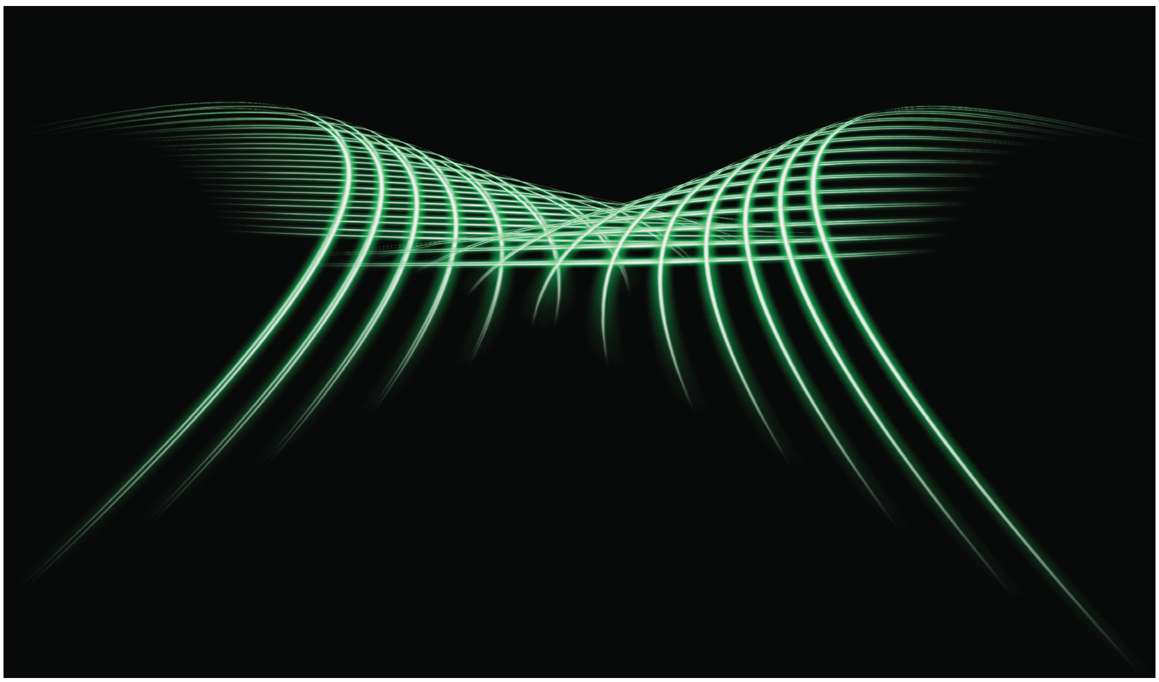
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 25

FREEWAY FACILITIES: SUPPLEMENTAL

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HCM2010

HIGHWAY CAPACITY MANUAL

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CHAPTER 25
FREEWAY FACILITIES: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

SCOPE OF CHAPTER

The freeway facility analytical methodology is described in Chapter 10. The computations contained in the methodology are detailed in this supplemental chapter. The documentation is closely tied to the computational engine for Chapter 10: FREEVAL-2010.

The FREEVAL (FREeway EVALuation) tool was initially developed for the 2000 edition of the *Highway Capacity Manual* (HCM) (*1*, *2*) and has been updated to reflect methodological changes in HCM 2010. All definitions and labels of variables and subroutines in this chapter are consistent with the computational code in FREEVAL. The Technical Reference Library in Volume 4 contains a FREEVAL user guide, which provides more details on how to use the computational engine.

Section 2 of this chapter presents a glossary of all relevant variables used in the procedure and the computational engine. Section 3 describes the overall procedure, and Sections 4 and 5 provide additional detail for the undersaturated and oversaturated flow regimes, respectively. Section 6 describes the directional facility module that aggregates performance measures for the overall facility. The chapter concludes with the formal documentation of the computational engine in Section 7 in the form of flowcharts and linkage lists.

LIMITATIONS

The completeness of the analysis will be limited if freeway segment cells in the first time interval, the last time interval, and the first freeway segment do not have demand-to-capacity ratios of 1.00 or less. The methodology can handle congestion in the first interval properly, although it will not quantify any congestion that could have occurred before the analysis. To ensure complete quantification of the effects of congestion, it is recommended that the analysis contain an initial undersaturated time interval. If all freeway segments in the last time interval do not exhibit demand-to-capacity ratios less than 1.00, congestion continues beyond the last time interval, and additional time intervals should be added. This fact will be noted as a difference between the vehicle miles of travel desired at the end of the analysis (demand flow) and the corresponding vehicle miles of travel flow generated (volume served). If queues extend upstream of the first segment, the analysis will not account for the congestion outside the freeway facility but will store the vehicles vertically until the congestion clears the first segment. The same process is followed for queues on on-ramp segments.

The methodology for oversaturated flow conditions described in this chapter is based on concepts of traffic flow theory and assumes a linear speed–flow relationship for densities greater than 45 passenger cars per mile per lane (pc/mi/ln). This relationship has not been extensively calibrated for field observations on U.S. freeways, and analysts should therefore perform their own validation from local data to obtain additional confidence in the results of this procedure. For an example of a validation exercise for this methodology, the reader is referred elsewhere (*3*).

The procedure described here becomes extremely complex when the queue from a downstream bottleneck extends into an upstream bottleneck, causing a queue collision. When such cases arise, the reliability of the methodology is questionable, and the user is cautioned about the validity of the results. For heavily congested directional freeway facilities with interacting bottleneck queues, a traffic simulation model might be more applicable. Noninteracting bottlenecks are addressed by the methodology.

The procedure focuses on analyzing a directional series of freeway segments. It describes the performance of a facility but falls short of addressing the broader transportation network. The analyst is cautioned that severe congestion on a freeway—especially freeway on-ramps—is likely to have an impact on the adjacent surface street network. Similarly, the procedure is limited in its ability to predict the impacts of an oversaturated off-ramp and the associated queues that may spill back onto the freeway. Alternative tools are suitable to evaluate these impacts.

2. GLOSSARY OF VARIABLE DEFINITIONS

This glossary defines internal variables used exclusively in the freeway facilities methodology. The variables are consistent with those used in the FREEVAL-2010 computational engine for the freeway facilities methodology. The glossary of variables covers six parts: global variables, segment variables, node variables, on-ramp variables, off-ramp variables, and facilitywide variables. Segment variables represent conditions on segments. Node variables denote flows across a node connecting two segments. On-ramp and off-ramp variables are variables that correspond to flow on ramps. Facilitywide variables pertain to aggregate traffic performance over the entire facility. In addition to these spatial categories, there are temporal divisions that represent characteristics over a time step or a time interval. The first dimension associated with each variable specifies whether the variable refers to segment or node characteristics. The labeling scheme for nodes and segments is such that segment i is immediately downstream of node i. The distinction of nodes and segments is used primarily in the oversaturated flow regime as discussed in Section 5 of this chapter.

Thus, there is always one more node than the number of segments on a facility. The second and third dimensions denote a time step t and a time interval p. Facility variables are estimates of the average performance over the length of the facility. The units of flow are in vehicles per time step. The selection of the time step size is discussed later in this chapter.

The variable symbols used internally by FREEVAL and replicated in this chapter frequently differ from the symbols used elsewhere in the HCM, particularly in Chapter 10, Freeway Facilities. For example, the HCM uses D_{jam} to represent jam density, whereas FREEVAL and this chapter use KJ.

GLOBAL VARIABLES

- i—index to segment or node number: $i = 1, 2, \ldots, NS$ (for segments) and $i = 1, 2, \ldots, NS + 1$ (for nodes).
- KC—ideal density at capacity [vehicles per mile per lane (veh/mi/ln)]. The density at capacity is 45 pc/mi/ln, which must be converted to veh/mi/ln by using the heavy-vehicle adjustment factor (f_{HV}) described in Chapter 11, Basic Freeway Segments.
- KJ—facilitywide jam density (veh/mi/ln).
- NS—number of segments on the facility.
- P—number of time intervals in the analysis period.
- p—time interval number: $p = 1, 2, \ldots, P$.
- S—number of time steps in a time interval (integer).
- t—time step number in a single interval: $t = 1, 2, \ldots, S$.
- T—number of time steps in 1 h (integer).

SEGMENT VARIABLES

- *ED*(*i*, *p*)—expected demand that would arrive at segment *i* on the basis of upstream conditions over time interval *p*. The upstream queuing effects include the metering of traffic from an upstream queue but not the spillback of vehicles from a downstream queue.
- *K*(*i*, *p*)—average traffic density of segment *i* over time interval *p*, as estimated by the oversaturated procedure.
- *KB*(*i*, *p*)—background density: segment *i* density (veh/mi/ln) over time interval *p* assuming there is no queuing on the segment. This density is calculated by using the expected demand on the segment in the corresponding undersaturated procedure in Chapters 11, 12, and 13.
- *KQ*(*i*, *t*, *p*)—queue density: vehicle density in the queue on segment *i* during time step *t* in time interval *p*. Queue density is calculated on the basis of a linear density–flow relationship in the congested regime.
- *L*(*i*)—length of segment *i* (mi).
- *N*(*i*, *p*)—number of lanes on segment *i* in time interval *p*. It could vary by time interval if a temporary lane closure is in effect.
- *NV*(*i*, *t*, *p*)—number of vehicles present on segment *i* at the end of time step *t* during time interval *p*. The number of vehicles is initially based on the calculations of Chapters 11, 12, and 13, but, as queues grow and dissipate, input–output analysis updates these values in each time step.
- *Q*(*i*, *t*, *p*)—total queue length on segment *i* at the end of time step *t* in time interval *p* (ft).
- *SC*(*i*, *p*)—segment capacity: maximum number of vehicles that can pass through segment *i* in time interval *p* based strictly on traffic and geometric properties. These capacities are calculated by using Chapters 11, 12, and 13.
- *SD*(*i*, *p*)—segment demand: desired flow rate through segment *i* including on- and off-ramp demands in time interval *p* (veh). This segment demand is calculated without any capacity constraints.
- *SF*(*i*, *t*, *p*)—segment flow out of segment *i* during time step *t* in time interval *p* (veh).
- *U*(*i*, p)—average space mean speed over the length of segment *i* during time interval *p* (mi/h).
- *UV*(*i*, *t*, *p*)—unserved vehicles: the additional number of vehicles stored on segment *i* at the end of time step *t* in time interval *p* due to a downstream bottleneck.
- *WS*(*i*, *p*)—wave speed: speed at which a front-clearing queue shock wave travels through segment *i* during time interval *p* (ft/s).
- *WTT*(*i*, *p*)—wave travel time: time taken by the shock wave traveling at wave speed *WS* to travel from the downstream end of segment *i* to the upstream end of the segment during time interval *p*, in time steps.

NODE VARIABLES

- *MF*(*i*, *t*, *p*)—actual mainline flow rate that can cross node *i* during time step *t* in time interval *p*.
- *MI*(*i*, *t*, *p*)—maximum mainline input: maximum flow desiring to enter node *i* during time step *t* in time interval *p*, based on flows from all upstream segments, taking into account all geometric and traffic constraints upstream of the node, including queues accumulated from previous time intervals.
- *MO1*(*i*, *t*, *p*)—maximum Mainline Output 1: maximum allowable mainline flow rate across node *i* during time step *t* in time interval *p*, limited by the flow from an on-ramp at node *i*.
- *MO2*(*i*, *t*, *p*)—maximum Mainline Output 2: maximum allowable mainline flow rate across node *i* during time step *t* in time interval *p*, limited by available storage on segment *i* due to a downstream queue.
- *MO3*(*i*, *t*, *p*)—maximum Mainline Output 3: maximum allowable mainline flow rate across node *i* during time step *t* in time interval *p*, limited by the presence of queued vehicles at the upstream end of segment *i* while the queue clears from the downstream end of segment *i*.

ON-RAMP VARIABLES

- *ONRC*(*i*, *p*)—geometric carrying capacity of on-ramp at node *i* roadway during time interval *p*.
- *ONRD*(*i*, *p*)—demand flow rate for on-ramp at node *i* in time interval *p*.
- *ONRF*(*i*, *t*, *p*)—actual ramp flow rate that can cross on-ramp node *i* during time step *t* in time interval *p*; takes into account control constraints (e.g., ramp meters).
- *ONRI*(*i*, *t*, *p*)—input flow rate desiring to enter the merge point at on-ramp *i* during time step *t* in time interval *p*, based on current ramp demand and ramp queues accumulated from previous time intervals.
- *ONRO*(*i*, *t*, *p*)—maximum output flow rate that can enter the merge point from on-ramp *i* during time step *t* in time interval *p*; constrained by Lane 1 (shoulder lane) flow on segment *i* and the segment *i* capacity or by a queue spillback filling the mainline segment from a bottleneck further downstream, whichever governs.
- *ONRQ*(*i*, *t*, *p*)—unmet demand that is stored as a queue on the on-ramp roadway at node *i* during time step *t* in time interval *p* (veh).
- *ONRQL*(*i*, *t*, *p*)—queue length on on-ramp *i* at the end of time step *t* in time interval *p*.
- *RM*(*i*, *p*)—maximum allowable rate of an on-ramp meter at the on-ramp at node *i* during time interval *p* (veh/h).

OFF-RAMP VARIABLES

- *DEF*(*i*, *t*, *p*)—deficit: unmet demand from a previous time interval *p* that flows past node *i* during time step *t*; used in off-ramp flow calculations downstream of a bottleneck.
- *OFRD*(*i*, *p*)—desired off-ramp demand flow exiting at off-ramp *i* during time interval *p*.
- *OFRF*(*i*, *t*, *p*)—actual flow that can exit at off-ramp *i* during time step *t* in time interval *p*.

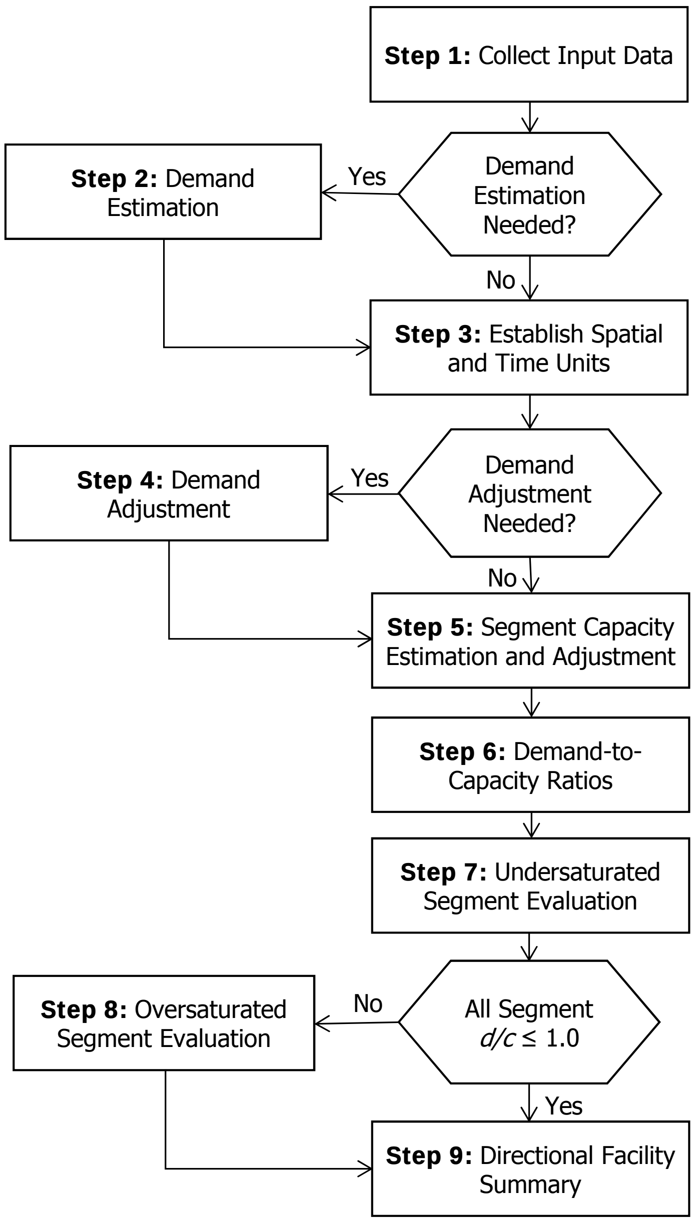
FACILITYWIDE VARIABLES

- *K*(*NS*, *P*)—average vehicle density over the entire facility during the entire analysis period *P*.
- *K*(*NS*, *p*)—average vehicle density over the entire facility during time interval *p*.
- *SMS*(*NS*, *P*)—average analysis period facility speed: average space mean speed over the entire facility during the entire analysis period *P*.
- *SMS*(*NS*, *p*)—average time interval facility speed: average space mean speed over the entire facility during time interval *p*.

3. OVERALL PROCEDURE DESCRIPTION

The procedure is described according to the nine-step process shown in Exhibit 25-1. The methodology is presented in a logical step-by-step process flow. Readers interested in technical details on how this methodology is implemented in the FREEVAL computational engine are referred to Section 7 of this chapter.

Exhibit 25-1
Overall Procedure Layout



STEP 1: COLLECT INPUT DATA

The first step in the methodology is to gather all geometric and traffic data. The most basic data are required for sizing the analysis. These basic data are listed below.

- *Number of time intervals:* the number of time intervals is input to size the analysis with the correct time dimension. There is no practical limit on the number of time intervals, although the current computational engine implementation is limited to 24 intervals.
- *Time interval duration:* the time interval duration is fixed to 15 min. The methodology assumes that there is instantaneous travel time between segments when demands are computed on segments. In other words, there is no demand shock wave at any point where the demand changes (i.e., when a new time interval begins). For this assumption to be reasonable, the uncongested travel time of the freeway facility being analyzed (which is directly related to its length) should not be longer than the duration of the time intervals being used.
- *Time step duration:* once oversaturation begins, the procedure moves to time steps. The analysis interval is reduced from a 15-min time interval to 1-min time steps to be able to track queuing effects in sufficient detail.
- *Number of segments:* the number of segments in the facility must be determined from the process given in Chapter 10, Freeway Facilities.
- *Jam density:* the systemwide jam density is required for oversaturated analysis. The default value is 190 pc/mi/ln, but jam density can be calibrated from user input.

The geometric, traffic, and demand data required for a freeway facility analysis are discussed in Chapter 10.

STEP 2: DEMAND ESTIMATION

The demand estimation module is needed when the methodology uses actual freeway counts and actual demand flows are unknown. If demand flows are known or can be projected, those values can be used directly. FREEVAL-2010 assumes that demand volumes are known; if they are not, the analyst should follow the discussion below to develop a demand volume matrix for the facility to input into the computational engine.

The demand estimation module is designed to convert the input set of freeway 15-min traffic counts into a set of freeway 15-min traffic demands. Freeway demand is defined as the number of vehicles that desire to use the freeway in a given 15-min time interval. This demand may not be represented by the 15-min count because of upstream freeway congestion within the freeway facility.

To estimate demands, the analyst sums the freeway entrance demands along the entire freeway facility (including the freeway mainline entrance) and compares it with the sum of the freeway exit counts along the entire freeway facility (including the freeway mainline exit) for each time interval. The ratio of the freeway entrance demands to the freeway exit counts is calculated for each time interval and is referred to as the *time interval scale factor*. Theoretically, the scale factor should approach 1.00 when the freeway exit counts are, in fact, freeway exit demands.

Scale factors greater than 1.00 indicate increasing congestion within the freeway facility (and storing of vehicles on the freeway). Here, the exit traffic counts underestimate the actual freeway exit demands. Scale factors less than 1.00 indicate decreasing congestion within the freeway facility (and release of stored vehicles on the freeway). Here, the exit traffic counts overestimate actual freeway exit demands. To obtain an estimate of freeway exit demand, each freeway exit count in the time interval is multiplied by the time interval scale factor.

*To obtain an estimate of freeway exit **demand**, each freeway exit **count** in the time interval is multiplied by the time interval scale factor.*

The accuracy of this procedure depends primarily on the quality of the freeway traffic counts and to a lesser extent on the length of the freeway facility. With the use of 15-min time intervals, freeway facility lengths up to 9 to 12 mi should not introduce significant errors in the procedure. The calculated scale factor pattern over the study period offers a means of checking the quality of the traffic count data. For example, if there is no congestion over the entire time–space domain, then there should be no pattern in the calculated 15-min scale factors, and they all should be within the range of 0.95 to 1.05.

If there is congestion within the time–space domain, then there should be a pattern in the calculated 15-min scale factors. During the early time intervals with no congestion, the scale factors are expected to approach 1.00 and to be within the range of 0.95 to 1.05. As congestion begins to occur and to increase over time, the scale factors are expected to exceed 1.00 and to be within the range of 1.00 to 1.10. When the extent of congestion reaches its highest level, the scale factor is expected to approach 1.00 and to be within the range of 0.95 to 1.05.

As the level of congestion recedes, the scale factor is expected to be less than 1.00 and to be within the range of 0.90 to 1.00. If the final time intervals exhibit no congestion over the complete time–space domain, then there should be no pattern in the calculated 15-min scale factors, and they all should be within the range of 0.95 to 1.05. Once the freeway entrance and exit demands are estimated by using the scale factors, the traffic demands for each freeway section in each time interval can be determined.

STEP 3: ESTABLISH SPATIAL AND TIME UNITS

The procedure analyzes a freeway in spatial units called segments, which are defined in Chapters 11, 12, and 13. The division of a freeway facility into segments is described in Chapter 10. Time units are described later in this chapter.

STEP 4: DEMAND ADJUSTMENT

Driver responses such as spatial, temporal, and modal shifts caused by traffic management strategies are not automatically incorporated in the methodology. On viewing the facility traffic performance results, the analyst can modify the demand input manually to simulate the effect of user demand responses or traffic growth effects. The accuracy of the results depends on the accuracy of the estimation of the user demand responses. Ramp-metering strategies are evaluated through adjusting the on-ramp roadway capacity, and this application is described in the segment capacity adjustment module.

The computational engine further provides origin–destination demand adjustment factors to adjust demand flows automatically by a multiplicative growth or shrinkage factor. For example, an origin demand adjustment factor of 1.15 will increase on-ramp demand by 15%. These factors can be applied to any segment in any time period. Separate origin and destination demand adjustment factors are provided to adjust on-ramp and off-ramp demand flows, respectively. By specifying a common factor to all segments and time periods, the analyst can test uniform overall growth in traffic demand.

STEP 5: SEGMENT CAPACITY ESTIMATION AND ADJUSTMENT

Segment capacity estimates are determined from Chapters 11, 12, and 13 for basic freeway segments, weaving segments, and ramp segments, respectively. All capacities are expressed in vehicles per hour. All estimates of segment capacity should be carefully reviewed and compared with local knowledge and available traffic information for the study site. The capacity value used for bottleneck segments has the greatest effect on predicted freeway traffic performance. Actual field-observed capacities at bottlenecks should be obtained when practical and should replace estimated capacities.

Actual field-observed capacities at bottlenecks should be obtained when practical and should replace estimated capacities.

On-ramp and off-ramp roadway capacities are also determined in this capacity module. On-ramp demands may exceed on-ramp capacities and limit the traffic demand entering the freeway. Off-ramp demands may exceed off-ramp capacities and cause congestion on the freeway, although this particular effect is not accounted for in the methodology and thus requires the use of alternative tools. The relationships of demand and capacity for each on-ramp and off-ramp, as well as for each freeway segment, are addressed later in the demand-to-capacity ratio module.

Again, unlike the analyses in the basic freeway segment, weaving, and ramp chapters, all analyses in this chapter measure capacity by using vehicles, rather than passenger cars, as the units.

The effect of a predetermined ramp-metering plan can be evaluated in this methodology by modifying the ramp roadway capacities. The capacity of each entrance ramp in each time interval is changed to the desired metering rate specified. This feature not only allows for evaluating the prespecified ramp-metering plan but also permits the user to experiment to obtain an improved ramp-metering plan.

Freeway design improvements can be evaluated within this methodology by modifying the design features of any segment or segments of the freeway facility, as described later in this chapter.

Reduced-capacity situations can also be investigated. The capacity in any cell of the time–space domain can be reduced to represent incident situations such as construction and maintenance activities, adverse weather, traffic accidents, and vehicle breakdowns. Similarly, capacity can be increased to match field measurements. When adjusted capacity situations are analyzed, it is important to use an alternative speed–flow relationship. The predicted speed for the alternative speed–flow model can be computed by using Equation 25-1. The relationship ensures a constant ideal density of 45 pc/mi/ln at capacity as indicated in Chapter 11, Basic Freeway Segments.

$$S = FFS + \left[1 - e^{\ln(FFS + 1 - \frac{C \times CAF}{45}) \frac{v_p}{C \times CAF}}\right]$$

Equation 25-1

where

S = segment speed (mi/h),

FFS = segment free-flow speed (mi/h),

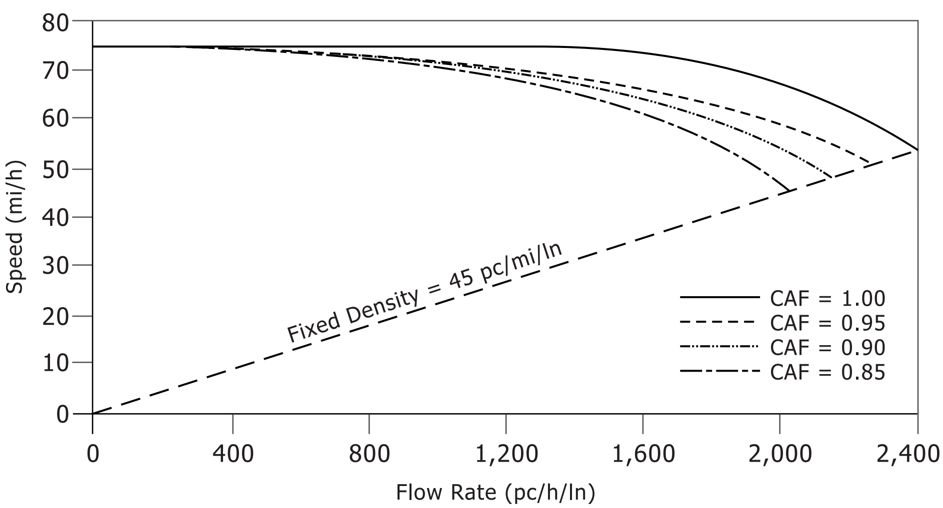
C = original segment capacity (pc/h/ln),

CAF = capacity adjustment factor (CAF = 1.0, use speed estimation procedures in Chapters 11, 12, and 13), and

v_p = segment flow rate (pc/h/ln).

Note that when v_p approaches zero in Equation 25-1, S approaches the free-flow speed. Similarly, when $v_p = C \times CAF$, S approaches the speed at capacity. Exhibit 25-2 shows speed–flow plots for capacity adjustment factors of 100%, 95%, 90%, and 85% of the original capacity.

Exhibit 25-2
Alternative Speed–Flow Curves for Indicated Capacity Adjustment Factors



Note: Free-flow speed = 75 mi/h (base conditions); *CAF* = capacity adjustment factor (proportion of available capacity).

STEP 6: DEMAND-TO-CAPACITY RATIOS

Once all freeway segment cells have been analyzed, demand-to-capacity ratios are modified into volume-to-capacity ratios for later use in calculating freeway traffic performance measures. As stated earlier, if all freeway segment cells are undersaturated (demands less than capacities), the volume-to-capacity ratios are identical to the demand-to-capacity ratios, and the analysis is simple. However, if demand exceeds capacity in one or more of the freeway segment cells, oversaturated flow conditions will occur, and the time step analysis procedure is invoked.

Until oversaturated conditions are encountered, segments are analyzed by using the undersaturated segment measure-of-effectiveness (MOE) module. All subsequent time intervals, however, are analyzed by using the oversaturated segment MOE module until all queues have cleared from the facility.

STEP 7: UNDERSATURATED SEGMENT EVALUATION

Segments are analyzed by using the Chapter 11, 12, and 13 methodologies for all time periods when the demand-to-capacity ratio is less than or equal to 1.0, *and* when there are no residual queues from an earlier period of congestion. The undersaturated segment evaluation is discussed in more detail in Section 4 of this chapter.

STEP 8: OVERSATURATED SEGMENT EVALUATION

The oversaturated segment evaluation is used once the demand on a segment exceeds its capacity ($v_d/c > 1.0$) in a time period. The oversaturated procedures are used as long as v_d/c remains greater than 1.0 and as long as a queue remains in the segment (even after v_d/c has dropped back below 1.0). Depending on the extent of the congestion, a queue is likely to spill over into adjacent upstream segments. If that occurs, the oversaturated evaluation is also used for these upstream segments, even though the v_d/c ratios for these segments may be less than 1.0. The oversaturated segment evaluation is discussed in more detail in Section 5 of this chapter.

STEP 9: DIRECTIONAL FACILITY SUMMARY

In the final analysis step, the calculated segment performance measures (e.g., average speed, density, travel time) are aggregated over the entire directional facility. The directional facility summary is discussed in more detail in Section 6 of this chapter.

4. UNDERSATURATED SEGMENT EVALUATION

This module begins with the first segment in the first time interval. For each cell, the flow (or volume) is equal to demand, the volume-to-capacity ratio is equal to the demand-to-capacity ratio, and undersaturated flow conditions prevail. Performance measures for the first segment during the first time interval are calculated by using the procedures for the corresponding segment type in Chapters 11, 12, and 13.

The analysis continues to the next downstream freeway segment in the same time interval, and the performance measures are calculated. The process is continued until the last downstream freeway segment cell in this time interval has been analyzed. For each cell, the volume-to-capacity ratio and performance measures are calculated for each freeway segment in the first time interval. The analysis continues in the second time interval beginning at the furthest upstream freeway segment and moving downstream until all freeway segments in that time interval have been analyzed. This pattern continues for the third time interval, fourth time interval, and so on until the methodology encounters a time interval that contains one or more segments with a demand-to-capacity ratio greater than 1.00 or when the last segment in the last time interval is analyzed. If no oversaturated segments are encountered, the segment performance measures are taken directly from Chapters 11, 12, and 13, and the facility performance measures are calculated as described in Section 6 of this chapter.

When the analysis moves from isolated segments to a facility, an additional constraint is necessary that controls the relative speed between two segments. To limit the speeds downstream of a segment experiencing a low average speed, a maximum achievable speed is imposed on the downstream segments. This maximum speed is based on acceleration characteristics reported elsewhere (*4*) and is shown in Equation 25-2.

On the facility level, a speed constraint is introduced that limits the maximum achievable speed downstream of a segment experiencing a low average speed.

Equation 25-2

$$V_{max} = FFS - (FFS - V_{prev})e^{-0.00162L}$$

where

V_{max} = maximum achievable segment speed (mi/h),

FFS = segment free-flow speed (mi/h),

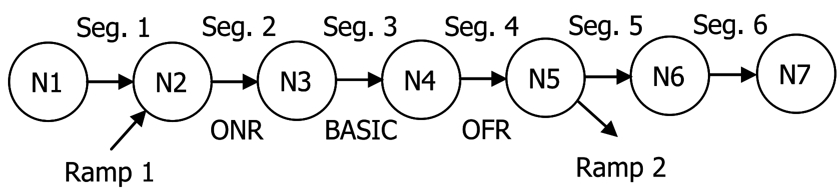
V_{prev} = average speed on immediate upstream segment (mi/h), and

L = distance from midpoints of the upstream segment and the subject segment (ft).

5. OVERSATURATED SEGMENT EVALUATION

Oversaturated flow conditions occur when the demand on one or more freeway segment cells exceeds its capacity. Once oversaturation is encountered, the methodology changes its temporal and spatial units of analysis. The spatial units become nodes and segments, and the temporal unit moves from a time interval to smaller time steps. A node is defined as the junction of two segments. There is always one more node than segment, with a node added at the beginning and end of each segment. The numbering of nodes and segments begins at the upstream end and moves to the downstream end, with the segment upstream of node *i* numbered segment *i* – 1 and the downstream segment numbered *i*, as shown in Exhibit 25-3. The intermediate segments and node numbers represent the division of the section between Ramps 1 and 2 into three segments numbered 2 (ONR), 3 (BASIC), and 4 (OFR). The oversaturated analysis moves from the first node to each downstream node in the same time step. After completion of a time step, the same nodal analysis is performed for subsequent time steps.

Exhibit 25-3
Node–Segment Representation of a Directional Freeway Facility



The oversaturated analysis focuses on the computation of segment average flows and densities in each time interval. These parameters are later aggregated to produce facilitywide estimates. Two key inputs into the flow estimation procedures are the time step duration for flow updates and a flow–density function. They are described in the next subsections.

PROCEDURE PARAMETERS

Time Step Duration

Segment flows are calculated in each time step and are used to calculate the number of vehicles on each segment at the end of every time step. The number of vehicles on each segment is used to track queue accumulation and discharge and to calculate the average segment density.

To provide accurate estimates of flows in oversaturated conditions, the time intervals are divided into smaller time steps. The conversion from time intervals to time steps occurs during the first oversaturated time interval and remains until the end of the analysis. The transition to time steps is essential because, at certain points in the methodology, future performance estimates are made on the basis of the past value of a variable. Time steps correspond to the following lengths in Exhibit 25-4.

Exhibit 25-4
Recommended Time Step Duration for Oversaturated Analysis

Shortest segment length (ft)	≤300	600	1,000	1,300	≥1,500
Time step duration (s)	15	25	40	60	60

The oversaturated methodology as implemented in FREEVAL-2010 assumes a time step of 15 s, which is adequate for segment lengths greater than 300 ft.

The FREEVAL-2010 computational engine assumes a time step of 15 s for the oversaturated flow computations, which is adequate for most facilities with a minimum segment length greater than 300 ft. For shorter segments, two problem situations may arise. The first situation occurs when segments are short and the rate of queue growth is rapid. Under these conditions, a short segment may be completely undersaturated in one time step and completely queued in another. The methodology may store more vehicles in this segment during a time step than space allows. Fortunately, the next time step compensates for this error, and the procedure continues to track queues and store vehicles accurately after this correction.

The second situation in which small time steps are important occurs when two queues interact. There is a temporary inaccuracy due to the maximum output of a segment changing, thus causing the estimation of available storage to be slightly in error. This situation results in the storage of too many vehicles on a particular segment. This supersaturation is temporary and is compensated for in the next time step. Inadequate time step size will result in erroneous estimation of queue lengths and may affect other performance measures as well. Regardless, if interacting queues occur, the results should be viewed with extreme caution.

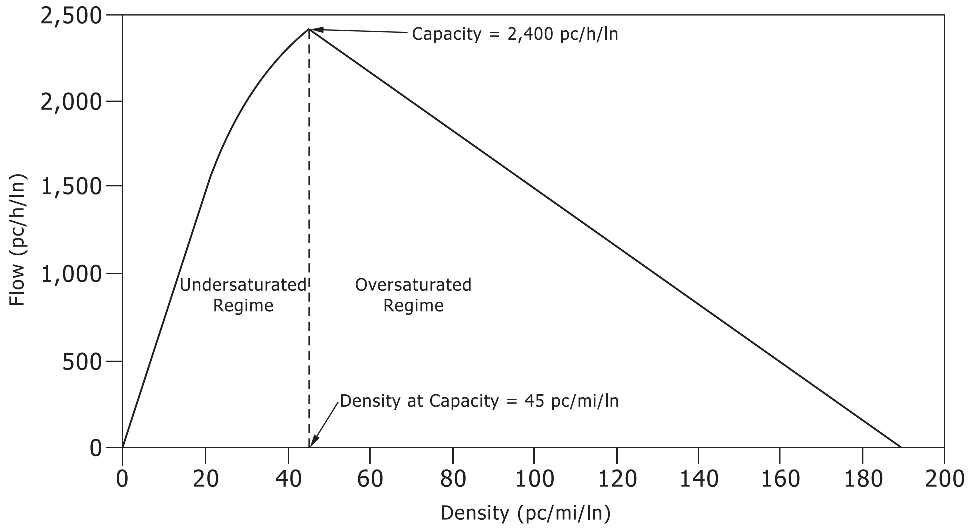
Flow–Density Relationship

Analysis of freeway segments depends on the relationships between segment speed, flow, and density. Chapter 11, Basic Freeway Segments, defines a relationship between these variables and the calculation of performance measures in the undersaturated regime. The freeway facilities methodology presented here uses the same relationships for undersaturated segments. In other words, when a segment is undersaturated the computations of this methodology are identical to the results obtained from Chapters 11, 12, and 13 for basic freeway segments, weaving segments, and ramp segments, respectively.

The calculations for oversaturated segments assume a simplified linear flow–density diagram in the congested region. Exhibit 25-5 shows this flow–density diagram for a segment having a free-flow speed of 75 mi/h. For other free-flow speeds, the corresponding capacities in Chapters 11, 12, and 13 should be used.

The oversaturated regime curve in Exhibit 25-5 is constructed from a user-specified jam density (default is 190 pc/mi/ln) and the known value of capacity, defined as the flow at a density of 45 pc/mi/ln. The flow–density relationship is assumed to be linear between these two points. The slope of the resulting line describes the speed of the shock wave at which queues grow and dissipate as discussed further below. The speed in a congested segment is obtained from the prevailing density in the segment, read along the linear flow–density relationship. Details on the theory of kinematic waves in highway traffic are given elsewhere (*5*–*7*).

Exhibit 25-5
Segment Flow–Density Function



Note: Assumed *FFS* = 75 mi/h.

FLOW ESTIMATION

The oversaturated portion of the methodology is detailed as a flowchart in Exhibit 25-6. The flowchart is divided into several parts, which are discussed in this section. Within each subsection, computations are detailed and labeled according to each step of the flowchart.

The procedure first calculates a number of flow variables starting at the first node during the first time step of oversaturation, followed by each downstream node and segment in the same time step. After all computations in the first time step are completed, calculations are performed at each node and segment during subsequent time steps for all remaining time intervals until the analysis is completed.

Exhibit 25-6
Oversaturated Analysis Procedure

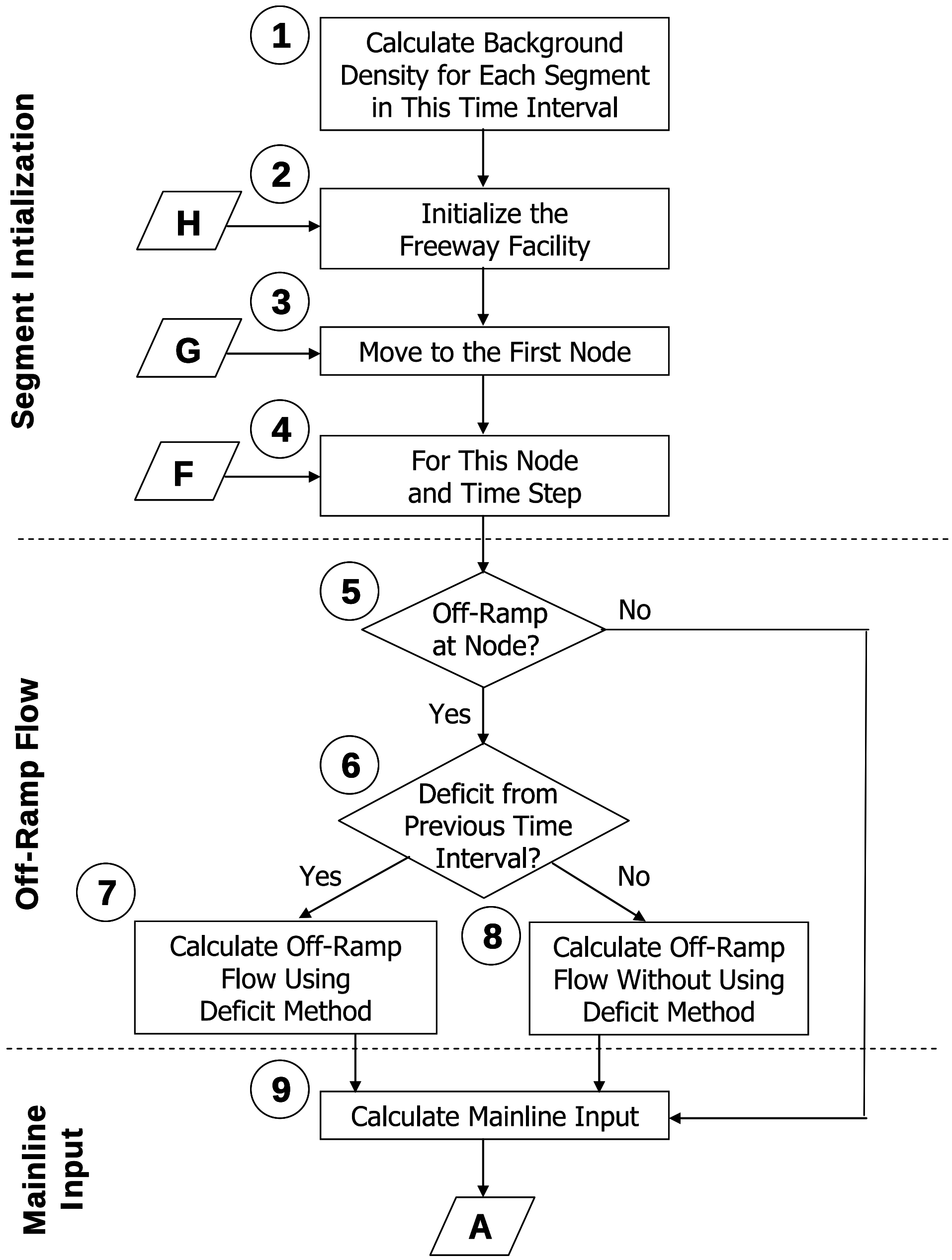


Exhibit 25-6 (cont'd.)
Oversaturated Analysis Procedure

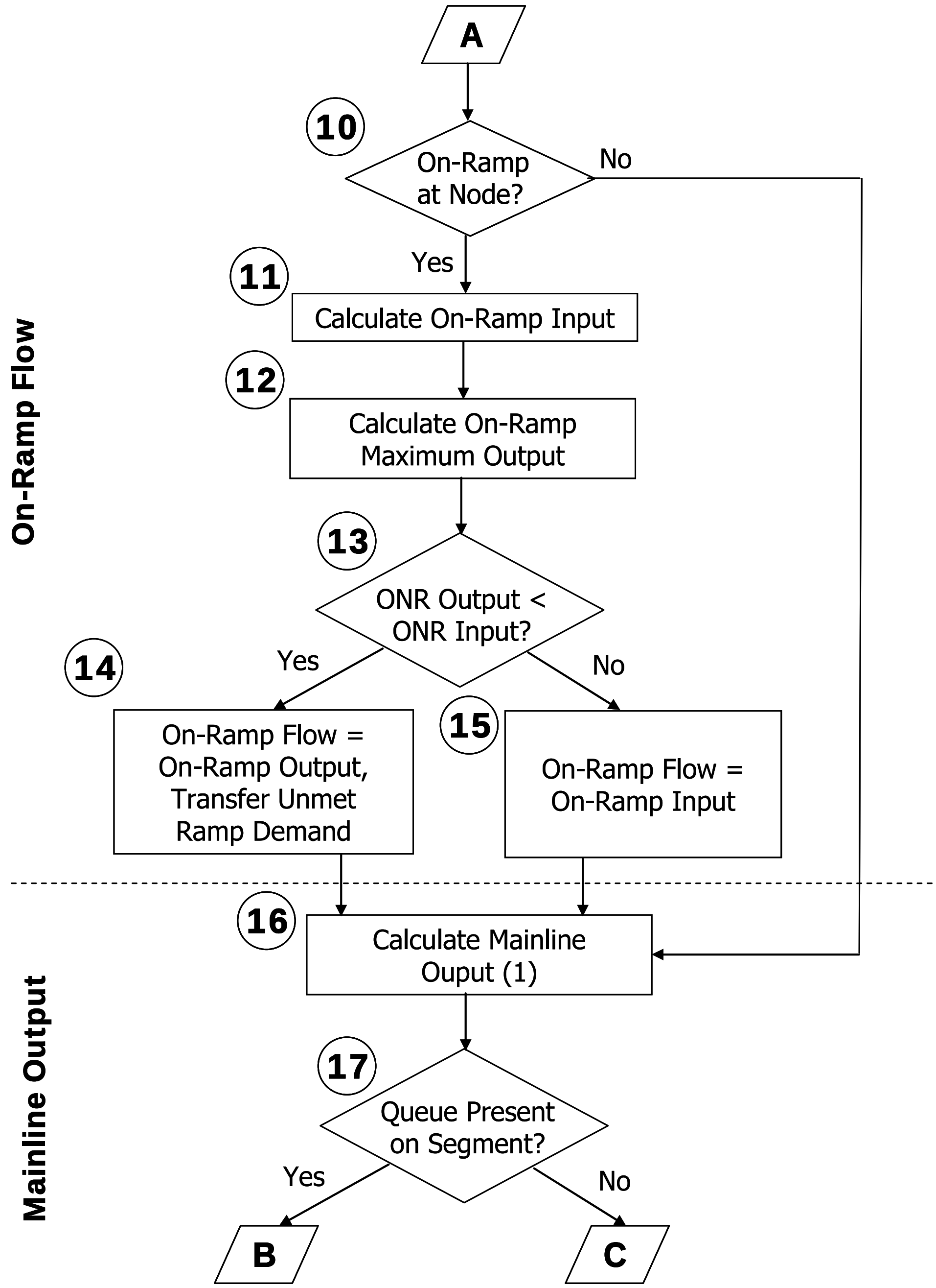


Exhibit 25-6 (cont'd.)
Oversaturated Analysis Procedure

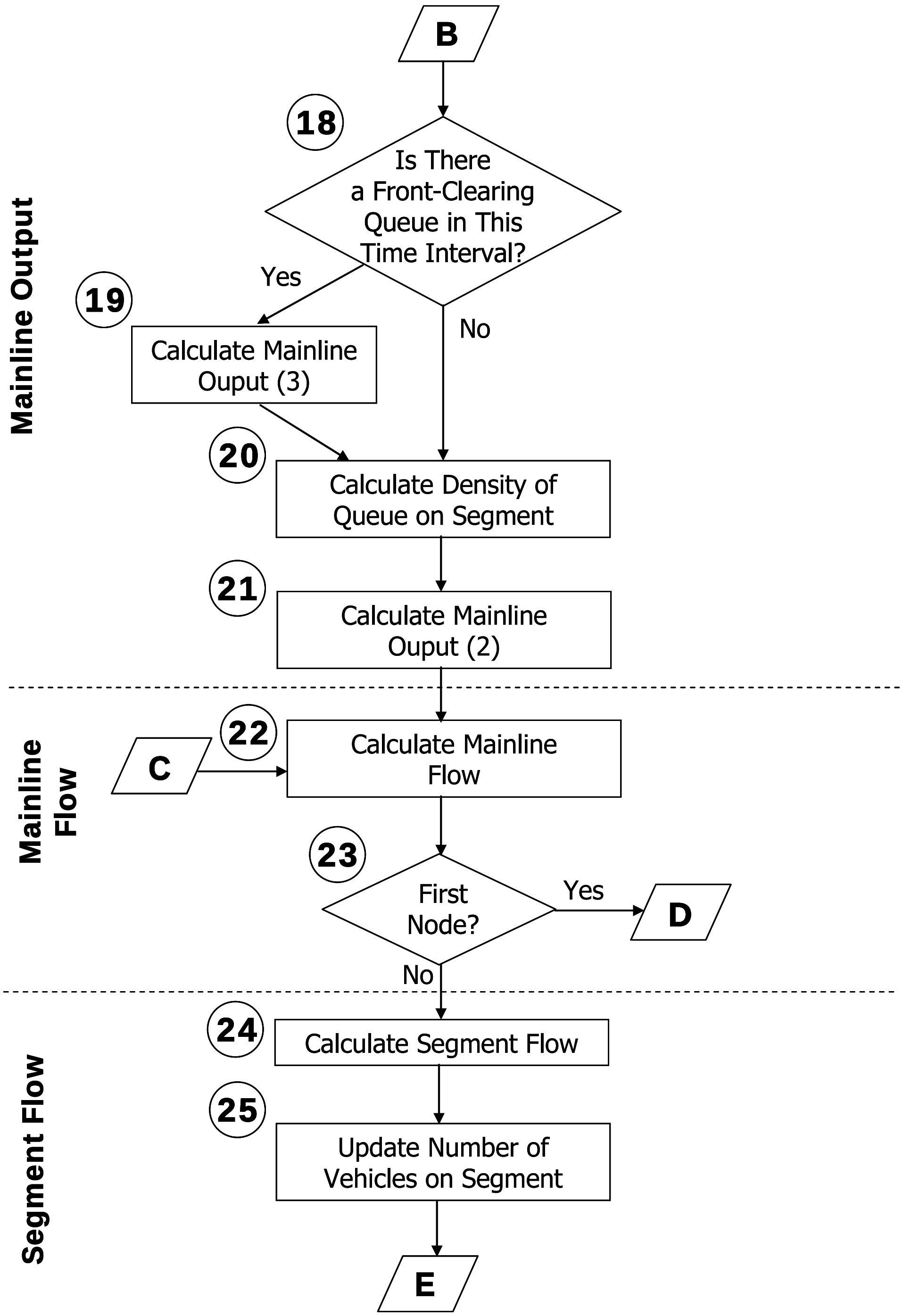
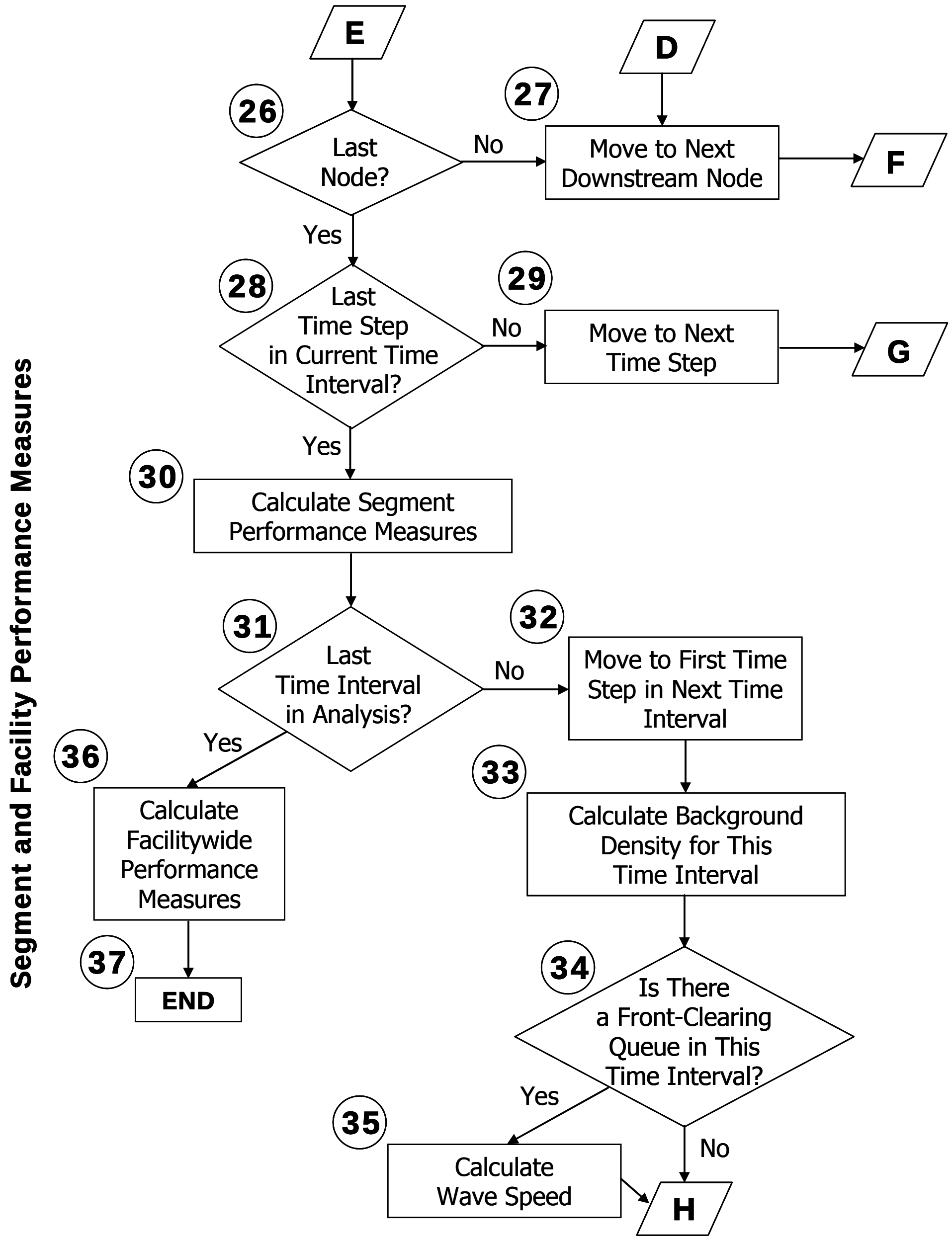


Exhibit 25-6 (cont'd.)
Oversaturated Analysis Procedure



Segment Initialization (Exhibit 25-6, Steps 1–4)

Steps 1 through 4 of the oversaturated procedure prepare the flow calculations for the first time step and specify return points for later time steps. To calculate the number of vehicles on each segment at the various time steps, the segments must contain the proper number of vehicles before the queuing analysis places unserved vehicles on segments. The initialization of each segment is described below. A simplified queuing analysis is initially performed to account for the effects of upstream bottlenecks. These bottlenecks meter traffic downstream of their location. The storage of unserved vehicles (those unable to enter the bottleneck) on upstream segments is performed in a later module. To obtain the proper number of vehicles on each segment, the expected demand *ED* is calculated. *ED* is based on demands for and capacities of the segment and includes the effects of all upstream segments. The expected demand is the flow of traffic expected to arrive at each segment if all queues were stacked vertically (i.e., no upstream effects of queues). In other words, all segments upstream of a bottleneck have expected demands equal to their actual demand. The expected demand of the bottleneck segment and all further downstream segments is calculated by assuming a capacity constraint at the bottleneck, which meters traffic to downstream segments. The expected demand is calculated for each segment with Equation 25-3:

$$ED(i,p) = \min\left[SC(i,p), ED(i-1,p) + ONRD(i,p) - OFRD(i,p)\right]$$

Equation 25-3

The segment capacity *SC* applies to the length of the segment. With the expected demand calculated, the background density *KB* can be obtained for each segment by using the appropriate segment density estimation procedures in Chapters 11, 12, and 13. The background density is used to calculate the number of vehicles *NV* on each segment by using Equation 25-4. If there are unserved vehicles at the end of the preceding time interval, the unserved vehicles *UV* are transferred to the current time interval. Here, *S* refers to the last time step in the preceding time interval. The (0) term in *NV* represents the start of the first time step in time interval *p*. The corresponding term at the end of the time step is *NV*(*i*, 1, *p*).

$$NV(i,0,p) = KB(i,p) \times L(i) + UV(i,S,p-1)$$

Equation 25-4

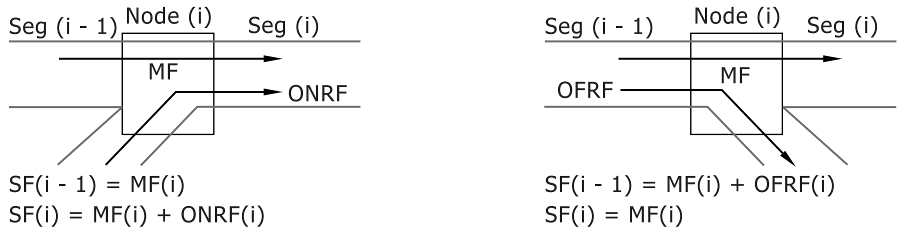
The number of vehicles calculated from the background density is the minimum number of vehicles that can be on the segment at any time. This is a powerful check on the methodology because the existence of queues downstream cannot reduce this minimum. Rather, the segment can only store additional vehicles. The storage of unserved vehicles is determined in the segment flow calculation module later in this chapter.

Mainline Flow Calculations (Exhibit 25-6, Steps 9 and 16–23)

The description of ramp flows follows the description of mainline flows. Thus, Steps 5–8 and 10–15 are skipped at this time to focus first on mainline flow computations. Because of skipping steps in the descriptions, some computations may include variables that have not been described but that have already been calculated in the flowchart.

Flows analyzed in oversaturated conditions are calculated every time step and are expressed in terms of vehicles per time step. The procedure separately analyzes the flow across a node on the basis of the origin and destination of the flow across the node. The mainline flow is defined as the flow passing from upstream segment *i* – 1 to downstream segment *i*. It does not include the on-ramp flow. The flow to an off-ramp is the off-ramp flow. The flow from an on-ramp is the on-ramp flow. Each of these flows is shown in Exhibit 25-7 with the origin, destination, and relationship to segment *i* and node *i*.

Exhibit 25-7
Definitions of Mainline and Segment Flows



The segment flow is the total output of a segment, as shown in Exhibit 25-7. Segment flows are calculated by determining the mainline and ramp flows. The mainline flow is calculated as the minimum of six constraints: mainline input (*MI*), *MO1*, *MO2*, *MO3*, upstream segment $i - 1$ capacity, and downstream segment i capacity, as explained next.

Mainline Input (Exhibit 25-6, Step 9)

MI is the number of vehicles that wish to travel through a node during the time step. The calculation includes (*a*) the effects of bottlenecks upstream of the analysis node, (*b*) the metering of traffic during queue accumulation, and (*c*) the presence of additional traffic during upstream queue discharge.

MI is calculated by taking the number of vehicles entering the node upstream of the analysis node, adding on-ramp flows or subtracting off-ramp flows, and adding the number of unserved vehicles on the upstream segment. This is the maximum number of vehicles that wish to enter a node during a time step. *MI* is calculated by using Equation 25-5, where all values have units of vehicles per time step.

Equation 25-5

$$MI(i,t,p) = MF(i-1,t,p) + ONRF(i-1,t,p) - OFRF(i,t,p) + UV(i-1,t-1,p)$$

Mainline Output (Exhibit 25-6, Steps 16–21)

The mainline output is the maximum number of vehicles that can exit a node, constrained by downstream bottlenecks or by merging on-ramp traffic. Different constraints on the output of a node result in three separate types of mainline outputs (*MO1*, *MO2*, and *MO3*).

Mainline Output 1—Ramp Flows (Exhibit 25-6, Step 16)

MO1 is the constraint caused by the flow of vehicles from an on-ramp. The capacity of an on-ramp segment is shared by two competing flows. This on-ramp flow limits the flow from the mainline through this node. The total flow that can pass the node is estimated as the minimum of the segment i capacity and the mainline outputs from the preceding time step. The sharing of Lane 1 (shoulder lane) capacity is determined in the calculation of the on-ramp. *MO1* is calculated by using Equation 25-6.

Equation 25-6

$$MO1(i,t,p) = \min\begin{Bmatrix} SC(i,t,p) - ONRF(i,t,p) \\ MO2(i,t-1,p) \\ MO3(i,t-1,p) \end{Bmatrix}$$

Mainline Output 2—Segment Storage (Exhibit 25-6, Steps 20 and 21)

The second constraint on the output of mainline flow through a node is caused by the growth of queues on a downstream segment. As a queue grows on a segment, it may eventually limit the flow into the current segment once the boundary of the queue reaches the upstream end of the segment. The boundary of the queue is treated as a shock wave. *MO2* is a limit on the flow exiting a node due to the presence of a queue on the downstream segment.

The *MO2* limitation is determined first by calculating the maximum number of vehicles allowed on a segment at a given queue density. The maximum flow that can enter a queued segment is the number of vehicles that leave the segment plus the difference between the maximum number of vehicles allowed on the segment and the number of vehicles already on the segment. The density of the queue is calculated by using Equation 25-7 for the linear density–flow relationship shown in Exhibit 25-5 earlier.

$$KQ(i,t,p) = KJ - \left[(KJ - KC) \times SF(i,t-1,p)\right] / SC(i,p)$$

Equation 25-7

Once the queue density is computed, *MO2* can be computed by using Equation 25-8.

$$MO2(i,t,p) = SF(i,t-1,p) - ONRF(i,t,p) + \left[KQ(i,t,p) \times L(i)\right] - NV(i,t-1,p)$$

Equation 25-8

Performance of the downstream node is estimated by taking the performance during the preceding time step. This estimation remains valid when there are no interacting queues. When queues do interact and the time steps are small enough, the error in the estimations is corrected in the next time step.

Mainline Output 3—Front-Clearing Queues (Exhibit 25-6, Steps 17–19)

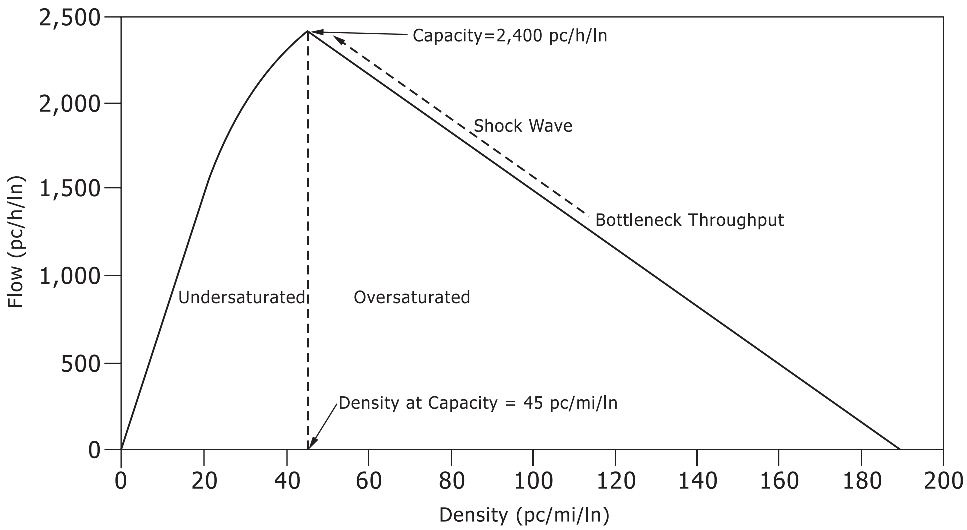
The final constraint on exiting mainline flows at a node is caused by downstream queues clearing from their downstream end. These front-clearing queues are typically caused by incidents in which there is a temporary reduction in capacity. A queue will clear from the front if two conditions are satisfied. First, the segment capacity (minus the on-ramp demand if present) for this time interval must be greater than the segment capacity (minus the ramp demand if present) in the preceding time interval. The second condition is that the segment capacity minus the ramp demand for this time interval be greater than the segment demand for this time interval. A queue will clear from the front if both conditions in the following inequality (Equation 25-9) are met.

$$\text{If } \left[SC(i,p) - ONRD(i,p)\right] > \left[SC(i,p-1) - ONRD(i,p-1)\right]$$
$$\text{and } \left[SC(i,p) - ONRD(i,p)\right] > SD(i,p)$$

Equation 25-9

A segment with a front-clearing queue will have the number of vehicles stored decrease during recovery, while the back of the queue position is unaffected. Thus, the clearing does not affect the segment throughput until the recovery wave has reached the upstream end of the front-clearing queue. The computational engine implementation is simplified by assuming that the downstream segment is fully queued when the *MO3* constraint is applied. In the flow–density graph shown in Exhibit 25-8, the wave speed is estimated by the slope of the dashed line connecting the bottleneck throughput and the segment capacity points.

Exhibit 25-8
Flow–Density Function with a Shock Wave



Note: Assumed *FFS* = 75 mi/h.

The assumption of a linear flow–density function greatly simplifies the calculated wave speed. The bottleneck throughput value is not required to estimate the speed of the shock wave that travels along a known line. All that is required is the slope of the line, which is calculated with Equation 25-10.

Equation 25-10

$$WS(i,p) = SC(i,p) / \left[N(i,p) \times (KJ - KC) \right]$$

The wave speed is used to calculate the time it takes the front queue-clearing shock wave to traverse this segment, called the wave travel time, *WTT*. Dividing the wave speed *WS* by the segment length in miles gives *WTT*.

The recovery wave travel time is the time required for the conditions at the downstream end of the current segment to reach the upstream end of the current segment. To place a limit on the current node, the conditions at the downstream node are observed at a time in the past. This time is the wave travel time. This constraint on the current node is *MO3*. The calculation of *MO3* uses Equation 25-11 and Equation 25-12. If the wave travel time is not an integer number of time steps, then the weighted average performance of each variable is taken for the time steps nearest the wave travel time. This method is based on a process described elsewhere (*5*–*7*).

Equation 25-11

$$WTT = T \times L(i) / WS(i,p)$$

Equation 25-12

$$MO3(i,t,p) = \min \left\{ \begin{array}{l} MO1(i+1, t-WTT, p) \\ MO2(i+1, t-WTT, p) + OFRF(i+1, t-WTT, p) \\ MO3(i+1, t-WTT, p) + OFRF(i+1, t-WTT, p) \\ SC(i, t-WTT, p) \\ SC(i+1, t-WTT, p) + OFRF(i+1, t-WTT, p) \end{array} \right\} - ONRF(i,t,p)$$

Mainline Flow (Exhibit 25-6, Steps 22 and 23)

The flow across a node is called the mainline flow *MF* and is the minimum of the following variables: *MI*, *MO1*, *MO2*, *MO3*, upstream segment $i - 1$ capacity, and downstream segment *i* capacity, as shown in Equation 25-13.

$$MF(i,t,p) = \min \begin{Bmatrix} MI(i,t,p) \\ MO1(i,t,p) \\ MO2(i,t,p) \\ MO3(i,t,p) \\ SC(i,t,p) \\ SC(i-1,t,p) \end{Bmatrix}$$

Equation 25-13

In addition to mainline flows, ramp flows must be analyzed. The presence of mainline queues also affects ramp flows.

On-Ramp Calculations (Exhibit 25-6, Steps 10–15)

On-Ramp Input (Exhibit 25-6, Steps 10 and 11)

The maximum on-ramp input *ONRI* is calculated by adding the on-ramp demand and the number of vehicles queued on the ramp. The queued vehicles are treated as unmet ramp demand that was not served in previous time steps. The on-ramp input is calculated with Equation 25-14.

$$ONRI(i,t,p) = ONRD(i,t,p) + ONRQ(i,t-1,p)$$

Equation 25-14

On-Ramp Output (Exhibit 25-6, Step 12)

The maximum on-ramp output *ONRO* is calculated on the basis of the mainline traffic through the node where the on-ramp is located. The on-ramp output is the minimum of two values. The first is segment *i* capacity minus *MI*, in the absence of downstream queues. Otherwise, the segment capacity is replaced by the throughput of the queue. This estimation implies that vehicles entering an on-ramp segment will fill Lanes 2 to *N* (where *N* is the number of lanes on the current segment) to capacity before entering Lane 1. This assumption is consistent with the estimation of V_{12} from Chapter 13, Freeway Merge and Diverge Segments.

The second case occurs when the Lane 1 flow on segment *i* is greater than one-half of the Lane 1 capacity. At this point, the on-ramp maximum output is set to one-half of Lane 1 capacity. This implies that when the demands from the freeway and the on-ramp are very high, there will be forced merging in a one-to-one fashion on the freeway from the freeway mainline and the on-ramp in Lane 1. An important characteristic of traffic behavior is that, in a forced merging situation, ramp and right-lane freeway vehicles will generally merge one on one, sharing the capacity of the rightmost freeway lane (*8*). In all cases, the on-ramp maximum output is also limited to the physical ramp road capacity and the ramp-metering rate, if present. The maximum on-ramp output is an important limitation on the ramp flow. Queuing occurs when the combined demand from the upstream segment and the on-ramp exceeds the throughput of the ramp segment. The queue can be located on the upstream segment, on the ramp, or on both and depends on the on-ramp maximum output. Equation 25-15 determines the value of the maximum on-ramp output.

Equation 25-15

$$ONRO(i,t,p) = \min \begin{Bmatrix} RM(i,t,p) \\ ONRC(i,t,p) \\ \max \begin{bmatrix} \min \begin{Bmatrix} SC(i,t,p) \\ MF(i+1,t-1,p) + ONRF(i,t-1,p) \\ MO3(i,t-1,p) + ONRF(i,t-1,p) \end{Bmatrix} - MI(i,t,p) \\ \min \begin{Bmatrix} SC(i,t,p) \\ MF(i+1,t-1,p) + ONRF(i,t-1,p) \\ MO3(i,t-1,p) + ONRF(i,t-1,p) \end{Bmatrix} / 2N(i,p) \end{bmatrix} \end{Bmatrix}$$

This model incorporates the maximum mainline output constraints from downstream queues, not just the segment capacity. This fact is significant because as a queue spills over an on-ramp segment, the flow through Lane 1 is constrained. This, in turn, limits the flow that can enter Lane 1 from the on-ramp. The values of *MO2* and *MO3* for this time step are not yet known, so they are estimated from the preceding time step. This estimation is one rationale for using small time steps. If there is forced merging during the time step when the queue spills back over the current node, the on-ramp will discharge more than its share of vehicles (i.e., more than 50% of the Lane 1 flow). This situation will cause the mainline flow past node *i* to be underestimated. But during the next time step, the on-ramp flow will be at its correct flow rate, and a one-to-one sharing of Lane 1 will occur.

On-Ramp Flows, Queues, and Delays (Exhibit 25-6, Steps 13–15)

Finally, the on-ramp flow is calculated on the basis of the on-ramp input and output values computed above. If the on-ramp input is less than the on-ramp output, then the on-ramp demand can be fully served in this time step and Equation 25-16 is used.

Equation 25-16

$$ONRF(i,t,p) = ONRI(i,t,p)$$

Otherwise, the ramp flow is constrained by the maximum on-ramp output, and Equation 25-17 is used.

Equation 25-17

$$ONRF(i,t,p) = ONRO(i,t,p)$$

In the latter case, the number of vehicles in the ramp queue is updated by using Equation 25-18.

Equation 25-18

$$ONRQ(i,t,p) = ONRQ(i,t-1,p) + ONRI(i,t,p) - ONRO(i,t,p)$$

The total delay for on-ramp vehicles can be estimated by integrating the value of on-ramp queues over time. The methodology uses the discrete queue lengths estimated at the end of each interval, $ONRQ(i, S, p)$, to produce overall ramp delays by time interval.

Off-Ramp Flow Calculation (Exhibit 25-6, Steps 5–8)

The off-ramp flow is determined by calculating a diverge percentage on the basis of the segment and off-ramp demands. The diverge percentage varies only by time interval and remains constant for vehicles that are associated with a particular time interval. If there is an upstream queue, traffic may be metered to this off-ramp, which will cause a decrease in the off-ramp flow. When the vehicles that were metered arrive in the next time interval, they use the diverge percentage associated with the preceding time interval. A deficit in flow, caused by traffic from an upstream queue meter, creates delays for vehicles destined to this off-ramp and other downstream destinations. The upstream segment flow is used because the procedure assumes that a vehicle destined for an off-ramp is able to exit at the off-ramp once it enters the off-ramp segment. This deficit is calculated with Equation 25-19.

$$DEF(i,t,p) = \max\left\{\begin{matrix} 0 \\ \left\{\begin{matrix} \sum_{X=1}^{p-1} SD(i-1,X) - \sum_{X=1}^{p-1}\sum_{t=1}^{T}\left[MF(i-1,t,X) + ONRF(i-1,t,X)\right] \\ + \sum_{t=1}^{t-1}\left[MF(i-1,t,p) + ONRF(i-1,t,p)\right] \end{matrix}\right\} \end{matrix}\right\}$$

Equation 25-19

If there is a deficit, then the off-ramp flow is calculated by using the deficit method. The deficit method is used differently in two different situations. If the upstream mainline flow plus the flow from an on-ramp at the upstream node (if present) is less than the deficit for this time step, then the off-ramp flow is equal to the mainline and on-ramp flows times the off-ramp turning percentage in the preceding time interval, as indicated in Equation 25-20.

$$OFRF(i,t,p) = \left[MF(i-1,t,p) + ONRF(i-1,t,p)\right] \times \left[OFRD(i,p-1)/SD(i-1,p-1)\right]$$

Equation 25-20

However, if the deficit is less than the upstream mainline flow plus the on-ramp flow from an on-ramp at the upstream node (if present), then Equation 25-21 is used. This equation separates the flow into the remaining deficit flow and the balance of the arriving flow.

$$\begin{aligned} OFRF(i,t,p) = {} & DEF(i,t,p) \times \left[OFRD(i,p-1)/SD(i-1,p-1)\right] + \\ & \left[MF(i-1,t,p) + ONRF(i-1,t,p) - DEF(i,t,p)\right] \times \\ & \left[OFRD(i,p)/SD(i-1,p)\right] \end{aligned}$$

Equation 25-21

If there is no deficit, then the off-ramp flow is equal to the sum of upstream mainline flow plus the on-ramp flow from an on-ramp at the upstream node (if present) multiplied by the off-ramp turning percentage for this time interval according to Equation 25-22.

$$OFRF(i,t,p) = \left[MF(i-1,t,p) + ONRF(i-1,t,p)\right] \times \left[OFRD(i,p)/SD(i-1,p)\right]$$

Equation 25-22

The procedure does not incorporate any delay or queue length computations for off-ramps.

Segment Flow Calculation (Exhibit 25-6, Steps 24 and 25)

The segment flow is the number of vehicles that flow out of a segment during the current time step. These vehicles enter the current segment either to the mainline or to an off-ramp at the current node. The vehicles that entered the upstream segment may or may not have become queued within the segment. The segment flow is calculated with Equation 25-23.

Equation 25-23

$$SF(i-1,t,p) = MF(i,t,p) + OFRF(i,t,p)$$

The number of vehicles on each segment is calculated on the basis of the number of vehicles that were on the segment in the preceding time step, the number of vehicles that entered the segment in this time step, and the number of vehicles that leave the segment in this time step. Because the number of vehicles that leave a segment must be known, the number of vehicles on the current segment cannot be determined until the upstream segment is analyzed. The number of vehicles on each segment is calculated with Equation 25-24.

Equation 25-24

$$NV(i-1,t,p) = NV(i-1,t-1,p) + MF(i-1,t,p) + ONRF(i-1,t,p) - MF(i,t,p) - OFRF(i,t,p)$$

The number of unserved vehicles stored on a segment is calculated as the difference between the number of vehicles on the segment and the number of vehicles that would be on the segment at the background density. The number of unserved vehicles stored on a segment is calculated with Equation 25-25.

Equation 25-25

$$UV(i-1,t,p) = NV(i-1,t,p) - \left[KB(i-1,p) \times L(i-1)\right]$$

SEGMENT AND RAMP PERFORMANCE MEASURES

In the last time step of a time interval, the segment flows are averaged over the time interval, and the performance measures for each segment are calculated. If there was no queue on a particular segment during the entire time interval, then the performance measures are calculated from the corresponding Chapter 11, 12, or 13 method for that segment. Since there are T time steps in an hour, the average segment flow rate in vehicles per hour in time interval p is calculated by using Equation 25-26.

Equation 25-26

$$SF(i,p) = \frac{T}{S}\sum_{t=1}^{S} SF(i,t,p)$$

If $T = 60$ (1-min time step) and $S = 15$ (interval = 15 min), then $T/S = 4$. If there was a queue on the current segment in any time step during the time interval, then the segment performance measures are calculated in three steps. First, the average number of vehicles over a time interval is calculated for each segment by using Equation 25-27.

Equation 25-27

$$NV(i,p) = \frac{1}{S}\sum_{t=1}^{S} NV(i,t,p)$$

Next, the average segment density is calculated by taking the average number of vehicles NV for all time steps in the time interval and dividing it by the segment length (see Equation 25-28).

$$K(i,p)=\frac{NV(i,p)}{L(i)}$$

Equation 25-28

Next, the average speed on the current segment *i* during the current time interval *p* is calculated with Equation 25-29.

$$U(i,p)=\frac{SF(i,p)}{K(i,p)}$$

Equation 25-29

Additional segment performance measures can be derived from the basic measures shown in Equation 25-26 through Equation 25-29. Most prominent is segment delay, which can be computed as the difference in segment travel time at speed $U(i, p)$ and at the segment free-flow speed.

The final segment performance measure is the length of the queue at the end of the time interval (i.e., Step *S* in time interval *p*). The length of a queue on the segment, in feet, is calculated with Equation 25-30.

Equation 25-30

$$Q(i,p)=\frac{UV(i,S,p)}{KQ(i,S,p)-KB(i,p)}\times 5{,}280$$

Queue length on on-ramps can also be calculated. A queue will form on the on-ramp roadway only if the flow is limited by a metering rate or by the merge area capacity. If the flow is limited by the ramp capacity, then unserved vehicles will be stored upstream of the ramp roadway, most likely a surface street. The methodology does not account for this delay, since vehicles cannot enter the ramp roadway. However, the unserved vehicles in this case are transferred as added demand in subsequent time intervals. If the queue is on the ramp roadway, the queue length is calculated by using the difference in background density and queue density. For an on-ramp, the background density is assumed to be the density at capacity and the queue density is calculated with Equation 25-31. For on-ramp queue length, Equation 25-31 is used.

$$ONRQL(i,S,p)=\frac{ONRQ(i,S,p)}{KJ-\dfrac{\min\left\{RM(i,p),ONRO(i,S,p)\times(KJ-KC)\right\}}{ONRC(i,p)}}$$

Equation 25-31

6. DIRECTIONAL FACILITY MODULE

The previously discussed traffic performance measures can be aggregated over the length of the directional freeway facility, over the time duration of the study interval, or over the entire time–space domain. Each is discussed in the following paragraphs.

Aggregating the estimated traffic performance measures over the entire length of the freeway facility provides facilitywide estimates for each time interval. Facilitywide travel times, vehicle distance of travel, and vehicle hours of travel and delay can be computed, and patterns of their variation over the connected time intervals can be assessed. The FREEVAL-2010 computational engine is limited to 15-min time intervals and 1-min time steps.

Aggregating the estimated traffic performance measures over the time duration of the study interval provides an assessment of the performance of each segment along the freeway facility. Average and cumulative distributions of speed and density for each segment can be determined, and patterns of the variation over connected freeway segments can be compared. Average trip times, vehicle distance of travel, and vehicle hours of travel are easily assessed for each segment and compared.

Aggregating the estimated traffic performance measures over the entire time–space domain provides an overall assessment over the study interval time duration. Overall average speeds, average trip times, total vehicle distance traveled, and total vehicle hours of travel and delay are the most obvious overall traffic performance measures. Equation 25-32 through Equation 25-35 show how the facilitywide performance measures are calculated.

Facility space mean speed in time interval p:

Equation 25-32

$$SMS(NS,p)=\frac{\sum_{i=1}^{NS} SF(i,p)\times L(i)}{\sum_{i=1}^{NS} SF(i,p)\times \frac{L(i)}{U(i,p)}}$$

Average facility density in time interval p:

Equation 25-33

$$K(NS,p)=\frac{\sum_{i=1}^{NS} K(i,p)\times L(i)}{\sum_{i=1}^{NS} L(i)N(i,p)}$$

Overall space mean speed across all intervals:

Equation 25-34

$$SMS(NS,P)=\frac{\sum_{p=1}^{P}\sum_{i=1}^{NS} SF(i,p)L(i)}{\sum_{p=1}^{P}\sum_{i=1}^{NS} SF(i,p)\frac{L(i)}{U(i,p)}}$$

Overall average density across all intervals:

$$K(NS,P)=\frac{\sum_{p=1}^{P}\sum_{i=1}^{NS}K(i,p)\times L(i)}{\sum_{p=1}^{P}\sum_{i=1}^{NS}L(i)N(i,p)}$$

Equation 25-35

These performance measures can be compared for different alternatives to assess the impacts of different volume scenarios or the effects of geometric improvements to the facility.

7. COMPUTATIONAL ENGINE DOCUMENTATION

This section focuses on how the freeway facilities methodology is implemented in the FREEVAL computational engine. It presents the layout of the engine in the form of flowcharts and linkage lists.

FLOWCHARTS

The methodology flowchart is shown above in Exhibit 25-1. A detailed overview of the oversaturated calculation procedure is presented in Exhibit 25-6. In the FREEVAL computational engine implementation, the methodology consists of seven modules:

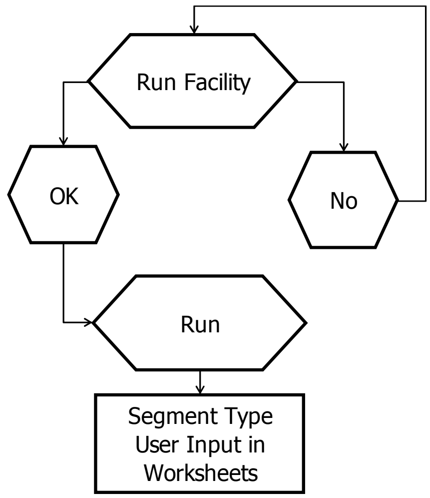
- Opening Dialog Module (Exhibit 25-9)
- Input Formatting Module (Exhibit 25-10)
- Input Revision Module
- Weaving Calculator Input Module (Exhibit 25-11)
- Main Analysis Module (Exhibit 25-12)
- MOE Calculation Module (Exhibit 25-13)
- Supplemental Calculation Module

This subsection provides a separate flowchart for each of these modules, except for the Input Revision and the Supplemental Calculation Modules. The Input Revision Module allows the analyst to revise input data after completing an analysis. Its functionality is thus similar to the Input Formatting Module in terms of reformatting the input–output screens in FREEVAL and then taking the user back to the beginning of the procedure. The Supplemental Calculation Module contains procedures that were removed from the Main Analysis Module because it exceeded coding limits of the programming language. The two modules are therefore discussed concurrently.

The FREEVAL computational engine is composed of a series of worksheets that contain the input and output data for however many time periods the user specifies. Data entry occurs in the actual worksheets as well as in some separate input dialog boxes. The following discussion focuses on the use of computational modules and references the graphical user interface of the engine only when absolutely necessary.

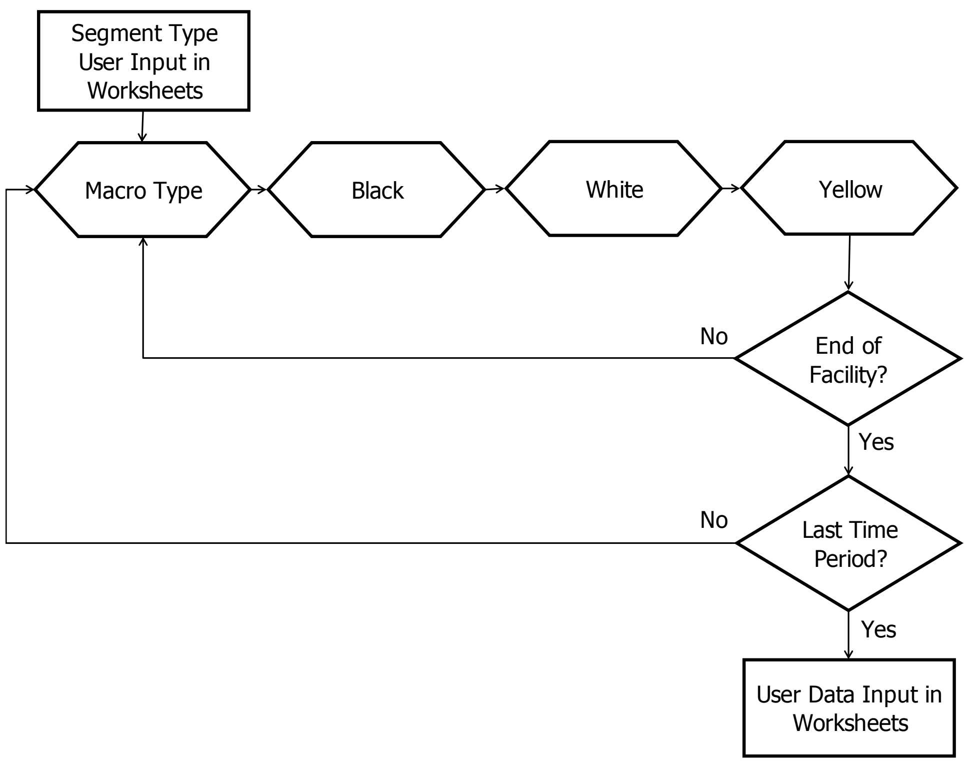
The FREEVAL engine starts with the *Opening Dialog Module* (Exhibit 25-9), which prompts the user to enter some basic information about the facility. The most critical inputs are the number of segments and time periods to be included in the analysis. Upon entering that information and hitting the "Run" button, the user is taken to the first input worksheet, where the facility can be defined in more detail.

Exhibit 25-9
Opening Dialog Module Flowchart



After the user finishes entering all segment types, the "Segment Types Entered" selection button opens the *Input Formatting Module* (Exhibit 25-10). This module serves to make data entry more user-friendly by automatically highlighting required input fields and blacking out unnecessary fields for a specific segment type. The module automatically cycles through all segments and all time periods in the analysis domain.

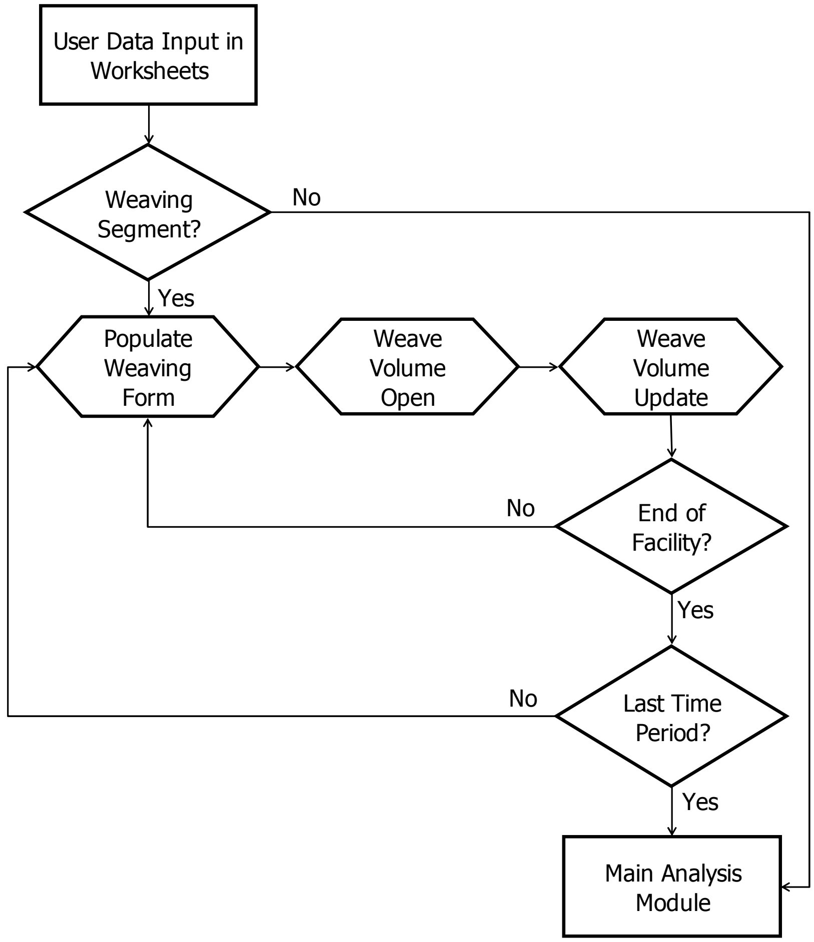
Exhibit 25-10
Input Formatting Module Flowchart



After the input worksheets have been formatted for user input, the analyst enters all necessary input data as discussed in Chapter 10, Freeway Facilities. The input data vary by segment type and are consistent with input requirements in the segment-specific Chapters 11, 12, and 13.

Most input data are entered directly in the input worksheets. The user can further pull up applicable HCM exhibits to obtain heavy-vehicle adjustment factors. They are described more closely in the linkage list section below. Since the input requirements for weaving segments are more complex, an additional input dialog is used for data specific to Chapter 12. The module responsible for the weaving input data is the *Weaving Calculator Input Module* (Exhibit 25-11).

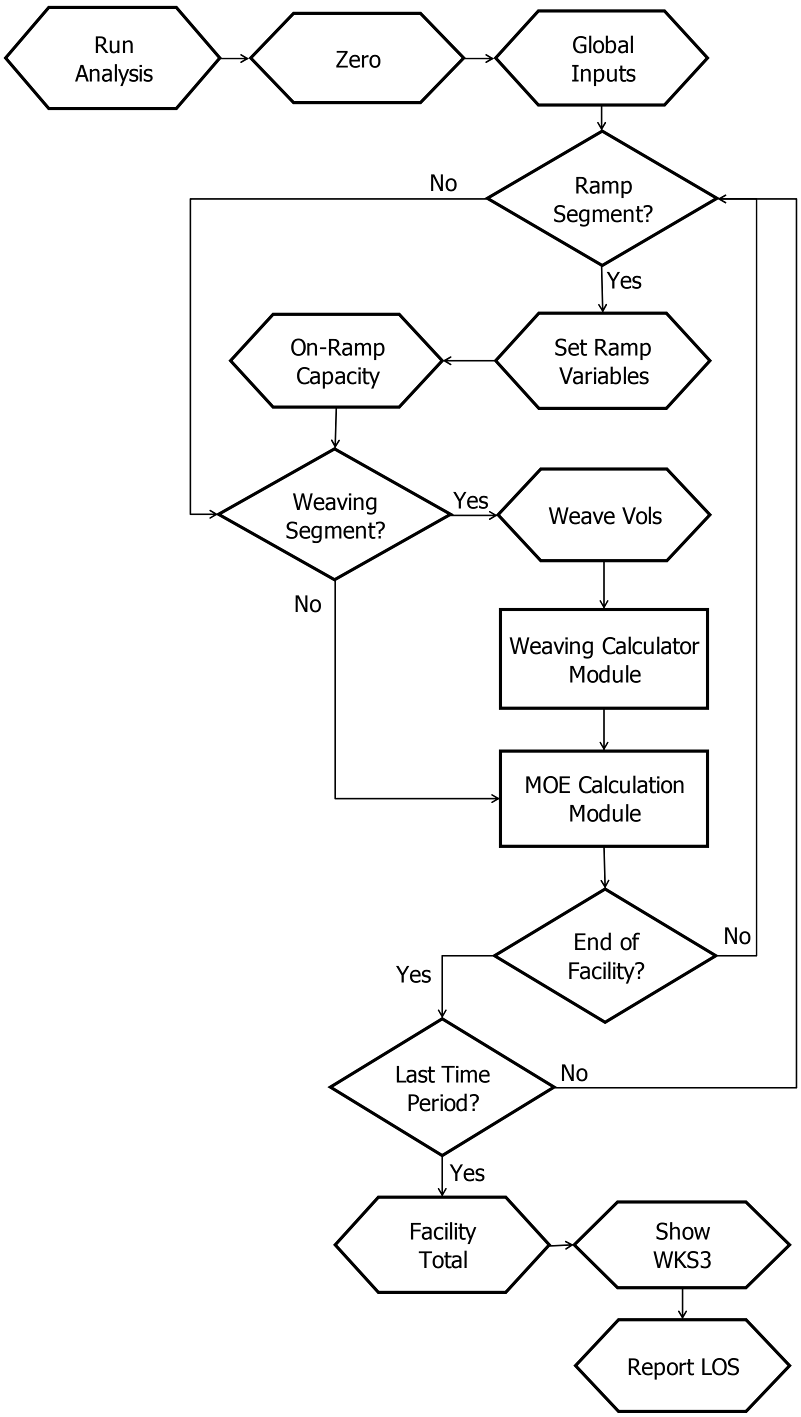
Exhibit 25-11
Weaving Calculator Input Module Flowchart



The module shown in Exhibit 25-11 opens the weaving input for any segments that were coded as a weaving segment and for each time period. The weaving calculator handles all input specific to Chapter 12, including geometry of the weaving segment and volume patterns. The user is required to enter data for each weaving segment and each time period, although geometric data are required only for the first time interval for each weaving segment.

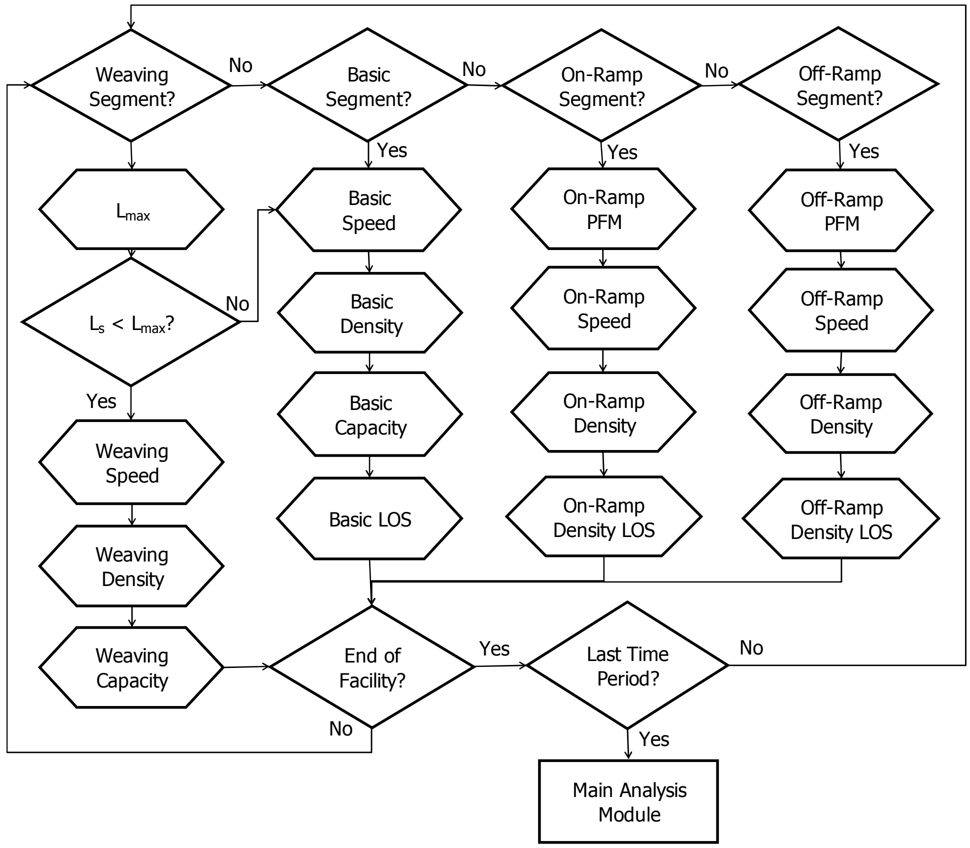
After data entry for all weaving segments has been completed, the *Main Analysis Module* (Exhibit 25-12) is executed. The module follows the Chapter 10 methodology presented in Exhibit 25-1 and contains all computations for undersaturated and oversaturated conditions. The latter contain the oversaturated computation procedure presented in Exhibit 25-6 as well as all queuing and shock-wave calculations discussed in this chapter.

Exhibit 25-12
Main Analysis Module Flowchart



The Main Analysis Module uses the procedure in Exhibit 25-6 for all oversaturated segments and time periods. For undersaturated segments and time periods, the freeway facilities procedure uses the procedure for the different segment types as described in Chapters 11, 12, and 13. The MOEs for these undersaturated procedures are computed by using the *MOE Calculation Module* shown in Exhibit 25-13.

Exhibit 25-13
MOE Calculation Module Flowchart



The individual subroutines contained in the flowcharts shown in Exhibit 25-9 through Exhibit 25-13 are described more closely in the linkage lists below.

The FREEVAL computational engine further contains a series of formatted output worksheets, MOE summary tables, and graphics that are not described in more detail here. For further discussion, the reader is referred to the FREEVAL user guide contained in the Technical Reference Library in Volume 4.

LINKAGE LISTS

This subsection uses linkage lists to describe the main routines that compose the FREEVAL-2010 computational engine. Each table represents one computational module and the subroutines contained within. It further describes conditions for use of each subroutine. The different linkage lists are consistent with the module flowcharts described in the previous section. In particular, the tables describe the following modules:

- Opening Dialog Module (Exhibit 25-14)
- Input Formatting Module (Exhibit 25-15)
- Input Revision Module (Exhibit 25-16)
- Weaving Calculator Input Module (Exhibit 25-17)
- Main Analysis Module (Exhibit 25-18)
- Supplemental Calculation Module (Exhibit 25-19)
- MOE Calculation Module (Exhibit 25-20)

Exhibit 25-14
Opening Dialog Module Routines

Routine	Subroutine	Condition for Use
Run_Facility	Opens an initial dialog box to collect general problem parameters (number of segments, time periods, terrain, etc.).	—
OK	Closes input dialog and opens a verification dialog box before running problem.	—
No	If user clicks "No" in the verification dialog box, the intro page is shown without running the analysis.	—
Run	Collects information from the general dialog box and customizes the spreadsheet by deleting unneeded time periods and segments. Creates output graphs.	Need to have completed initial general dialog box.

Exhibit 25-15
Input Formatting Module Routines

Routine	Subroutine	Condition for Use
Macro Type	Once user inputs segment types, the button that is pressed runs this macro, which customizes the input requirements for each segment, depending on the segment type.	Segment types must be input for each segment (TP1 only).
Black	Makes a cell black if an input variable is not needed for the segment type.	—
White	Makes a cell white if an input variable is needed for the segment type.	—
Yellow	Makes a cell yellow if an input variable is needed for the segment type and default values are not provided.	—

Exhibit 25-16
Input Revision Module Routines

Routine	Subroutine	Condition for Use
Macro 1116	Shows a table with truck equivalencies for various terrain conditions when a button is clicked by the user.	—
Macro 1117	Shows a table with recreational vehicle equivalencies for various terrain conditions when a button is clicked by the user.	—
Input data	Unhides input worksheets once information is entered into the revised input dialog box.	Any revisions to input data (ramp metering, free-flow speed, jam density).
Kj	Opens dialog box when the "Revise Input Data" button is pressed.	—

Exhibit 25-17
Weaving Calculator Input Module Routines

Routine	Subroutine	Condition for Use
Populate Weaving Form	Opens the weaving segment dialog box and enters values from input data for information or defaults.	Input data such as volumes, length, and percent trucks and recreational vehicles. Defaults for weaving parameters.
Weave Vol Open	Makes initial calculations when the volume dialog box is opened.	—
Weave Vol Update	Updates the weaving segment dialog box when a variable is changed.	Calculates other variables based on the variable that has been changed.
Round	Rounds a value to nearest integer.	—

Exhibit 25-18
Main Analysis Module Routines

Routine	Subroutine	Condition for Use
Run Analysis	Runs the analysis, for both under- and oversaturated conditions.	See the methodology flowchart, Exhibit 25-1.
Facility Total	Displays facility total performance measures in the facility total column	Uses internal variables calculated in Run Analysis.
Show WKS3	Shows Worksheet 3, which is the average result for each segment over every time period.	—
Zero	Zeros out some internal variables between time periods.	—
Report LOS	Calculates level of service.	Segment type and density.
Global Inputs	Collects global variables from the introduction dialog box for the methodology.	—
Set Ramp Variables	Used to determine nearest adjacent ramp for ramp analysis.	—
OnRamp Capacity	Calculates capacity of an on-ramp.	On-ramp speed and number of lanes.
Weave Vols	Takes outputs from the weaving form and assigns values to methodology parameters.	—

Exhibit 25-19
Supplemental Calculation Module Routines

Routine	Subroutine	Condition for Use
Number Vehicles	Subroutine pulled out of methodology to compute number of vehicles on a segment.	—
Mainline Flow	Subroutine pulled out of methodology to compute mainline flow for a node.	—

Exhibit 25-20
MOE Calculation Module Routines

Routine	Subroutine	Condition for Use
Basic Speed	Calculates the speed of a basic freeway segment.	See Chapter 11.
Round FFS	Rounds the free-flow speed to nearest 5 mi/h.	—
Basic Density	Calculates the density of a basic segment.	See Chapter 11.
Basic Capacity	Calculates the capacity of a basic segment.	See Chapter 11.
OnRamp Density	Calculates the density of an on-ramp segment.	See Chapter 13.
OnRamp Density LOS	Calculates the density of the ramp influence area for an on-ramp segment.	See Chapter 13.
OnRamp pfm	Calculates P_{fm} for an on-ramp segment.	See Chapter 13.
OnRamp Speed	Calculates the speed of an on-ramp segment.	See Chapter 13.
OFRPfd	Calculates P_{fd} for an off-ramp segment.	See Chapter 13.
OffRamp Density	Calculates the density of an off-ramp segment.	See Chapter 13.
OffRamp Density LOS	Calculates the density of the ramp influence area for an off-ramp segment.	See Chapter 13.
OffRamp Speed	Calculates the speed of an off-ramp segment.	See Chapter 13.
Weaving Speed	Calculates the speed of a weaving segment.	See Chapter 12.
Lmax	Calculates the maximum length of a weaving segment.	See Chapter 12.
Weaving Density	Calculates the density of a weaving segment.	See Chapter 12.
Weaving Capacity	Calculates the capacity of a weaving segment.	See Chapter 12.
LN	Calculates a natural log.	—
Heavy Vehicle	Calculated f_{hv}.	–
Lane Width Reduction	Calculates free-flow speed reduction based on lane width.	See Chapter 11.
LatClear Reduction	Calculates free-flow speed reduction based on lateral clearance.	See Chapter 11.
BasicLOS	Calculates LOS for basic freeway segments.	See Chapter 11.

8. REFERENCES

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