.

A linear directional freeway and ramp lane plan is needed to identify the location of all on-ramps and off-ramps as well as the number of lanes on each ramp and along each subsection of the freeway between ramps. Factors that affect ramp and freeway capacities should be obtained such as lane widths, shoulder widths, design of on- and off-ramps, ramp merge areas, ramp diverge areas, and freeway add/drop lane locations. The essential data needed can be envisioned as the data that can be seen in an aerial photograph of the directional freeway.

The horizontal alignment and vertical profile of the directional freeway study section and associated ramps are needed. Such data is needed to support the estimation of freeway and ramp capacities and as input in determining the effect of horizontal alignment and vertical profile on vehicle performance.

In addition to obtaining the geometric details of the freeway, the objective of the supply-side data is to estimate capacity for each component of the freeway system. Procedures for estimating capacity for various components of the freeway system were covered earlier in Chapter 1.3. There are many situations encountered in freeway analysis projects that require special considerations. Some of these special situations are identified and briefly described in the earlier Chapter 1.6. They included giving special attention to the vertical and horizontal alignment of the freeway, on-freeway design features such as left-side on- and off-ramps, freeway lane drop locations, on-ramp merge designs, off-ramp diverge designs, weaving sections, and many others.
CHAPTER 2.8 DEMAND-SIDE DATA

This chapter will describe and discuss the demand-side data to be obtained during the data collection effort. The demand-side data includes:

- freeway entrance and exit counts
- vehicle type classification distributions
- vehicle occupancy level distributions

It is very desirable to have these demand-side field measurements obtained during the same period of time and for several days. If the study is to be of a freeway corridor, additional information is required of the arterial street portions of the freeway corridor. Obtaining demand-side data for the arterial street system is a very significant undertaking and its description is beyond the scope of this Manual.

2.8.1 Freeway Entrance and Exit Counts

Traffic counts are needed (preferable for three mid-week days) at each freeway entrance and exit including the mainline freeway entrance and exit. Such counts are needed for each time interval (i.e., 15-minutes generally) during the study duration period. The locations where these traffic counts are obtained are extremely important.

In the freeway analysis phase, it will be assumed that freeway entrance counts are equivalent to freeway origin demands. Therefore there should be free-flow conditions at these locations and queues from the freeway should not back over these count locations. This is also true for the mainline freeway entrance count location. If this does occur, adjustments in the freeway entrance counts will be required.

It is also important to select locations for the freeway exit counts at locations where free-flow (non-congested) conditions. Therefore there should be freeway flow conditions at these locations and queues from the off-ramp exit to the arterial street system should not back over these count locations. This is also true for the mainline freeway exit count location. If this does occur, adjustments in the freeway exit counts will be required.

2.8.2 Vehicle Type Classification Distributions

Samples of vehicle type classification distributions are needed at selected freeway entrances and exits during selected time intervals. The classification should be based upon vehicle performance ability. The HCM2000 suggests that the vehicle classification include passenger vehicles, trucks/buses (more than four tires touching the pavement), and recreational vehicles. Such data is extremely important on those projects that either include a high percentage of low performance vehicles and/or long steep grades (grades greater than two percent). These distributions are also important later in estimating vehicle emission and fuel consumption.
2.8.3 Vehicle Occupancy Level Distributions

Samples of vehicle occupancy distributions are needed at selected freeway entrances and exits during selected time intervals. Vehicle occupancy classes include single occupant vehicles, vehicles carrying two persons, vehicles carrying three or more persons, and buses. Such data is extremely important on those projects in which consideration is given to on-freeway and/or on-ramp HOV operations. These distributions are also important later in estimating traffic performance in terms of passenger-miles and passenger-hours of travel rather than in vehicle terms.
CHAPTER 2.9 CONTROL DATA

Operational control features are also needed as input to the freeway analysis process. These operational control features include:

- existing ramp metering operations
- on-freeway HOV lanes
- other control features such as speed limits and lane use control

If the study is to be of a freeway corridor, additional information is required of the arterial street portions of the freeway corridor such as intersection signal control. Obtaining control-side data for the arterial street system is a very significant undertaking and its description is beyond the scope of this Manual.

2.9.1 Existing Ramp Metering Operations

If there is an existing ramp metering operations on the freeway, information is needed to model such operations. This would include:

- the type of ramp metering (general or HOV metering)
- if HOV metering, the restrictions for HOV use (i.e., minimum occupancy requirement)
- number of metered lanes and HOV lanes
- the metering rate at each metered on-ramp for each time interval
- an estimate of queue length at each metered on-ramp for each time interval (used in the calibration process)

2.9.2 Existing HOV Lane Operations

If there is an existing on-freeway HOV lane(s), information is needed to model such operations. This would include:

- the beginning and ending physical location of the HOV lane
- the starting and ending time of the HOV lane operation
- the minimum occupancy level for HOV lane use
- the location of any barriers separating the HOV lane from the adjacent lane

2.9.3 Other Control Features

Data is also needed in regard to any other control features such as speed limits, lane use control, and freeway signing. Speed limits are indicative of the effect of the geometric design features upon traffic operations and varying speed limits along a freeway alerts the analyst to possible areas of greatest concern. Speed limits also give the analyst some idea of the expected free-flow speed. Lane use control features such as truck restriction lanes or destination-restricted lanes are also needed as input data in the modeling process. Certain types of freeway signs may also significantly affect the driver behavior along a
freeway such as warning signs and directional signs for lane use approaching interchanges.
CHAPTER 2.10 TRAFFIC PERFORMANCE DATA

Traffic performance measures over time and space are needed as potential input and also importantly used in the calibration and validation process. Traffic performance measures include:

- freeway performance measures from traffic detectors
- freeway performance measures from tach runs
- freeway ramp performance measures
- other performance measures

If the study is to be of a freeway corridor, additional traffic performance measures are required in the arterial street portions of the freeway corridor.

Obtaining traffic performance measures for the arterial street system is a very significant undertaking and its description is beyond the scope of this Manual.

2.10.1 Freeway Performance Measures from Traffic Detectors

Freeway and ramp detectors provide extremely valuable sources of information as input for the freeway analysis process and as data for model calibration and validation. If the study section contains such detectors, a map of the exact locations of the detectors should be prepared. Prior to the data collection effort, the quality of the detector data should be checked and if necessary adjustments made to the detector system in order to obtain accurate traffic information for the time intervals during the study duration period. Obviously, detector data has many advantages over other data sources because of the ease of collecting such traffic data automatically over long periods of time.

Presence-type detectors can provide traffic counts, percent occupancy data, and in some cases estimates of traffic speeds. Such detector data along the freeway can be used to develop traffic count, percent occupancy and/or speed contour maps that are extremely helpful in the calibration process. Such detector data on on-ramps and off-ramps can provide traffic count data needed for developing O-D demand tables and can possibly provide percent occupancy data as a surrogate for estimating when queues extend through the detector location.

2.10.2 Freeway Performance from Tach Runs

Series of floating car or tach runs provide essential data for the calibration process. Such data can be used to develop speed contour maps and provide trip travel times between the various freeway origins and destinations over time. The conduct of such runs require close supervision in order to maintain a schedule of the individual runs, provide guidance that the drivers are ‘floating’ with traffic, and to insure that the data is collected accurately and systematically. If the tach run data is collected manually, special forms are required for recording the speedometer reading at frequent intervals (suggested to be at 0.2 mile intervals during free-flow conditions and 0.1 mile intervals during congested-flow conditions).
The observer in the vehicle can also provide much additional information that will be helpful in better understanding the traffic performance along the freeway and at the ramps. For example, the observer can note queuing situations in the vicinity of on-ramps and off-ramps, the time and location of any incidents that affect the freeway traffic, and any unusual traffic performance occurrences.

2.10.3 Freeway Ramp Performance Measures

If detectors are not available or are insufficient, other approaches are needed to obtain freeway ramp performance measures. This is particularly true if ramp metering is in operation during the data collection period.

Observations are needed as to possible queues at each on-ramp just upstream of the ramp entrance and just upstream of the freeway-ramp merge area. If queues due occur, the approximate number of vehicles in the queue at the end of each time interval should be estimated.

Observations are needed as to possible queues at each off-ramp just upstream of the freeway-ramp diverge area (ramp vehicles only), and just upstream of the ramp exit into the street system. If queues due occur, the approximate number of vehicles in the queue at the end of each time interval should be estimated.

2.10.4 Other Performance Measures

Weather and the occurrence of incidents may affect the traffic performance on the freeway and its ramps. Records should be kept during the data collection period as to approximate temperatures, wind velocities, and moisture conditions (rain, fog, snow, etc). Records should be obtained of all major incidents along the study route during the study duration period. These incidents may include accidents, disabled vehicles, maintenance activities, and the like. The location, time, and type of incident should be recorded for each major incident.