NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Comparison of the 1994 *Highway Capacity Manual's* Ramp Analysis Procedures and the FRESIM Model

Transportation Research Board
National Research Council

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Comparison of the 1994 *Highway Capacity Manual's* Ramp Analysis Procedures and the FRESIM Model

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Staff
Transportation Research Board

This report describes the results of comparing two methods for analyzing the operation of ramp-freeway junctions. The contents of the report are of interest to practitioners who use the *Highway Capacity Manual* or FRESIM to analyze freeways. Both of these methods were used to analyze an independent database, with the analysis results compared to the actual field measurements.

NCHRP Project 3-37, *Capacity and Level of Service at Ramp-Freeway Junctions*, was completed in December 1993 and produced a new method for analyzing ramp-freeway junctions. This method was included in Chapter 5 of the 1994 Update of the *Highway Capacity Manual*. As of November 1996, over 11,000 copies of the 1994 Update of the *Highway Capacity Manual* have been distributed. This is an indication of the potential use of this method.

An alternative analysis method is the use of microscopic simulation, of which the most popular model for freeways is FRESIM. FRESIM is sponsored and supported by the Federal Highway Administration. It models each individual vehicle in the freeway section on a second-by-second basis using car-following and lane-changing algorithms.

An analyst contemplating a freeway analysis must decide on an analysis method. Typically, a simulation approach will require more data and effort which, it is hoped, will result in more accurate answers. Knowledge of the strengths and weaknesses of each method is needed to decide whether the additional effort will be worthwhile.

The Transportation Research Board's Committee on Highway Capacity and Quality of Service is responsible for the contents of the *Highway Capacity Manual*. There have been numerous discussions within the Committee over the past few years on the relationship between the *Highway Capacity Manual* and simulation models.

This research effort was a follow-up to NCHRP Project 3-37 and attempted to answer some of the questions posed by users and the Committee. It used both methods to analyze data collected in the field, but not used in the development of either method. This testing was used to identify and investigate (1) common ranges of application, as well as ranges where one or the other model might be inappropriate for use; (2) consistency of internal logic used in each model; (3) consistency of results when models are properly applied to the same case; (4) comparative sensitivities of the models to key input variables; and (5) potential modifications to models, which would improve the consistency of results where both models are properly applied.

Weaknesses were identified in both analysis methods. FRESIM appears to produce reasonable systemwide results but the analysis of a small point appears less reasonable. The 1994 *Highway Capacity Manual* method, like many regression-based models, only reflects the conditions at the field sites used to develop the model, and the inconsistency between equations makes it difficult to understand how the driver responds to the traffic and roadway conditions. This research report provides practitioners a better understanding of both methods, helping them to effectively analyze the operation of a freeway.

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CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROJECT DESCRIPTION AND OBJECTIVES

Over the last 10 years, the 1985 *Highway Capacity Manual* (85HCM) (*1*) underwent a series of significant revisions resulting from major research projects under the sponsorship of the National Cooperative Highway Research Program (NCHRP) and the Federal Highway Administration (FHWA). The outcomes of these efforts are presented in seven new chapters of the revised *Highway Capacity Manual* published in December 1994 (94HCM) (*2*).

The 94HCM describes the methodologies and provides the necessary procedures for calculating capacities and levels of service for interrupted and uninterrupted flow facilities. The procedures are widely used and consistently yield valid results acceptable to both practitioners and researchers alike.

As a participant in the NCHRP-sponsored research (Project 3-37: Capacity and Level of Service at Ramp-Freeway Junctions), the Transportation Training and Research Center at Polytechnic University undertook a major data collection effort at over 60 ramp-freeway junction sites throughout the continental United States. The project resulted in the formulation of new regression-based models for the prediction of capacity and operating conditions in the vicinity of ramp-freeway junctions. It also resulted in a new Chapter 5 of the 1994 *Highway Capacity Manual.*

In mid 1994, the FHWA developed its latest freeway simulator, FRESIM (FREeway SIMulator), which was released for general use through the McTrans Center. The simulator is capable of generating operational descriptions of ramp-merge and ramp-diverge areas. Although the 94HCM models for ramp-junctions are based on an extensive database, gaps do exist, particularly for 8-lane freeways. A calibrated microscopic model, such as the FRESIM program, can be used to fill the gaps in the database and help fine-tune the models. It is the general objective of this research to identify and investigate

- common ranges of application, as well as ranges where one or the other model might be inappropriate for use,
- consistency of internal logic used in each model,
- consistency of results when models are properly applied to the same case,
- comparative sensitivities of the models to key input variables, and
- potential modifications to models which would improve the consistency of results where both models are properly applied.

HISTORICAL BACKGROUND OF FRESIM

FRESIM is the successor to FHWA's freeway simulation program (INTRAS), developed in the late 1970s to assess the effectiveness of freeway control and management strategies. The FRESIM program has been extensively enhanced, tested and validated (*3,4*). In addition to successfully being used in various research work (*5,6*), it has been used to evaluate the operation of major freeway weaving sections (*7*) and freeway reconstruction alternatives (*8*).

FRESIM is part of FHWA's TRAF group of traffic simulation programs, and was developed by JFT Associates in 1990 at the request of FHWA. It is a microscopic, stochastic, time-interval-stepping simulation program that models individual vehicle movements based on an individual driver's decision/action relative to other vehicles and freeway geometrics.

To a large extent, the extensive computing power requirement, the high cost of operation on a mainframe, and the complex input format of the INTRAS program limited its use by researchers and professionals. FRESIM, unlike its predecessor, was developed with the microcomputer in mind. In addition, the rapidly advancing technology of microcomputers, with large computing power and increasingly faster processing speed, has made FRESIM a more attractive tool for evaluating freeway improvement alternatives, highway design alternatives, and innovative traffic engineering strategies for alleviating traffic congestion.

CHARACTERISTICS OF THE FRESIM MODEL

Microscopic simulation models, such as FRESIM, model traffic in an explicit manner, treating each vehicle as an entity based on car-following and lane-changing logic. Individual vehicle attributes are selected from an embedded vehicle operational characteristics table.

FRESIM uses several mathematically sophisticated algorithms which model complex behavior such as car-following, lane-changing, and crash avoidance maneuvers, as well as origin-destination assignment. To help illustrate the logic of FRESIM, consider the interaction between two vehicles on a freeway as depicted in Figure 1-1.

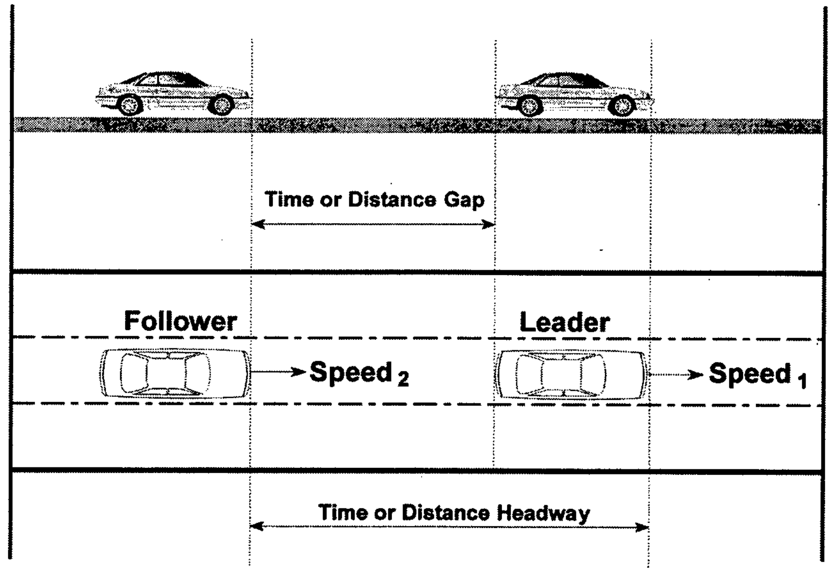


Figure 1-1. Typical vehicle interaction on a freeway.

Vehicle Movement Logic

In the FRESIM model, each vehicle in each time increment of the simulator clock is assigned one of the following characteristics:

- a follower (i.e., a vehicle following another vehicle) or
- a leader (i.e., a vehicle with no leader).

Furthermore, each vehicle is categorized as being in one of five possible motion states:

- In motion,
- Moving in a queue,
- Stopped,
- Stopped behind a metering signal, or
- Moving through a metering signal.

Behavior of a Follower Vehicle

The car-following law assumes that a follower vehicle will maintain a safe gap between itself and its leader. The gap is given by Equation 1 of the PITT Car-Following Model as presented in Appendix A. When the gap is insufficient to maintain a "time-space safety cushion" to avoid a collision, the vehicle will decelerate in order to maintain a safe distance. At any given time interval, the acceleration of the follower vehicle is determined by the behavior of the "leader" vehicle and the downstream upcoming geometric conditions. This acceleration is compared against the vehicle's performance capabilities and adjusted if necessary. In order to avoid a collision, an emergency constraint overrides the car-following acceleration, thereby maintaining a safety cushion.

Behavior of a Leader Vehicle

The behavior of a leader vehicle is dependent on the upcoming geometric characteristics (e.g., grade, curvature, lane-add/drop, etc.). Upcoming geometrics over a distance of 500 ft are scanned and each vehicle's behavior is determined in response to the geometrics. Different states are assigned to each vehicle as follows:

Vehicle Is Approaching a Lane Drop. When approaching a lane drop, the lead vehicle car-follows an assumed stopped vehicle which represents the location of the lane drop. Similar to the car-following logic, the required deceleration is measured against the deceleration from the kinematic law for stopping the vehicle at the point the lane is dropped. The maximum of the two decelerations is assigned to the vehicle. If a determination is made that the vehicle does not have to decelerate in the current time step, then the computed acceleration is subjected to the vehicle's performance parameters (e.g., max acceleration, jerk, and speed not to exceed the desired free-flow speed) and is assigned to the vehicle. The lead vehicle approaching a lane drop continues to move under this logic until the distance between the point of the lane drop and the vehicle's front bumper is reduced to less than or equal to 5 ft. At this moment, the vehicle is moved to the point of the lane drop and the speed and acceleration are both set at zero.

Vehicle Is Approaching a Blockage Incident. Similar to the lane drop situation, when the lead vehicle approaches a lane blockage, the required deceleration is measured against the deceleration from the kinematic law for stopping the vehicle at the point of blockage. The maximum of the two decelerations is assigned to the vehicle. In applying the car-following logic, a stopped vehicle is assumed to be present at the leading edge of the blockage. This situation continues until the distance between the blockage and the vehicle's front bumper is reduced to less than or equal to 5 ft. The vehicle is then moved at this time behind the blockage and its speed and acceleration are set at zero.

Vehicle Is Approaching a Metering Signal. When a vehicle approaches a metering signal its projected location is used to determine if the vehicle can stop in time. A vehicle that is unable to stop is assumed to go through the red signal, as well as those tagged as noncompliant drivers. For those vehicles that are designated to stop at the meter, the deceleration in the current time step is computed based on the assumption that the vehicle should be able to decelerate at a nonemergency deceleration rate in the future time steps and stop at the meter. The vehicle will then await the "green" in order to proceed through the meter. Once the vehicle is tagged for discharge and subsequently goes through the "green" signal, its behavior is governed by the requirements as prescribed above for a lead vehicle or a follower vehicle.

Vehicle Is Approaching the End of an Auxiliary Lane. The behavior of a vehicle approaching the end of an acceleration auxiliary lane is identical to that of the lane-drop behavior as described above.

Vehicle Is Approaching an Exit Interface Node. The lead vehicle approaching an exit interface node will look beyond the node to identify the status of its lead vehicle on the surface street. If a lead vehicle is identified, then car-following and collision avoidance rules are applied to determine the vehicle's deceleration for the current simulation time step. If there is no lead vehicle on the surface street, the vehicle will continue to accelerate at the maximum possible rate, subject to its performance capabilities.

Vehicle Is Not Affected by Geometrics. Any vehicle that is not influenced by any of the above described cases will attempt to increase its acceleration to the maximum possible rate in an effort to attain the free-flow speed of the facility (defined as the speed at LOS A), which depends on the freeway geometrics and on the vehicle's operational characteristics.

Lane-Changing Logic

Lane-changing logic determines the amount of risk that a driver of a lane-changing vehicle will accept (i.e., lead gap) and the amount of risk that a driver in the lane-changing vehicle's target lane (or putative follower) will accept (i.e., lag gap). Refer to Figure 1-2 for an illustration of this concept.

The FRESIM program provides for three types of lane changing schemes as described below:

Mandatory Lane Changing. The mandatory lane change is the most stringent of the three, where the driver accepts the largest risk and tests the limits of the vehicle performance characteristics. A mandatory lane change can occur under any of the following conditions:

- The vehicle is traveling in an acceleration auxiliary lane and must change lanes in order to merge with the mainline freeway traffic.
- The vehicle is not in the proper lane when scheduled to exit the freeway and has passed an off-ramp advanced warning sign.
- The vehicle is in a lane which will be dropped downstream and has passed a lane-drop advanced warning sign.
- The vehicle is in a lane that is blocked downstream.

For the above four conditions, the acceptable risk (deceleration) is increased as the vehicle approaches the time when it must perform a lane change.

For vehicles in an auxiliary lane, the acceptable risk is set at a minimum value of –8 ft/sec^2 and is then increased as a function of the square root of the remaining distance to the end of the auxiliary lane, up to a maximum of –15 ft/sec^2.

For vehicles set to exit the freeway, the risk is set at –5 ft/sec^2 once it has passed the advanced warning sign and is then increased as a function of the square root of the remaining distance to the off-ramp.

For a vehicle approaching a lane-drop, the risk is set at –5 ft/sec^2 once it has passed the advanced warning sign and is then increased as a function of the square root of the remaining distance to the lane-drop.

Similar to the above two cases, for a vehicle approaching a lane blockage, the risk is set at –5 ft/sec^2 at an imaginary advanced warning sign (set at 1,500 ft from the blockage). Once again, the risk is increased as a function of the square root of the remaining distance to the blockage.

The concept of the increasing acceptable risk as a function of the square root of the remaining distance to the "mandatory" lane change is modeled in FRESIM as

$$risk = e_{\min} + (e_{\max} - e_{\min})\sqrt{\frac{(x - y)}{(x_r - y)}}$$

where x = current position of the vehicle
x_r = position of the vehicle at which it begins to respond to the condition
y = position of the event causing the lane change
$e_{\min}$ = minimum risk (set at –5 ft/sec^2)
$e_{\max}$ = maximum risk (set at –15 ft/sec^2)

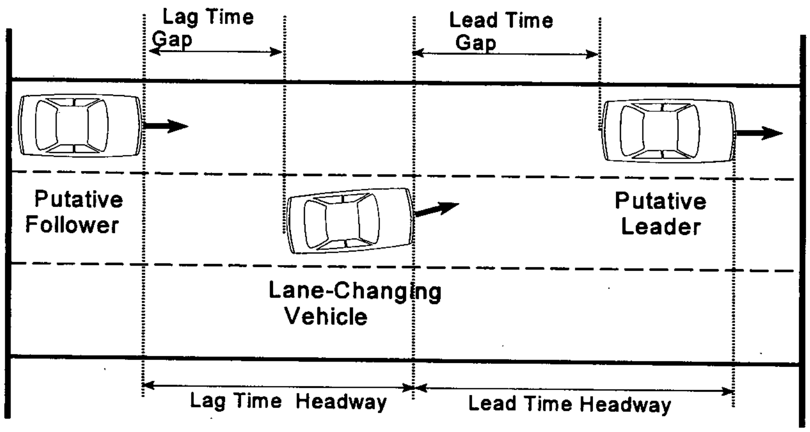


Figure 1-2. Illustration of the lane-changing concept.

Discretionary Lane Changing. Discretionary lane changing refers to vehicles that change lanes in order to obtain a more favorable position (i.e., to attain a higher speed in order to reach the desired free-flow speed) or to pass a slower-moving vehicle.

The FRESIM model for discretionary lane changing depends on several driver behavioral parameters: (1) motivation, (2) advantage, and (3) urgency.

Motivation models a vehicle's desire for a lane change. The model assumes a certain "degree of desire" to change lanes, which is a function of the vehicle's present speed and driver's characteristics. FRESIM assigns an "intolerable" speed computed as

$$v_i = v_f \times \left(\frac{50 + 2C}{100}\right)$$

where v_f = desired free-flow speed (speed at LOS A as defined in HCM)
C = driver type, determined by a random number between 1 and 10

The driver's desire (measured in percent) to make a lane change is then computed from

$$D = \begin{cases} 100 & v \leq v_i \\ 100\left(1 - \dfrac{(v - v_i)}{(v_f - v_i)}\right) & v_i < v < v_f \\ 0 & v \geq v_f \end{cases}$$

where D = desire to change lane (in percent)
v = speed of vehicle desiring to change lane

If a vehicle is traveling below its intolerable speed, the desire to change lanes will exist. The desire factor reduces linearly between the intolerable and desired speeds. A stochastic test is performed to determine if the vehicle desires a lane change.

When a vehicle desires to change lanes, the logic determines if any benefit exists in performing the change. The advantage in performing the lane change is modeled using a Lead Factor (F_L) and a Putative Factor (F_P).

The Lead Factor represents the disadvantage associated with remaining in the lane with respect to the vehicle's current leader. The Lead Factor is computed based on the vehicle's current headway

$$F_L = \frac{h - h_{min}}{h_{max} - h_{min}}$$

where h_{min} = minimum headway
h_{max} = maximum headway
h = existing headway in the vehicle's current lane

$$h = \frac{D_x - F_s v_d}{v_f}$$

where D_x = the separation between the vehicle and its leader in the current lane
F_S = the speed threshold factor
v_d = the speed difference between the vehicle and its leader in the current lane
v_f = the vehicle's desired free-flow speed

Note that the Lead Factor is a disadvantage measure; large values indicate that the lane change is not beneficial to the driver. For the headway below the specified minimum of 2 sec, the vehicle will find it advantageous to perform a lane change. Between the minimum and maximum headways, the advantage of performing the lane change decreases linearly.

The Putative Factor, F_P, represents the perceived gain in moving to a new lane. The logic computes the Putative Factor for both adjacent lanes (if both exist), and the lane with the largest Putative Factor is selected as the lane change target lane. Computation of F_P is similar to F_L and can be computed as

$$F_P = \frac{h_{max} - h}{h_{max} - h_{min}}$$

The overall Advantage Factor F_A is then computed as

$$F_A = F_P - F_L$$

Any vehicle with a computed Advantage Factor above the specified threshold value (set at a default value of 0.40) will attempt to make a lane change.

Urgency models determine how strong a desire for a lane change exists. Urgency affects the acceptable risk in changing lanes. The model assumes that a driver who was motivated in the previous time steps to perform a lane change, but was unable to do so, would gradually become impatient and accept a higher risk in performing the lane change. This Urgency Factor, F_U can be computed as

$$F_U = (1 - F_L)IMP(t)$$

FRESIM defines an Impatience Factor *IMP(t),* which is a function of the driver type, and the driver's behavior in the previous time step. The Impatience Factor at time t is defined by

$$IMP(t) = a \times IMP(t - \Delta t) + (1 - a) \times X(t)$$

where t = current time

Δt = the simulation time step

$$a = 1 - \left(\frac{C + 1}{20}\right)$$

$$X(t) = \begin{cases} 0, & \text{when vehicle does not want to make a lane change} \\ 1, & \text{when vehicle wants to make a lane change} \end{cases}$$

The Impatience Factor is set at 0 when a driver desires to make a lane change and finds it advantageous and is set at 1 when a vehicle successfully makes a lane change. The value of acceptable risk varies linearly with respect to the Urgency Factor.

The relationships of the three key factors described above (Lead Factor, Putative Factor, and Urgency Factor), with respect to headway and acceptable risk, is graphically illustrated in Figure 1-3.

Anticipatory Lane Changing. Anticipatory lane changing refers to the lane changes that are performed by through-moving vehicles to avoid potential slowdown caused by the traffic merging from a downstream on-ramp. In the FRESIM model an advanced warning sign is associated with each on-ramp that is located 1,500 ft upstream of the on-ramp gore. For each vehicle arriving at the warning sign, the logic determines if the vehicle's current lane aligns with the downstream lane receiving the merging traffic; hence there is a potential for slowdown due to low-speed merges. If so, the logic next determines if there is any benefit in performing an anticipatory lane change. Similar to the discretionary lane change logic, the benefit in performing the lane change is measured in terms of the disadvantage in vacating the current lane and the advantage in moving to a new lane.

The advantage to vacating the current lane is quantified in terms of a lead factor which is computed as follows:

1. The lead factor is assigned a value of 1 if the on-ramp flow exceeds 1,000 vehicles per hour per lane (vphpl).
2. When the on-ramp flow is below 1,000 vphpl, the logic computes the average instantaneous speed of all vehicles in the vicinity of the on-ramp gore and over the freeway lanes that directly receive the merging traffic. The vehicle's current speed is compared to the computed average speed and the least of the two is selected and used in computing the lead factor. The lead factor is set at 1 when the selected speed is below the vehicle's tolerable speed and it is set at 0 when it exceeds the vehicle's desired free-flow speed. For speeds between the tolerable speed and the desired free-flow speed, the lead factor is assigned a value between 0 and 1 based on linear interpolation.

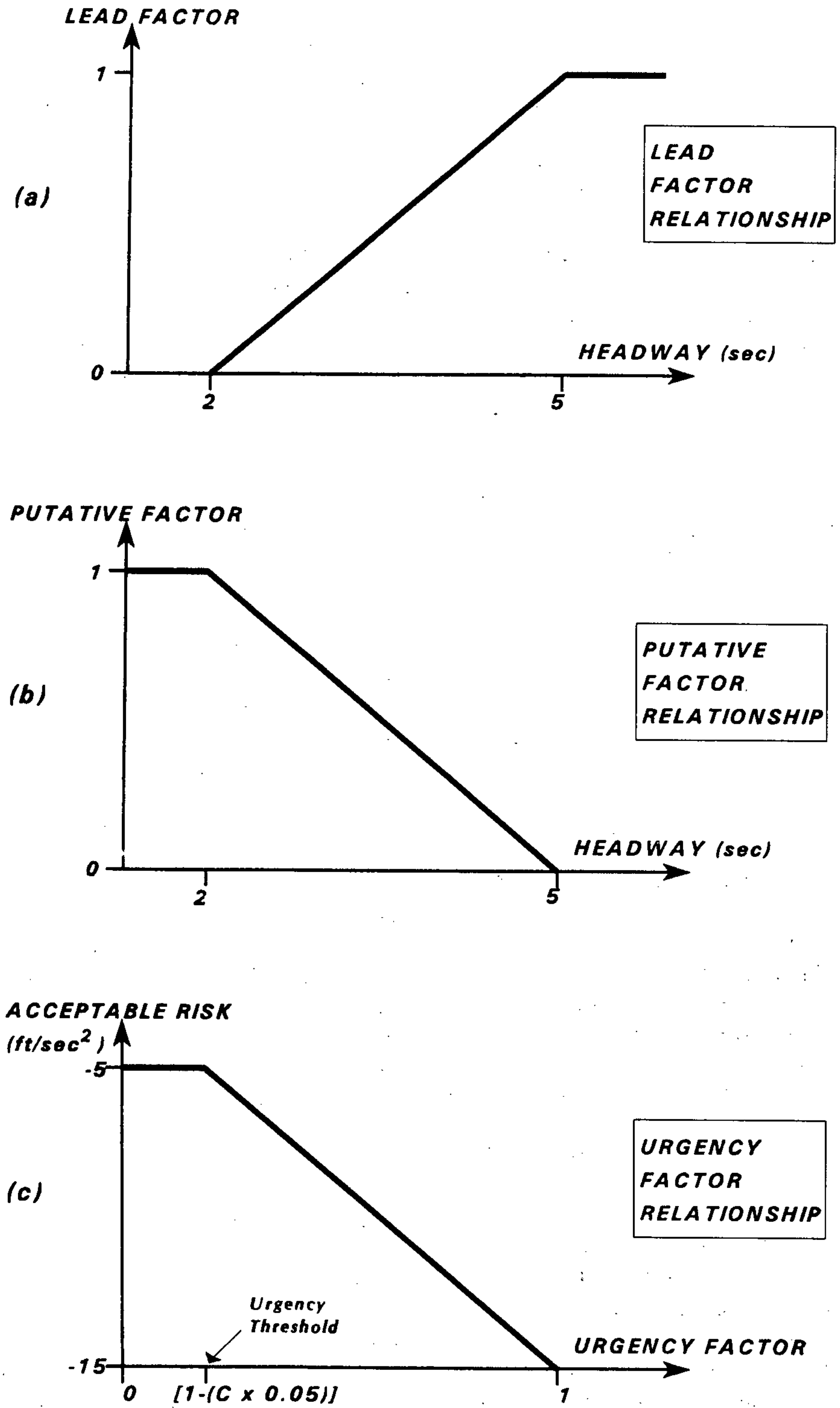
The disadvantage of moving to a new lane is quantified in terms of a putative factor which is computed based on the average speed of all vehicles in the vicinity of the on-ramp gore and over all lanes that do not directly receive the merging traffic. The putative factor is assigned a value of 1 if the computed average speed is below the average speed over the lanes directly receiving the merging traffic and it is set at 0 if the computed average speed exceeds the vehicle's desired free-flow speed. For other values of computed average speed, the putative factor is assigned a value between 0 and 1 based on linear interpolation.

The overall advantage in performing the lane change is computed as the difference between the lead and putative factors and the vehicle attempts to make a lane change if the overall advantage exceeds the prespecified advantage threshold (set at 0.4).

In performing the anticipatory lane change, the vehicle will accept the risk of -10 ft/sec^2.

Vehicle Generation Logic

Vehicles are allocated to the network via an imaginary link which feeds the first link of the freeway and entry ramp. The vehicle characteristics (such as type of vehicle, driver type, desired lane, and desired speed) are stochastically assigned. After these have been established, actual speed and position of the vehicle is determined. Initially, the vehicle is given an actual speed which is its desired speed (based on driver type) or the actual speed of the next vehicle ahead, whichever is lower. Vehicles enter the freeway from the entry nodes at constant intervals (e.g., if an entry node has a flow rate of 1,800 vph, then one vehicle is emitted onto the freeway every 2 sec).



Note: All values shown are default settings. Source: Ref. 10

Figure 1-3. Function relationship of key factors.

TABLE 1-1 Vehicle operational characteristics

	Vehicle Fleet Type	Length(ft)	Percent Fleet Component	Maximum Emergency Deceleration (ft/sec^2)	Maximum Non-emergency Deceleration	Maximum Jerk (ft/sec^3)
CARS	Low Performance Passenger Car	14	25	-15	-8	7
CARS	High Performance Passenger Car	16	75	-15	-8	7
TRUCKS	Single Unit Truck	35	31	-15	-8	7
TRUCKS	Semi-Trailer Truck with Medium Load	53	36	-15	-8	7
TRUCKS	Semi-Trailer Truck with Full Load	53	24	-15	-8	7
TRUCKS	Double-Bottom Trailer Truck	64	9	-15	-8	7
BUS	Intercity Bus	40	100	-15	-8	7

For each vehicle the following characteristics are assigned:

- *Vehicle Identification Number.* Each vehicle is assigned a unique number in a consecutive sequence between 1 and 10,000 for purposes of tracking it through each link representative of the freeway section.

- *Driver Type Code.* A driver type code from 1 to 10 (1 being the most timid and 10 the most aggressive) is randomly generated from a discrete uniform distribution, with the probability distribution function:

$$Prob(Driver\ Type,\ C=k) = \begin{cases} 0.10, k = 1, 2, 3, \ldots 10 \\ 0,\ Otherwise \end{cases}$$

- *Vehicle Type Code.* A vehicle type code is assigned based on a random sampling of the default fleet component distribution shown in Table 1-1. This code affects several of the operational vehicle characteristics (e.g., maximum and minimum acceleration, and jerk). FRESIM contains vehicle operational characteristics (which can be modified by the user) for seven types of vehicles consisting of three fleet types (passenger cars, trucks, and buses). In addition, the distribution of vehicles by fleet type can also be modified.

- *Lane Distribution and Allocation.* FRESIM allocates vehicles based on a random sampling of an embedded vehicle lane distribution. The allocation is equally distributed as a function of the number of lanes[1] as shown in Table 1-2.

- *Desired Free-Flow Speed.* The user input value of the desired mean free-flow speed for the freeway (speed corresponding to LOS A as defined in the HCM) is multiplied by an embedded value of the lane mean speed factor[2] (this factor is a function of the number of through lanes, similar to the lane distribution allocations). This

[1] The project team obtained a modified version of the FRESIM program that allows altering of the embedded equal lane distribution values (i.e., percent distribution of vehicles by lane is an input value rather than a constant, as shown in Table 1-2). Both versions of FRESIM were used in the analysis part of this research effort.

[2] Presently, the lane mean speed factor is set to 1.00 for all freeway sizes. Further research is needed to calibrate this factor.

TABLE 1-2 Default vehicle distribution across lanes[1]

Number of Through Lanes	1	2	3	4	5
1	1.00				
2	0.50	0.50			
3	0.33	0.33	0.34		
4	0.25	0.25	0.25	0.25	
5	0.20	0.20	0.20	0.20	0.20

[1] An exception to these embedded values exists when the selected lane violates the minimum 2.2 second headway requirement, in which case the vehicle is allocated to the lane with the maximum headway.

computed value is then adjusted by multiplying by the mean speed percentage as shown in Table 1-3. For example, driver type 1 (corresponding to the most timid driver) would have correspondingly the lowest mean speed percentage, and driver type 10 (most aggressive) would have the highest.

- *Driver Sensitivity Factor.* The driver sensitivity factor, which is directly associated with the car-following time gap that drivers of vehicles are willing to accept and maintain between themselves, is used to realistically model the variability in drivers present in the traffic stream. These values can be adjusted by the user as a means of calibrating FRESIM to the actual traffic conditions. Refer to Table 1-3 for the current default settings.

Ramp Metering Logic

Simulation of ramp metering is accomplished by introducing a node at a location upstream of the ramp-freeway interface as shown in Figure 1-4, with the upstream section subject to the normal queue discharge logic applied at signalized intersections, and the downstream section representing the ramp link. The introduced node is equivalent to the placing of a traffic signal for control of the ramp flow. FRESIM supports four types of ramp-metering strategies:

Clock-Time Metering. To simulate clock-time metering of on-ramps, a fixed metering headway is specified at the node. The metering headway is the time, in seconds, between two successive green indications of the meter. A count-down clock is assigned to the on-ramp node, and the signal is set to "green" each time the clock returns to zero, and subsequently is reset to the user-specified metering headway. After a vehicle is discharged at the "green" signal, the signal is set back to "red." A noncompliance percent is also applied to vehicles that arrive during the "red" signal, representing the percentage of vehicles that go through the "red" signal.

Demand/Capacity Metering. To simulate demand/capacity metering, a desired freeway capacity is specified in vehicles per hour per lane. A maximum metering rate is calculated based on counts from detectors placed upstream of the metered ramp so that the capacity of the freeway section is not exceeded. Metering rate (the inverse of metering headway) is similarly applied to the clock-time metering. A minimum metering rate of three vehicles/minute is used to allow vehicles to merge properly between the ramp connection to the freeway and the meter.

Speed Control Metering. Similar to the demand/capacity metering strategy, a metering rate is calculated based on speeds obtained from detectors placed upstream of the metered ramp. Up to three speed thresholds and corresponding metering headways can be specified and these are then compared to the measured freeway speeds to obtain an appropriate metering headway.

Gap Acceptance Metering. This method of ramp metering uses the ramp signal control to release ramp vehicles in order to merge smoothly into gaps detected in the rightmost lane (lane 1) of the mainline freeway. Gaps above a user-specified minimum acceptable gap size are selected and vehicle release times are computed to allow for the merge. Here again, detectors are placed upstream of the merge junction to measure the acceptable gaps.

A detailed description of input and output formats for FRESIM is provided in Appendix B or the reader may consult References *9*, *10*, and *11*.

Incident Detection

FRESIM has a comprehensive incident-detection model based on three algorithms developed in the early 1970s by

TABLE 1-3 Driver type, mean speed percentage, and driver-sensitivity factor

Driver Type	1	2	3	4	5	6	7	8	9	10
Mean Speed Percentage	88	91	94	97	99	101	103	106	109	112
Driver Sensitivity Factor	15	14	13	12	11	10	9	8	7	6

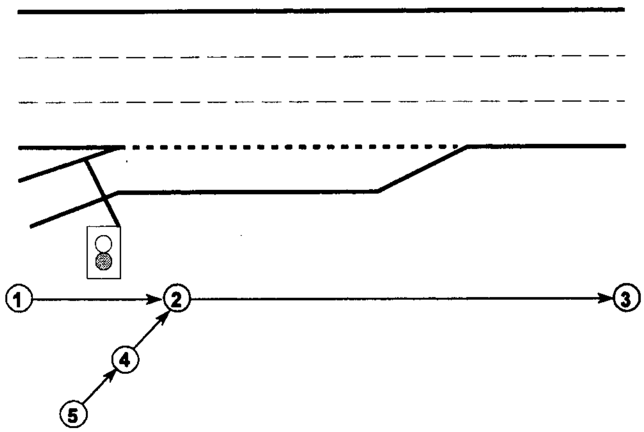


Figure 1-4. Metered ramp geometry.

Payne et al. (*12–14*). The program analyzes detector data to determine if an incident has occurred on the freeway and will output the onset and end of each incident as defined by the algorithm.

The first algorithm is based on the California logic that uses occupancies at sensor stations to determine the onset of the incident, its approximate location, and the end of the incident. The second algorithm uses compression wave suppression logic to avoid false alarms due to the presence of transient compression waves in the traffic stream. The third algorithm uses the double exponential smoothing method to reduce the number of incident false alarms. For a more detailed analysis of these algorithms the reader is referred to References *12* through *14*.

DEFICIENCIES AND LIMITATIONS OF FRESIM

Although FRESIM is probably the best freeway simulation program available, it does have some limitations that could be overcome with minor programming changes and enhancements.

One of the main problems encountered by the research team was FRESIM's inability to predict the merging process with a high degree of accuracy. In almost all instances, FRESIM predicted the merging at ramp junctions to occur within the first 100 ft measured from the gore area. Much of the data collected as part of the original Project 3-37 database and that obtained from the Traffic Evaluator System showed that at distances of 250–300 ft as much as 5 percent of the traffic had not yet merged into lane 1. It is the understanding of the research team that the developers have made changes to the logic for merge operations to better replicate the merging process and that future releases of FRESIM will have these changes implemented.

Another problem encountered by the research team pertained to diverge junctions. When specifying a certain percentage of exiting vehicles at a diverge site, FRESIM showed some of the vehicles missing the exit ramp and continuing on the freeway. Although the recommended 2,500-ft warning sign for exiting vehicles was placed as recommended, it still showed some vehicles missing the exit, especially when the percentage of exiting vehicles was high.

Unlike merge junctions where the user can control the percentage of heavy vehicles, FRESIM is not capable of accepting this value for diverge/exit junctions. It will use the percentage that exists on the mainline freeway as the corresponding value for the exiting ramp. In addition, FRESIM does not accept an exiting volume for diverge junctions as is available for merge junctions (i.e., one cannot specify that 500 vehicles are exiting the freeway with 10 percent trucks). FRESIM will accept percentages corresponding to those vehicles wishing to exit and those continuing on, but because some vehicles miss the exit, the exact number that one wishes to simulate exiting the facility cannot be replicated precisely.

One easily resolved deficiency is in the statistics reporting of FRESIM. Some of the summary statistics are reported on a cumulative basis, which in many instances require the user to perform additional math to calculate the actual statistic for a particular time period. The FRESIM program provides no graphical output of some of the key statistics, which would be more useful to the end-user than the tabular format that it currently supports.

Although not relevant to the scope of the research effort, FRESIM does not have the capability to model HOV facilities or the effect of lane width or reduced shoulder width on traffic operations. In addition, the research team found that the documentation on many aspects of the input requirements lacked clarity.

Though FRESIM is a much more user-friendly program than its predecessor, it is still not as user-friendly as it should be if it is to become as widely used as the highway capacity software. The project team reviewed the prerelease version of CORSIM (which incorporates both NETSIM and FRESIM) and were impressed with the ease of use of the graphical interface created for generating the sometimes cumbersome coding requirements of both FRESIM and NETSIM.

Much of the programming logic in FRESIM is based on field data that in some instances may not have been as extensive as would have been desired. Many of the deficiencies noted above can be overcome by conducting additional calibration/validation and sensitivity analyses to refine the models. The research team believes that making the program more user-friendly will result in the establishment of an extensive database; this will provide a means for the continued refinement of the lane-changing, merging behavior, and car-following logic of the program.

ONGOING DEVELOPMENT: CORSIM

If one wants to microscopically simulate the operation of a section of freeway, the program to use is FRESIM. If one wants to simulate an arterial network or an isolated intersection, the program to use is NETSIM. Until recently, there was no *one* comprehensive, easy-to-use package to simulate both freeway sections and arterial networks without having to take the results of one as input to the other and vice versa.

CORSIM is the latest addition to FHWA's TRAF family. It combines the latest versions of FRESIM and NETSIM. With CORSIM one is able to model the freeway and surface street networks without having to code and run each program separately. Graphical preprocessor and postprocessor modules (ITRAF and TRAPHIX) have also been added.

ITRAF is a Windows™-based interactive program developed to simplify and speed up the cumbersome task of coding the required inputs to both FRESIM and NETSIM. ITRAF can also be used for coding other elements of the TRAF family of packages. The main advantage of using ITRAF is its ability to graphically create and/or modify all of the information associated with the geometry of the simulated network such as nodes, links, and traffic volume. TRAPHIX is a graphics postprocessor capable of generating animated displays of simulated traffic flow operations. Although it is still under development, it will have the ability to display graphical attributes of links and nodes that FRESIM currently provides in tabular format only.

CORSIM is undergoing extensive beta-testing in addition to both the ITRAF and TRAPHIX packages. It is expected to be available for general use sometime in mid 1996.

TES DATA AND ITS ORIGIN

The Traffic Evaluator System (TES) was developed for the FHWA in the late 1970s. It is a large-scale traffic-data collection system consisting of both hardware and software capable of collecting, recording, and reducing most traffic measures (e.g., speeds, headways, volumes/flow rates by lane, individual trajectories, and vehicle type) that are of interest to transportation researchers at uninterrupted flow facilities.

TES is a combination of hardware, software, and people and support, each of which contributes equally to the successful implementation of the system. Figure 1-5 presents a schematic representation of the TES system showing the relationship between the hardware and software elements.

The TES Hardware Element

The hardware element is made up of three parts as described below:

- *Electronics Unit.* This is the heart of TES. It consists of input signal conditioners, a quartz crystal clock, data multiplexers, memory, and a digital magnetic tape transport, all in an environmental case with the capability to accept up to 60 inputs from sensors, which may include tape switches, pneumatic tubes, relay contacts, manual actuated switches, or any input that approximates a contact closure, including outputs from most traffic control equipment.

- *Linkage Network.* The linkage network (i.e., main data cables and junction boxes) is that portion of the system that carries the data from the sensors to the electronics unit. The main data cables are 33-ft-long segments of six individually shielded, twisted pairs of wire in a durable black polyurethane outer jacket, with one male and one female pin connector terminus. These cables can be connected to each other to allow signal transmission over varying distances. The junction boxes are the connecting devices that link the sensors to the data cables or directly to the electronics unit. The sensor input is accommodated via a terminal strip capable of receiving a maximum of six inputs.

- *Input Devices.* Input devices may include tape switches, pneumatic tubes, relay contacts, manual actuated switches, or any other input that approximates a contact closure, including outputs from most traffic control equipment. The most frequently used input device is a tape switch affixed to the road-surface via adhesives. A tape switch is simply a long thin pair of metal contacts, separated along their edges by insulating material and encased in a waterproof vinyl sheathing with lead wires attached. It functions as a momentary contact switch that is normally open. In addition, button boxes are used to input observational data directly to the electronics unit. The button boxes are a series of, momentary contact (normally open), individual push-button switches mounted in a protective box.

TES is a sophisticated multiple-event recorder designed as a traffic-data collection system capable of continuous sensing and recording of up to 60 simultaneous traffic events. Each time a sensor is activated, an internal clock is interrogated and the result of the time of activation and the corresponding sensor location is stored in one of two internal buffers. When the buffer in use is filled, the data is automatically dumped and written on magnetic tape. During the dump/write operation, the second buffer is available to accept additional data from other sensors to avoid any data loss.

In addition to the automatic recording of data from the sensors, other types of data (e.g., a brake light application, an out-of-state license plate, etc.) can be entered manually. For each activation of a sensor, two pieces of data are recorded and stored:

- n, a number from 1 to 60 that identifies the particular sensor location and
- T, the time of activation.

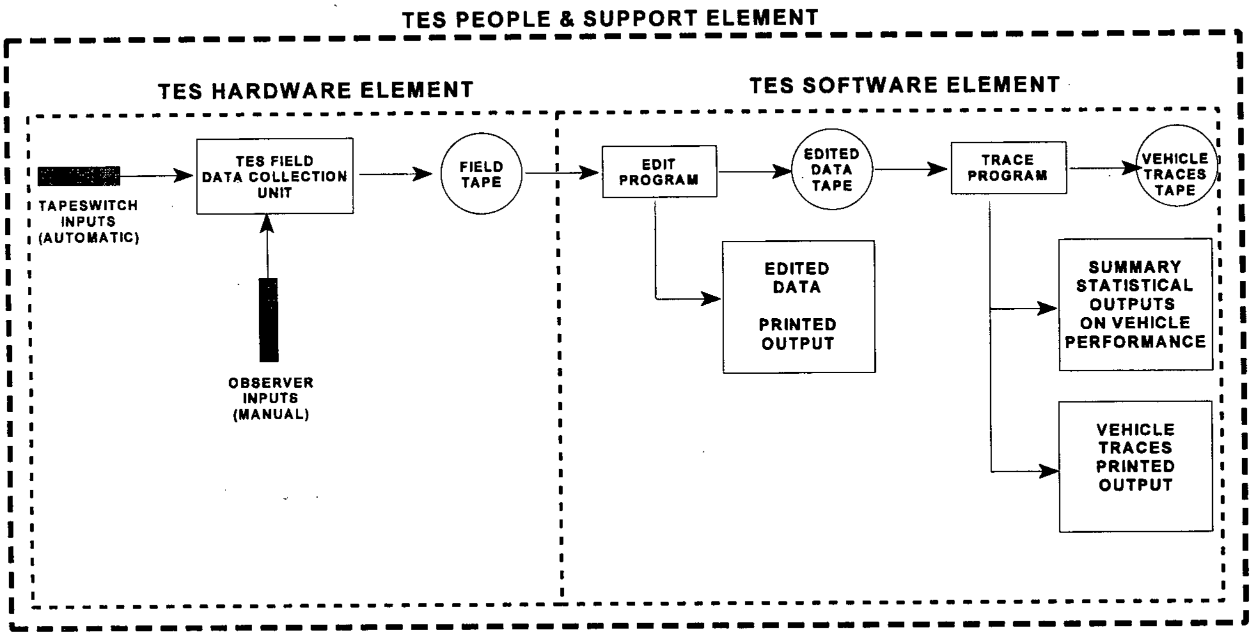


Figure 1-5. Schematic representation of the integrated TES system.

The typical deployment of the system consists of placing pairs of tape switches affixed to the roadway perpendicular to traffic, spaced 4 ft apart for each lane. Each pair of tape switches defines a trap for a particular lane. Inter-trap intervals are uniformly spaced within a range of 150–325 ft. Figure 1-6 illustrates a typical TES system deployment.

For each trap, vehicle speeds can be extracted by simply calculating the time difference between actuations. Consider the results of the vehicle shown in Figure 1-6 that just passed sensors 1 and 2 of Trap 1.

Axle	*Sensor number (n)*	*Time (T) in milliseconds*
Front	1	000100
Front	2	000145
Rear	1	001068
Rear	2	001113

With the sensors placed 4 ft apart, the time differences ($\text{Front}_2 - \text{Front}_1$) and ($\text{Rear}_2 - \text{Rear}_1$) provide two estimates of vehicle speed. Thus,

$$(\text{Front}_2 - \text{Front}_1) \quad 000145 - 000100 = 45 \text{ ms}$$
$$(\text{Rear}_2 - \text{Rear}_1) \quad 001113 - 001068 = 45 \text{ ms}$$

and $4 \text{ ft} \div 0.045 \text{ sec} = 88 \text{ ft/sec} \times (3600 \div 5280) = 60 \text{ mph}$.

From this raw data most measures of interest to traffic engineers and researchers can be derived. It is important to note that one can measure wheelbase but cannot measure vehicle length directly. It can be approximated by adding front and rear overhang (front axle to front bumper and rear axle to rear bumper, respectively) to the measured wheelbase. This is directly associated with the TES-generated headways which are different from the conventional headway measurement. Figure 1-7 illustrates these points.

The TES Software Element

Once the data has been collected and written permanently onto magnetic tape, it is run through two FORTRAN programs: (1) EDIT—the utility program that interprets and "cleans" the raw data from the field tapes and (2) TRACE—the analysis program.

The main function of the EDIT program is to read the field tape and, after checking for errors that may arise due to hardware malfunction, to generate a "clean" tape in a more readable format for processing by the TRACE program.

TRACE is the main analysis program and performs a number of functions including

- creating a sequence of vehicles and gaps at each trap,
- generating vehicle traces which correspond to a record of a vehicle's presence at each trap crossed by the vehicle as it traverses the study site, and
- computing a number of vehicle performance characteristics, such as vehicle speeds, wheelbase, number of axles, position in the lane, time of arrival at a trap, and headway for each lane trap position within the deployment.

The primary use of the TRACE program is to process the EDIT-generated "clean" tape. Vehicle traces, consisting of a summary record followed by trap-by-trap records, are written as output to the TRACE tape. Three types of data records are output by the TRACE program which are generated as a result of analysis and interpretation of tape switch input data.

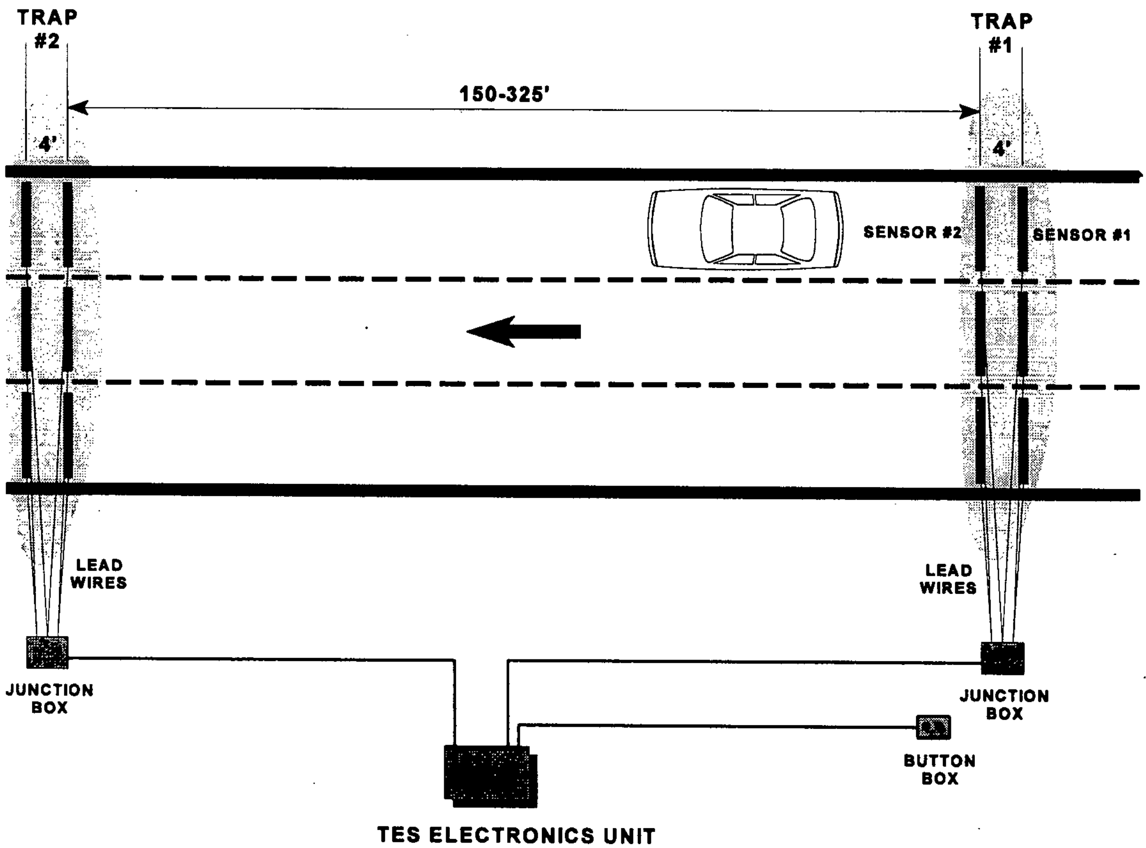


Figure 1-6. Typical field deployment of the TES system.

Only two are relevant to this report. The first is a summary data record (Type 0 Record). This record is computed for each vehicle traced completely or partially through the deployment. Table 1-4 presents the description of the Type 0 Record which contains the following pieces of information:

- vehicle ID number,
- vehicle type,
- number of axles,
- number of tandems,
- wheelbase,
- mean speed,
- standard deviation of speed,
- mean acceleration,
- data quality flag,
- data reasonableness flag,
- time vehicle entered deployment,
- vehicle trajectory through the deployment, and
- record type.

The second type of data (Type 1 Record) is produced for each lane/trap location within the deployment through which a vehicle is traced. For example, suppose a 3-lane freeway mainline was instrumented with seven traps for each of three lanes. A full vehicle trace would indicate that the TRACE program found the vehicle at six different lane/trap positions within the deployment. For this example, six Type 1 records would be generated. The records are output in ascending trap order (i.e., a full vehicle trace would have Type 1 records for traps 1, 2, . . . , n, where n is the maximum number of traps in the deployment). Table 1-5 presents the description of the Type 1 Record, which contains the following pieces of information:

- vehicle ID number,
- lane,
- trap,
- vehicle ID of lead vehicle at that lane trap position,
- number of axles,
- number of tandems,
- mean speed,
- mean acceleration/deceleration,
- lateral displacement,
- time headway,
- distance headway,
- relative speed between the vehicle and its leader,
- data quality flag,
- data reasonableness flag,
- time in hours, minutes, seconds,
- time in milliseconds, and
- record type.

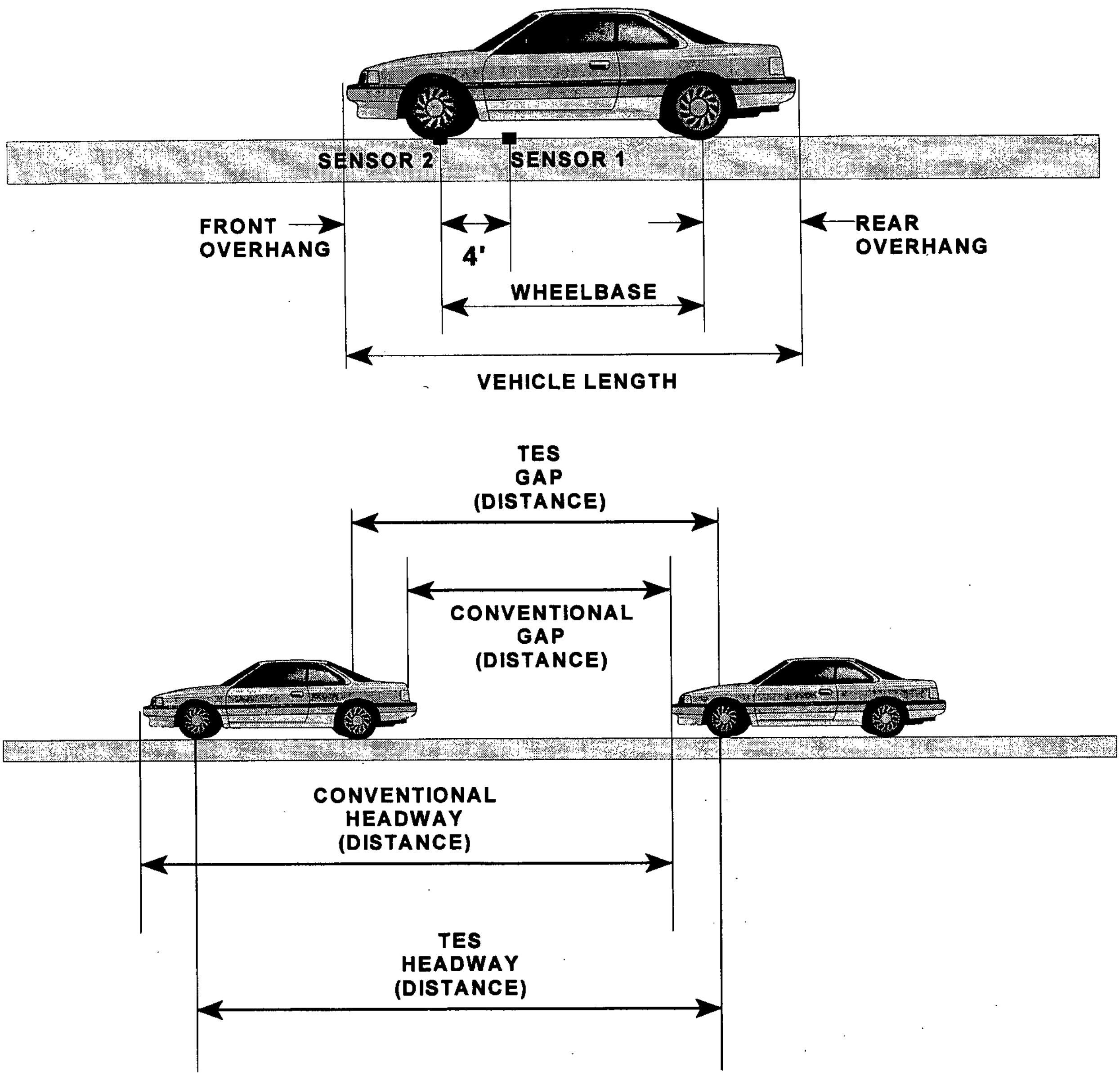


Figure 1-7. Illustration of differences between conventional and TES measurements.

Figure 1-8 shows a sample output from the TES TRACE output tapes as described in Tables 1-4 and 1-5.

The People and Support Element

The people and support element of the system is composed of the system operators (crew), vehicles, equipment, and materials necessary for the successful operation of the system. A minimum crew size of four technicians is required for a typical site.

Description of TES Sites

For the comparative analysis in this report, the project team acquired the field data tapes of five sites which were instrumented with the TES systems described in the previous section. Three of the sites are merge junctions and the remaining two are diverge junctions.

The following is a brief description of each site. Figure 1-9 through Figure 1-13 show a schematic of the instrumented TES deployment of these sites.

TABLE 1-4 Description of tape output variable format in vehicle summary (Type 0) record

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
400450	5	2	0	10.49	90.8	4.07	0.03	0	0				64934.644444400000000		0	

Variable	Format	Description
A	I7	Vehicle ID number: Digit 1: Blank Digit 2: Lane of Entry Digit 3-6: Sequential Vehicle Number Digit 7: Trace Type (0=Full, 9=Partial)
B	I2	Vehicle type.
C	I2	Total number of axles for vehicle.
D	I2	Number of tandem axles.
E	F7.2	Mean wheelbase across deployment: in feet.
F	F7.1	Mean speed across deployment: in feet/second.
G	F7.2	Standard deviation of speed: in feet/second.
H	F7.2	Mean acceleration/deceleration across deployment: in feet/^{seconds}
I	I4	Data quality flag.
J	I4	Data reasonable flag
K	I4	Hour portion of time of entry in 24 hour clock.
L	I2	Minutes portion of time of entry.
M	F5.2	Seconds portion of time of entry.
N	14I1	Vehicle trajectory trace - sequential listing of lane vehicle was at each trap in deployment.
O	23X	Blank spaces.
P	I1	Type zero record - represented in data by a blank.
Q	A2	Output units indicator: Blank=English units, SI=Metric units.

TABLE 1-5 Description of tape output variable format in trap-by-trap vehicle trace (Type 1) record

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O P Q	R S T
400450	**4**	**1**	**400449**	**2**	**0**	**94.6**	**0.40**	**0.0**	**1.75**	**160.1**	**3.1**	**0**	**0**	**64934.86**	**245745781**
400450	4	2	400449	2	0	94.8	0.40	0.0	1.67	155.3	1.8	0	0	64938.15	245781621
400450	4	3	400449	2	0	91.3	0.0	0.0	1.62	146.9	0.6	0	0	64941.45	245814651
400450	4	4	400449	2	0	92.2	-0.17	0.0	1.56	141.2	1.7	0	0	64944.83	245848331
400450	4	5	400449	2	0	86.6	-0.48	0.0	1.49	125.6	2.3	0	0	64948.24	245882551
400450	4	6	400449	2	0	85.1	0.0	0.0	1.40	114.1	3.6	0	0	64951.84	245918461

Variable	Format	Description
A	I7	Vehicle ID number: See description of Type 0 record for codes.
B	I2	Lane occupied at trap(I).
C	I2	Trap(I): I=1 to maximum number of traps (6 in the example shown above)
D	I7	Leader's ID: Vehicle ID of vehicle immediately preceding at trap(I).
E	I2	Total number of axles.
F	I2	Number of tandem axles.
G	F7.1	Speed at trap(I): in feet/second.
H	F7.2	Acceleration or deceleration at trap(I): in feet/second^2
I	F7.2	Lateral displacement at trap(I): in feet.
J	F10.2	Time headway at trap(I): in seconds.
K	F10.1	Distance headway at trap(I): in feet.
L	F7.1	Relative speed between vehicle and its leader at trap(I): in feet/second.
M	I4	Data quality flag.
N	I4	Data reasonableness flag.
O	I2	Hour portion of time at trap(I): 24 hour clock.
P	I2	Minute portion of time at trap(I).
Q	F5.2	Second portion of time at trap(I).
R	I10	Time at trap(I) in milliseconds.
S	I1	Type 1 record indicator.
T	A2	Output unit indicator: Blank=English units, SI=Metric units.

```
400010 3 2 0    9.65    83.4    2.22   -0.05    0    1    815 0.0044444000000000
400010 4 1         0 2 0    84.7    0.0     0.0         0.0          0.0   84.7    0   80 815 0.00    297000031
400010 4 2 400039 2 0    85.7    0.0     0.0         1.44       121.8    1.1    0    0 815 2.92    297029191
400010 4 3 400039 2 0    84.0    0.31    0.0         1.43       121.7   -1.1    0    0 815 5.87    297058701
400010 4 4 400039 2 0    82.5   -0.42    0.0         1.48       123.3   -0.8    0    0 815 8.87    297088661
400010 4 5 400039 2 0    80.0   -0.12    0.0         1.47       117.6    0.0    0    0 81511.95    297119531
200019 4 2 1    4.25    84.7    0.0    -4.87    0    1    815 0.0220000000000000
200019 2 1         0 2 1    84.7   -4.87    0.0         0.0          0.0   84.7    0   80 815 0.02    297000221
400029 3 2 0    9.58    82.6    1.88   -0.14    0    1    815 0.3204444000000000
400029 4 2         0 2 0    83.5    1.09    0.0         0.0          0.0   83.5    0   80 815 0.32    297003221
400029 4 3         0 2 0    84.7   -0.46    0.0         0.0          0.0   84.7    0   80 815 3.29    297032911
400029 4 4 400059 2 0    81.6   -0.41    0.0         4.00       314.4    3.0    0    0 815 6.28    297062781
400029 4 5 400059 2 0    80.5   -0.79    0.0         3.86       295.7    3.9    0    0 815 9.38    297093801
300010 3 2 0    9.59    88.3    2.68   -0.68    8    1    815 0.3633333000000000
300010 3 1         0 2 0    91.1   -1.89    0.0         0.0          0.0   91.1    0   80 815 0.36    297003641
300010 3 2 300059 2 0    88.9    0.0     0.0         1.12       105.6   -5.4    0    0 815 3.16    297031561
300010 3 3 300059 2 0    89.3   -0.73    0.0         1.23       114.4   -3.7    0    0 815 5.94    297059391
300010 3 4 300059 2 0    88.3   -1.55    0.0         1.35       121.6   -1.8    0    0 815 8.75    297087531
300010 3 5 300059 2 0    83.9    0.78    0.0         1.49       132.8   -5.2    0    0 81511.68    297116791
20002910 4 1  41.86    73.6    2.69   -0.04    0    1    815 0.4102222000000000
200029 2 2         0 4 1    76.0   -0.02    0.0         0.0          0.0   76.0    0   80 815 0.41    297004131
200029 2 3         0 4 1    75.5   -0.12    0.0         0.0          0.0   75.5    0   80 815 3.72    297037161
200029 2 4         0 4 1    72.7   -0.06    0.0         0.0          0.0   72.7    0   80 815 7.06    297070631
200029 2 5         0 4 1    70.2    0.04    0.0         0.0          0.0   70.2    0   80 81510.57    297105671
300029 2 2 0    9.01    87.1    1.78   -0.05    0    1    815 1.1703333000000000
300029 3 2         0 2 0    87.9    0.19    0.0         0.0          0.0   87.9    0   80 815 1.17    297011681
300029 3 3         0 2 0    88.7    0.0     0.0         0.0          0.0   88.7    0   80 815 3.99    297039901
300029 3 4         0 2 0    87.1   -0.90    0.0         0.0          0.0   87.1    0   80 815 6.80    297068021
```

Note: Highlighted field shows the Type 0 records as described in Table 1-5. All others are Type 1 records as described in Table 1-6.

Figure 1-8. Sample data from the TES TRACE output tapes.

TES Site 1

Site Description: Ramp Junction—Merge

Location: Houston, Texas. The Houston Standard Metropolitan Statistical Area (SMSA) Merge site is located on the southeastern perimeter of the city on SH 225 (La Porte Freeway) westbound. The precise area of interest is the merge movement from Pasadena Freeway to SH 225 near the Richey Street overpass on SH 225.

Geometric Characteristics: The instrumented area was 1000 ft in length, beginning at 250 ft upstream from the physical gore of the merge ramp. The ramp is upgrade with concrete embankments on both sides, resulting in limited sight distance of the downgrade mainline. A 770-ft straight taper is provided for the merge movement, and the width of each of the three mainline lanes is 12 ft through the site. The paved shoulder is of variable width, ranging from 3.5 to 10.5 ft; the paved shoulder adjacent to the median is 9 ft wide; a Jersey barrier with a chain-link fence attached separates opposing movements; road surface and shoulder conditions are generally good.

TES Site 2

Site Description: Ramp Junction—Merge

Location: Dallas, Texas. This site is located on I-45 in the southern portion of Dallas. The specific area of interest is I-45 Northbound in the vicinity of the on-ramp from Linfield Road.

Geometric Characteristics: The area of instrumentation on this site is 1,500 ft in length beginning at the physical gore and continuing downstream. Contained within the preceding 1,500 ft is a 1,320-ft straight taper originating from a slight upgrade ramp. There are three 12-ft mainline lanes and a 6- to 11-ft variable-width paved shoulder; opposing movements are separated by a wide, grass median strip. The condition of the road surface and shoulders is generally good.

TES Site 3

Site Description: Ramp Junction—Merge

Location: Atlanta, Georgia. This site is located in downtown Atlanta on I-20 westbound. The study area encompassed the entrance ramp from Bryan Street and the I-20 mainline in the vicinity of the Cherokee Avenue Overpass.

Geometric Characteristics: An acceleration lane 775-ft long is provided for the merge movement. There are three 12-ft-wide mainline lanes and a 3-ft-wide paved shoulder through the site. The entrance ramp is downgrade, providing unobstructed adequate mainline sight distance. Opposing movements are separated by a guardrail treated median strip. The condition of the road surface and shoulders is good.

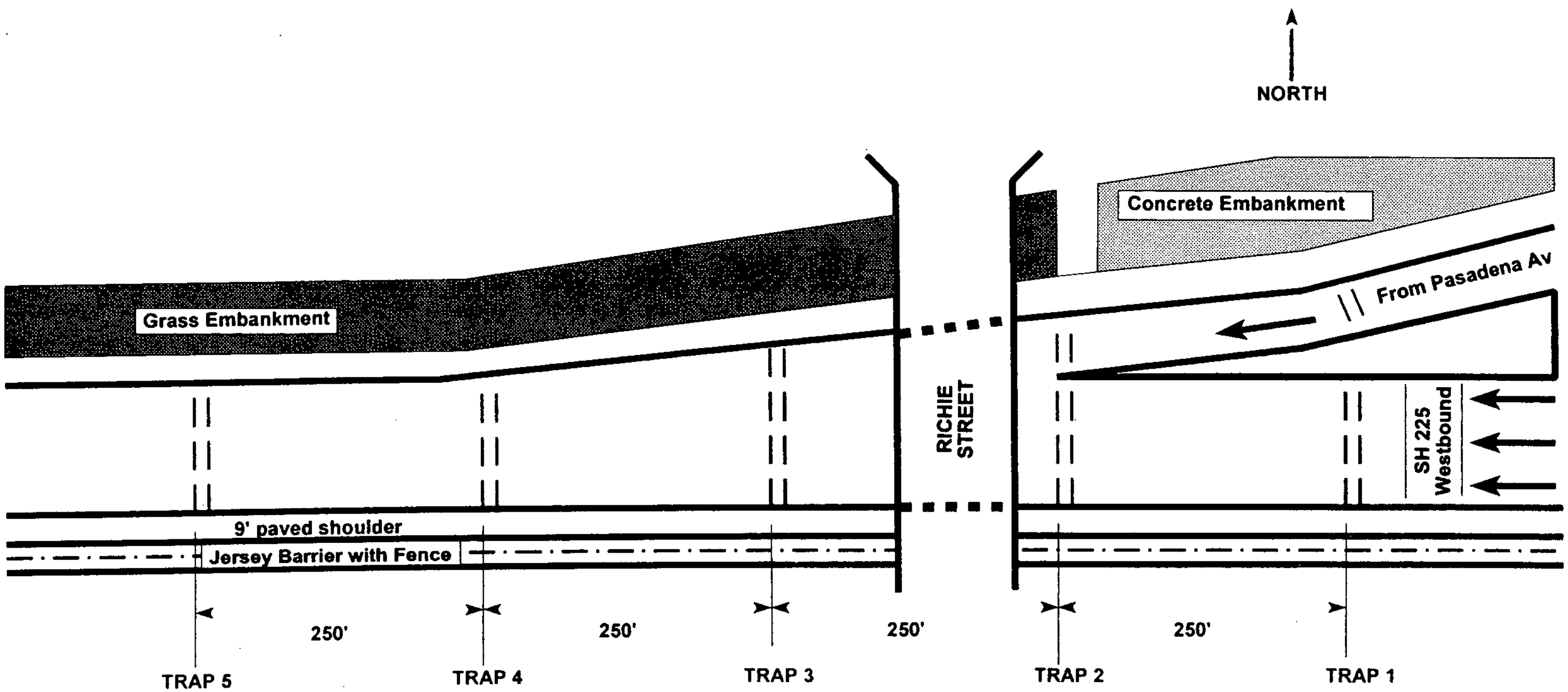


Figure 1-9. Schematic diagram of TES Site 1 field deployment.

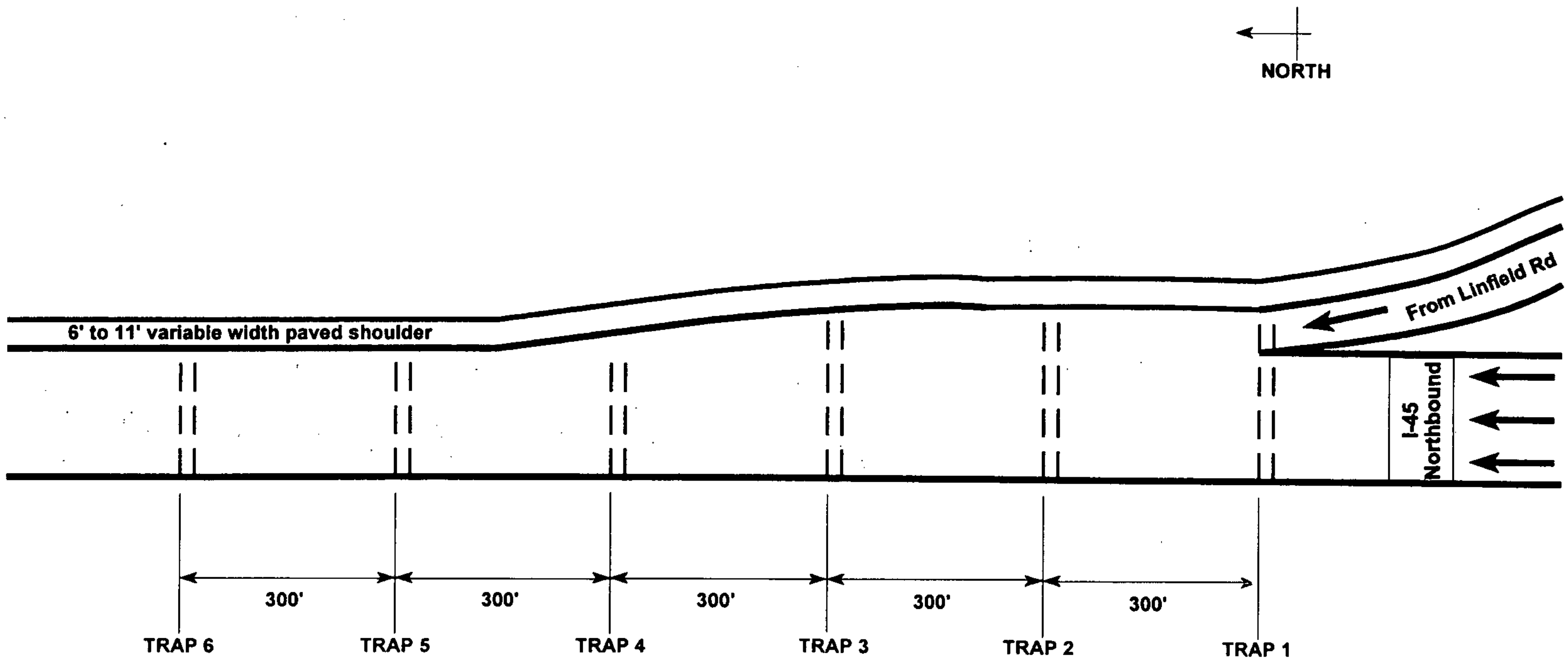


Figure 1-10. Schematic diagram of TES Site 2 field deployment.

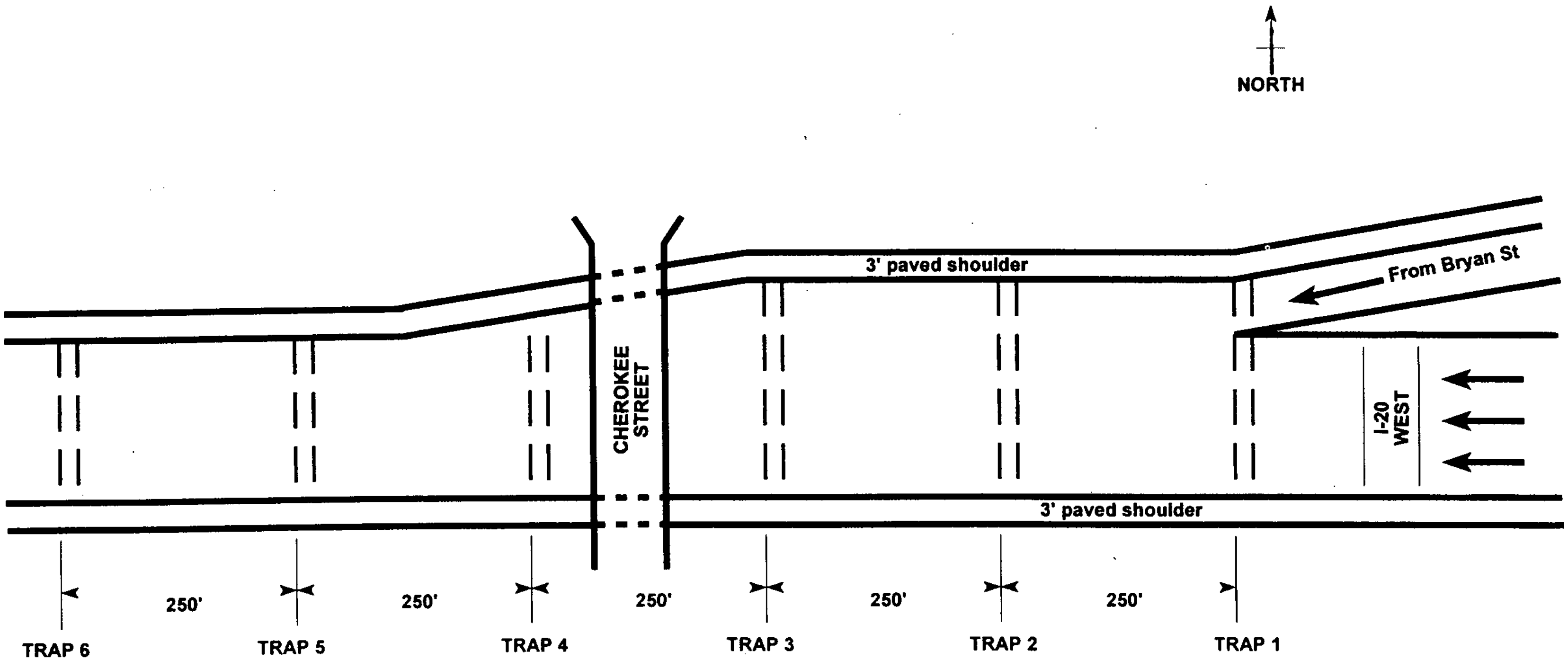


Figure 1-11. Schematic diagram of TES Site 3 field deployment.

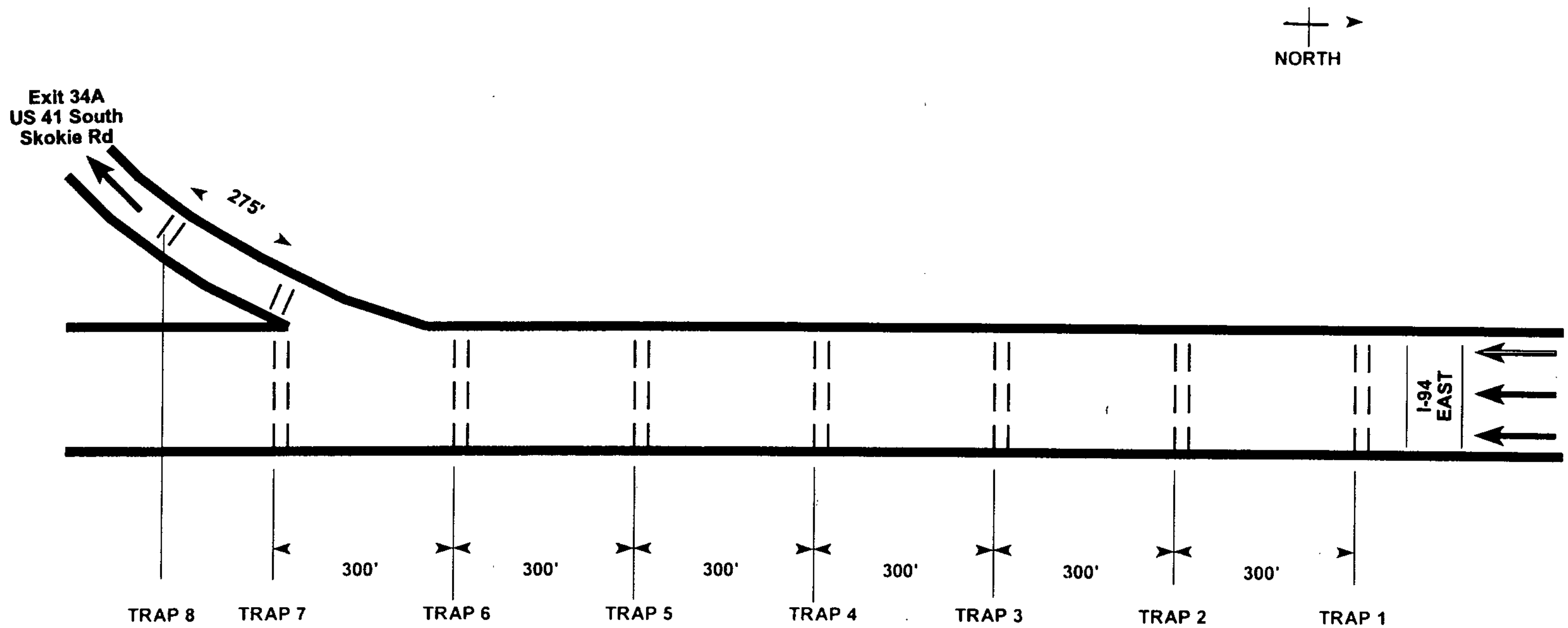


Figure 1-12. Schematic diagram of TES Site 4 field deployment.

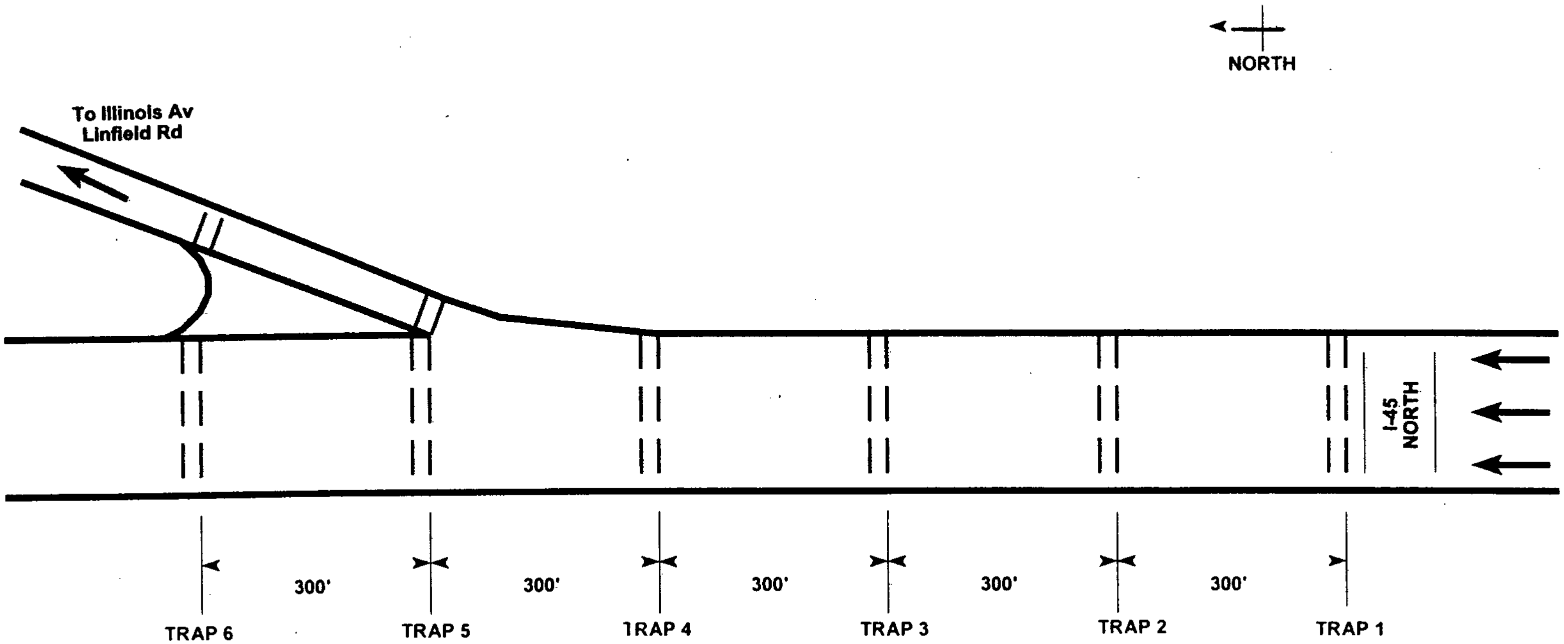


Figure 1-13. Schematic diagram of TES Site 5 field deployment.

TES Site 4

Site Description: Ramp Junction—Diverge

Location: Chicago, Illinois. The location of this site is on southbound I-94 East (Edens Expressway South) on the northern perimeter of the SMSA; specifically, southbound Exit 34A.

Geometric Characteristics: The instrumented area of the site is 1,800-ft long beginning at mile marker 33/63 upstream of the painted gore and terminating near the nose of the painted gore. There are three 12-ft-wide mainline lanes, a 7-ft-wide paved median shoulder, and a 12-ft-wide paved shoulder; condition of the road surface and shoulders is good to excellent.

TES Site 5

Site Description: Ramp Junction—Diverge

Location: Dallas, Texas. The general area of this study site is I-45 northbound in the south-central section of Dallas. Specifically, the area of interest is on I-45 in the vicinity of the Illinois Avenue-Linfield Road exit.

Geometric Characteristics: The instrumented area of the site is 1,200-ft long. The approach to the site and area of instrumentation is at grade changing to a very slight upgrade at the diverge. The three 12-ft-wide mainline lanes are in good repair as are the shoulders; opposing movements are separated by a wide grass median strip. Sight distance is excellent.

Field Data Conversion to 94HCM Format

A BASIC program was written to extract all pertinent data from the TES TRACE output tapes (as shown in Figure 1-8) necessary for the computation of vehicle performance measures. The program generated two output files. The first gives detailed volume and speed data for each lane and trap, while the second file gives a summary output for each period consisting of ramp and freeway volume; percentage of heavy vehicles; freeway, ramp, and influence area speeds. In addition, a spreadsheet was created to take the secondary output file and generate summary tables and graphical outputs of the data. Figure 1-14 shows a sample output of the two output files from this program.

All of the performance measures were easily derived from the TES output tapes. Some, such as the speed and density in the influence area (S_R and D_R), were approximated using the following process:

Consider the ramp junction shown in Figure 1-15 with volume and speed data extracted from the TES output tapes as described in Figure 1-14. The average speed of vehicles operating within the influence area is approximated by

$$S_R = \frac{\sum_{i=0}^{2}\sum_{j=1}^{n}(V_{i,j} \times S_{i,j})}{\sum_{i=0}^{2}\sum_{j=1}^{n} V_{i,j}}$$

where $V_{i,j}$ = Volume for lane I and trap j
$S_{i,j}$ = Speed for lane I and trap j

and the density within the influence area is approximated by

$$D_R = \frac{AVERAGE\{V_{T1} + V_{T2} + \ldots + V_{Tn}\}}{S_R}$$

where V_{Tn} = Sum of volumes at a given trap within the influence area,

for example, $V_{T1} = V_{0,1} + V_{1,1} + V_{2,1}$

NCHRP PROJECT 3-37(1) DATA AND ITS ORIGIN

The original Project 3-37 database was collected over a $1^1/_2$-year period in numerous cities located in 10 different states throughout the country. Most of the sites were merge junctions on 6-lane freeway sections, representative of the most prevalent freeway type in the United States. Table 1-6 presents a summary of the data collection study sites as presented in the NCHRP Project 3-37 (1) Final Report.

The data collection methodology consisted of multiple video-camera locations equally spaced at approximately 500 ft with a total coverage area within the ramp-freeway junction of 2,000 ft. Figure 1-16 shows a typical field deployment of the data collection equipment for both merge and diverge sections. In addition to the video-taping of the "main" ramp-junction (or study section), upstream and/or downstream ramp-junctions were recorded with the use of magnetic traffic counters capable of storing volume, speed, and vehicle classification data.

The data reduction was done by both manual and automated computer techniques. Several computer programs were developed for this task. The reader may refer to Appendix A of the 3-37(1) Final Report for a more detailed description of the programs.

The data, which consisted of volume, speed, and vehicle type by lane for each of the five traps, was summarized in 5-min and 15-min intervals and subsequently

Primary Output File

TRAP	VOLUMES 5	4	3	2	1	TRAP	SPEEDS 5	4	3	2	1		
L0	0.	0.	84.	340.	344.	L0	0.0	0.0	49.2	46.4	42.4	1	1
L1	700.	744.	712.	480.	480.	L1	51.1	52.8	54.0	56.1	56.6	1	1
L2	960.	936.	900.	896.	872.	L2	55.1	56.7	58.1	58.7	59.3	1	1
L3	940.	920.	896.	880.	860.	L3	58.9	60.3	61.9	61.1	61.5	1	1
	0.	0.	76.	256.	252.		0.0	0.0	50.3	46.4	42.8	1	1
	548.	584.	532.	364.	372.		51.4	53.1	54.3	56.7	57.1	1	1
	876.	864.	856.	856.	836.		56.1	57.4	58.9	59.2	59.8	1	1
	748.	716.	704.	700.	696.		59.0	60.6	61.9	62.0	61.6	1	1
	0.	0.	88.	280.	280.		0.0	0.0	49.6	47.2	43.4	1	1
	524.	560.	508.	356.	352.		51.7	53.5	54.8	57.5	57.1	1	1
	760.	760.	740.	696.	704.		55.6	57.0	58.4	58.7	59.3	1	1
	640.	588.	564.	572.	568.		59.3	60.9	62.3	62.5	62.1	1	1
	0.	0.	68.	176.	176.		0.0	0.0	49.1	47.7	43.7	1	1
	540.	552.	508.	408.	416.		50.8	52.3	53.9	55.1	55.6	1	1
	776.	764.	744.	740.	744.		55.1	56.7	57.9	57.8	58.6	1	1
	596.	584.	576.	572.	568.		58.6	60.3	61.9	62.3	62.1	1	1
	0.	0.	40.	224.	236.		0.0	0.0	51.4	46.6	42.4	1	1
	484.	524.	512.	340.	320.		50.7	52.6	53.6	55.1	55.9	1	1
	760.	732.	728.	716.	708.		54.9	56.3	57.4	58.1	78.9	1	1
	656.	648.	636.	624.	620.		59.2	60.6	61.8	61.9	61.8	1	1

Secondary Output File

VR	V1	V2	V3	VF	%V1	%V2	%V3	VO1	VO2	VO3	VOF	%HVR	%HVF	SRMP	SFWY	SR	DR	PD	Site
452	620	1180	912	2712	0.23	0.44	0.34	796	1376	1088	3260	0.05	0.04	42.2	60.1	57.3	37.7	1	1
344	580	1016	708	2304	0.25	0.44	0.31	736	1088	864	2688	0.05	0.05	44.2	62.1	59.4	31.3	2	1
472	640	1124	928	2692	0.24	0.42	0.34	860	1236	1116	3212	0.03	0.05	43.9	61.1	59.3	36.3	3	1
456	656	1316	1096	3068	0.21	0.43	0.36	868	1432	1248	3548	0.11	0.04	42.2	61.8	58.9	39.7	4	1
484	808	1372	1180	3360	0.24	0.41	0.35	972	1500	1436	3908	0.02	0.03	43.8	61.1	59.2	42.9	5	1
296	600	956	732	2288	0.26	0.42	0.32	664	1080	852	2596	0.01	0.06	44.3	62.8	60.5	29.7	6	1
296	484	752	556	1792	0.27	0.42	0.31	540	920	640	2100	0.05	0.07	42.2	62.3	59.7	25.0	7	1

Figure 1-14. Extracted output files from TRACE tapes used to summarize data.

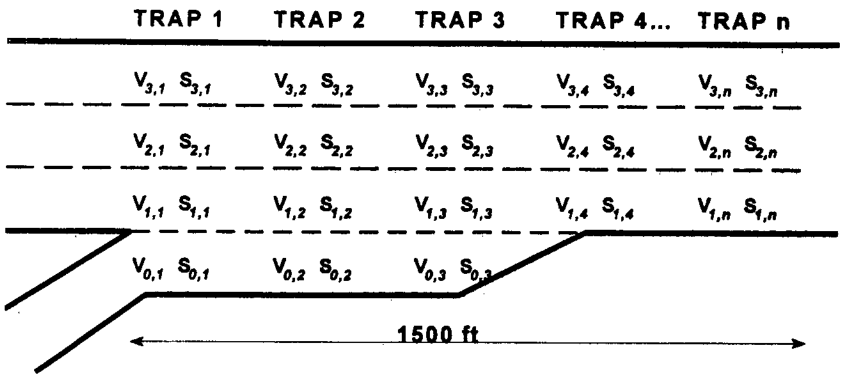


Figure 1-15. Illustration of merge ramp-junction influence area.

TABLE 1-6 Summary of full data-collection study sites

Type	4-Lane	6-Lane	8-Lane	10-Lane	Total
Merge (72%)	8	25	8	1	42
Diverge (28%)	6	7	3	0	16
Subtotal	**14**	**32**	**11**	**1**	**58**
Percent by Type	**24%**	**56%**	**20%**	**---**	**100%**
Double-On	0	2	0	0	2
Double-Off	0	1	0	0	1
Major Merge	0	1	0	0	1
Major Diverge	0	1	0	0	1
Metered ("On")	0	2	0	0	2
Metered ("Off")	0	3	0	0	3
TOTAL	**14**	**42**	**11**	**1**	**68**

Source: "Capacity of Ramp-Freeway Junctions" Final Report, March 1994.

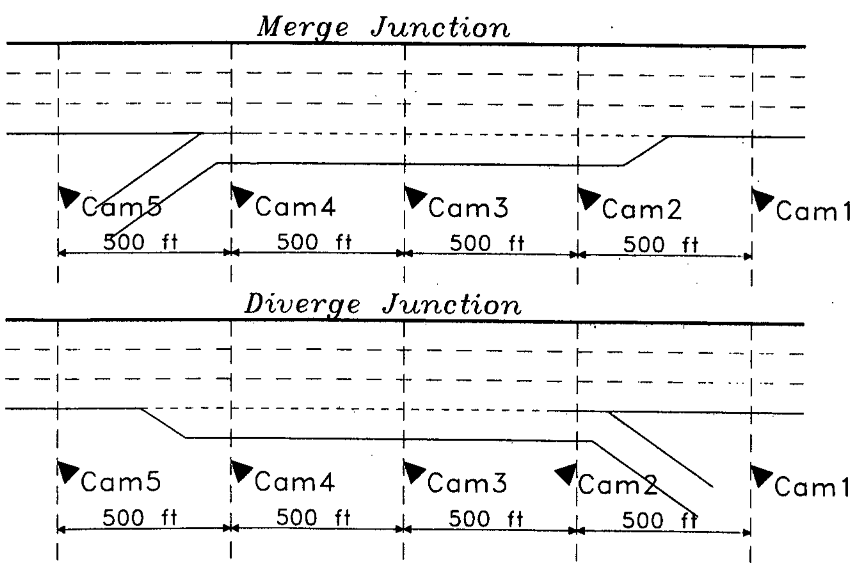


Figure 1-16. Typical field deployment for Project 3-37 data collection effort.

imported into a statistical analysis package for generating plots and performing basic statistical analysis of the data.

Description of NCHRP Project 3-37(1) Sites

From the 68 sites collected, 17 were selected for the purpose of the analysis presented in this report. The criterion used in the selection was simple—select sites that are as close as possible to "ideal" conditions in terms of traffic and geometry (i.e., flat terrain, 12-lane widths, adequate lateral clearance, and no presence of heavy vehicles). Table 1-7 shows the basic characteristics of the selected sites. In addition, the table shows combinations of all ramp-junction sequences possible. The numbers in the cells correspond to the site number as designated in the 3-37(1) final report. Table 1-8 gives a more detailed description of each of the sites for those variables used in the analysis as presented in Figure 1-17. The codes shown in Table 1-7 will be used for grouping the individual sites by configuration type (e.g., M1 corresponds to merge ramps at isolated junctions).

From the tables, the breakdown by type of ramp-junction is 65 percent merge and 35 percent diverge. The breakdown by size of freeway section is 35 percent for 4-lane, 53 percent for 6-lane and 12 percent for 8-lane sections.

Although at first glance the 17 sites seem to be an adequate sample size (25 percent of the total database), many gaps do exist given the possible combination of merge-diverge ramp sequences, especially in the 8-lane freeway sections. It is, however, a good representation of the Project 3-37 database, which had similar gaps.

In preparing the data for input to FRESIM and subsequently the output, procedures followed were similar to those outlined in the previous section, with the exception of converting volumes from vph to pcph, since the original data were already in pcph (due to the near "ideal" geometric and traffic conditions).

TABLE 1-7 Selected sites from Project NCHRP 3-37 database used for analysis

M1			**D1**		
4-Lane	**6-Lane**	**8-Lane**	**4-Lane**	**6-Lane**	**8-Lane**
-	-	-	-	-	-
M2			**D2**		
4-Lane	**6-Lane**	**8-Lane**	**4-Lane**	**6-Lane**	**8-Lane**
9	-	-	*36, 54, 56*	*15, 35, 37*	-
M3			**D3**		
4-Lane	**6-Lane**	**8-Lane**	**4-Lane**	**6-Lane**	**8-Lane**
40	*8, 10*	*46*	-	-	-
M4			**D4**		
4-Lane	**6-Lane**	**8-Lane**	**4-Lane**	**6-Lane**	**8-Lane**
-	*10, 26*	*46*	*36, 54, 56*	*15, 35, 37*	-
M5			**D5**		
4-Lane	**6-Lane**	**8-Lane**	**4-Lane**	**6-Lane**	**8-Lane**
16, 40	*8, 18, 23, 25*	*27*	-	-	-

TABLE 1-8 Description of selected sites for analysis

Site Number	No. Of Lanes	Type	D_U - Type	D_D - Type	L_A/L_{AP} or L_D/L_{DP}
08	3	ON	450 ft - OFF	6000 ft - OFF	350/450 ft
09	2	ON	N/A	1500 ft - ON	500/750 ft
10	3	ON	750 ft - ON	5800 ft - OFF	750/1,000 ft
15	**3**	**OFF**	**3,000 ft - ON**	**1000 ft - ON**	**150/300 ft**
16	2	ON	1,670 ft - OFF	N/A	1,000/1,325 ft
18	3	ON	1,500 ft - OFF	N/A	750/1,075 ft
23	3	ON	1,820 ft - OFF	N/A	1,700/2,300 ft
25	3	ON	1,600 ft - OFF	N/A	650/1,100 ft
26	3	ON	1,280 ft - ON	N/A	620/990 ft
27	4	ON	1,630 ft - OFF	N/A	970/1,335 ft
35	**3**	**OFF**	**4,500 ft - ON**	**900 ft - ON**	**0/300 ft**
36	**2**	**OFF**	**2,100 ft - ON**	**3,160 ft - ON**	**0/600 ft**
37	**3**	**OFF**	**3,850 ft - ON**	**1,600 ft - ON**	**0/300 ft**
40	2	ON	2,110 ft - OFF	3,160 ft - OFF	870/1,400 ft
46	4	ON	1,200 ft - ON	4,420 ft - OFF	265/815 ft
54	**2**	**OFF**	**3,160 ft - ON**	**1,720 ft - ON**	**245/490 ft**
56	**2**	**OFF**	**5,280 ft - ON**	**2,100 ft - ON**	**85/325 ft**

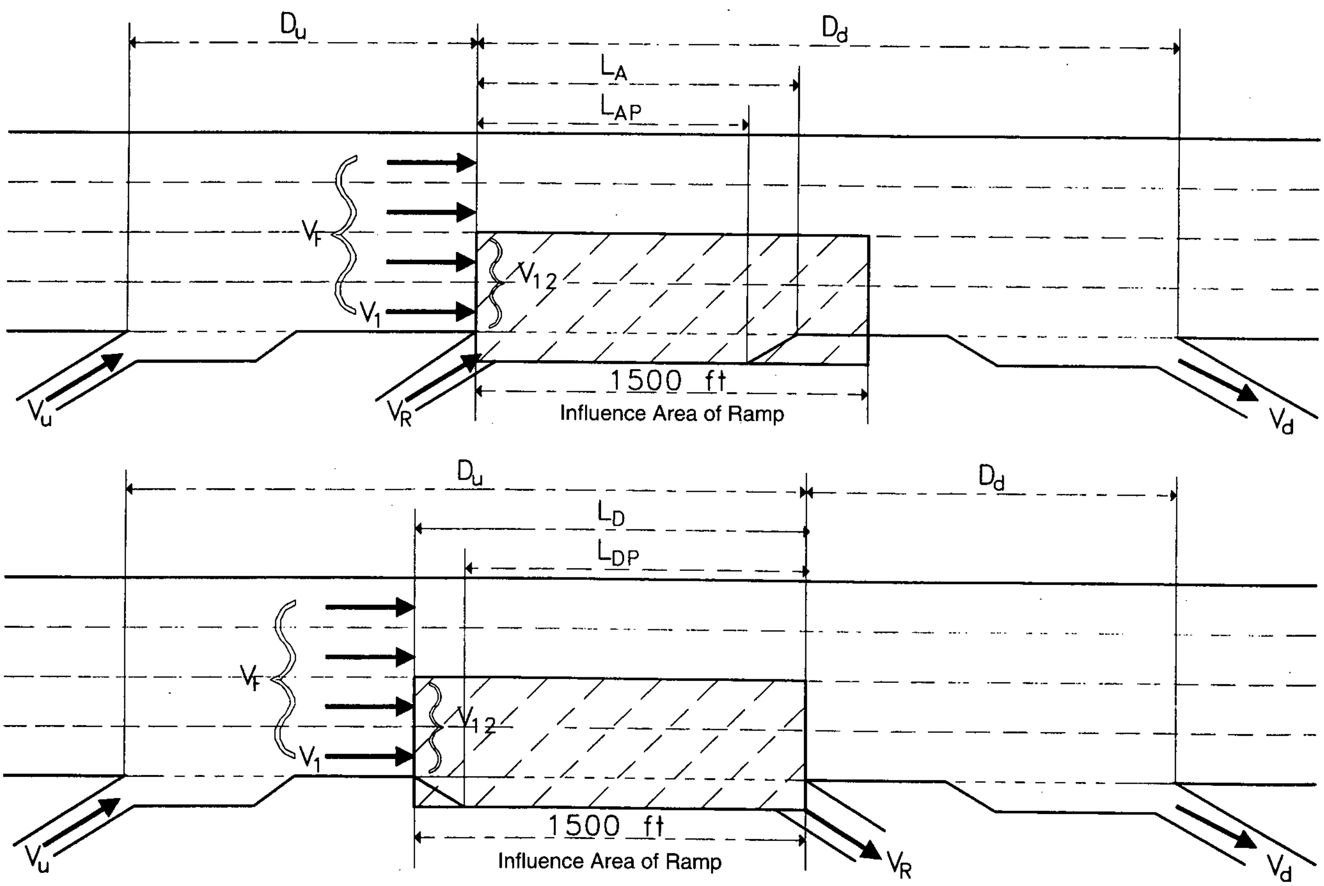


Figure 1-17. Illustration of ramp-junction variables.

CHAPTER 2
COMPARING PREDICTIONS OF LANE DISTRIBUTION

One of the critical analytic formulations of the 94HCM model for ramps is the prediction of volume in lanes 1 and 2 of the freeway immediately upstream of the ramp junction. A collection of analytic models is provided that predicts this value, depending on the specific configuration. Predictions depend on such variables as type of ramp (off-, on-), total upstream freeway volume, ramp volume, proximity and volume on adjacent upstream or downstream ramps, length of acceleration or deceleration lane, and free-flow speed of the ramp. The latter is an effective surrogate for such geometric details as angle of convergence (or divergence), superelevation, and degree of curvature.

Thus, in assessing the applicability of FRESIM to analysis of ramp junctions, its approach to lane distribution must be carefully studied and demonstrated.

LANE DISTRIBUTION IN FRESIM

FRESIM begins with an assumption of equal distribution of vehicles among available lanes. The simulator inputs vehicles on this basis. Internal parameters control driver aggressiveness in lane-changing, resulting in changes in lane distribution based upon the macroscopic result of individual behavior at points downstream.

To test the reaction of the simulator to a series of on- and off-ramps, the example illustrated in Figure 2-1 was created. Lane distribution was checked 1,500 ft downstream of the input flows and immediately upstream of each ramp in the sequence for four different volume scenarios, indicated as Scenarios A through D. Figures 2-2 and 2-3 illustrate the results: Figure 2-2 plots the percent of vehicles in lane 1 of the 3-lane freeway at each of the checkpoints; Figure 2-3 plots the percent of vehicles in lanes 1 and 2.

As illustrated in Figure 2-2, lane 1 usage 1,500 ft from the input remains relatively stable, hovering around 33 percent. The range of variation is not large, going from a high of 33.8 percent (for the lowest-volume Scenario A) to 32.2 percent. The latter, surprisingly, is not for the highest-volume Scenario D, but for Scenario C. In Figure 2-3, the total usage of lanes 1 and 2 at this location illustrates a pattern in which the concentration of vehicles in these lanes is greater than the proportional 66.7 percent for all scenarios. Values range from 69.2 percent for Scenario A to 67.4 percent for Scenario C. Scenarios B, C, and D are very similar, with the lowest-volume Scenario A showing the highest concentration of vehicles in these lanes.

Immediately upstream of the first ramp (an on-ramp), the concentration of vehicles in lane 1 declines for all four scenarios, with the lowest-volume Scenario A showing the sharpest decline. The percent volume in lane 1 ranges from 30 percent to 31.8 percent. The concentration of vehicles in lanes 1 and 2 declines for Scenarios B, C, and D to an almost uniform 67 percent. Under Scenario A, however, the concentration increases to 70 percent. This latter result is somewhat illogical. What this suggests is that as vehicles approach the first on-ramp, they move both from lane 1 to lane 2, and from lane 3 to lane 2. Taking Figures 2-2 and 2-3 together, they suggest that upstream of the first ramp, $70 - 30 = 40$ percent of the total flow in Scenario A is in lane 2. The implied movement from lane 3 to lane 2, even for a light volume scenario, is counter to the expected behavior of vehicles approaching an on-ramp conflict.

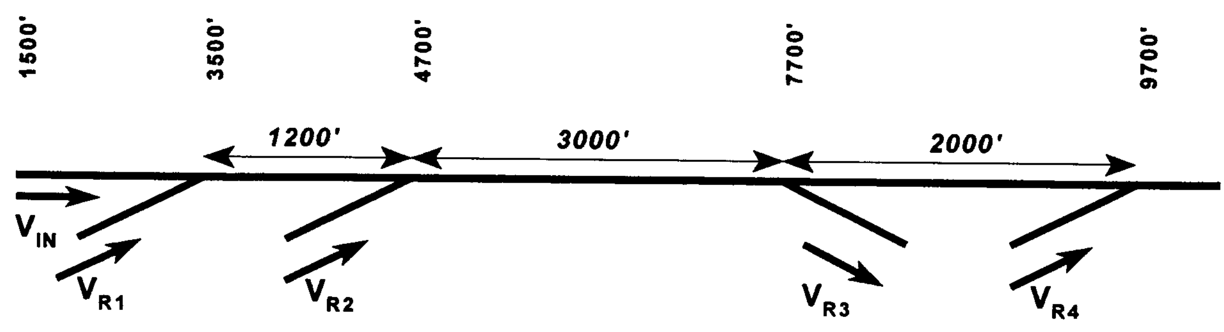
Upstream of the second on-ramp, the lane distribution suggested by FRESIM is even more difficult to understand. The concentration of vehicles in lane 1 increases (from the last checkpoint) to almost 33 percent for all scenarios. The concentration in lanes 1 and 2, taken together, however, varies considerably among the four scenarios. Again, for the light-volume Scenario A, concentration of vehicles in both lanes increases to 71.7 percent, implying a lane 2 concentration of $71.7 - 33 = 38.3$ percent. The suggestion is that vehicles continue to move towards the right, despite the existence of two moderately loaded on-ramps. For Scenario D, the total concentration of vehicles in lanes 1 and 2 begins to level off; it increases for Scenarios B and C.

At the third checkpoint, the off-ramp, results are also puzzling. In general, concentration of vehicles in lane 1 decreases, despite the off-ramp that forces some vehicles into the right lane. For all four scenarios, the concentration of vehicles in lanes 1 and 2 also declines, suggesting that vehicles are moving to the third lane at all flow levels in the vicinity of the off-ramp.

The last checkpoint is just upstream of the final on-ramp. For the Scenarios A and B, concentration of vehicles in lane 1 declines somewhat, as does the concentration of vehicles in lanes 1 and 2. For the heavier-flow Scenarios C and D, these concentrations increase or stabilize.

Several points can be made from this illustration:

1. FRESIM's predicted lane distributions are not highly sensitive to the existence of ramps or ramp flows. For all checkpoints and all flow scenarios, the concentration of vehicles in lane 1 varies from 28.7 percent to 33.8 percent, and the concentration of vehicles in lanes 1 and 2 varies from 64.8 percent to 71.6 percent. The range of variation is limited to 5 to 7 percent, surrounding (not symmetrically) the equal distribution scenario assumed at the input point.



Case	V_{IN}	V_{R1}	V_{R2}	V_{R3}	V_{R4}
A	2,000	150	100	~12% (325)	100
B	3,000	250	250	~12% (400)	150
C	4,000	350	400	~12% (540)	200
D	5,000	450	550	~11% (615)	250

PHF=1.00; %Trucks=0%; Level Terrain; L_A =600' ; L_D =400'; S_{FF} = 60mph; S_{FR} = 45 mph

Figure 2-1. Test section scenarios for lane distribution analysis of FRESIM.

2. Conventional wisdom indicates that freeway vehicles tend to move away from on-ramp junctions and towards off-ramp junctions, the latter dominated by the fact that off-ramp vehicles must be in lane 1 at the junction. The illustration demonstrates that FRESIM does not consistently indicate this kind of behavior.

3. The results suggest a degree of randomness to the process of lane distribution, as trends are not consistent.

These fundamental characteristics of the FRESIM model are compared to actual data for ramp junctions in subsequent sections of this chapter.

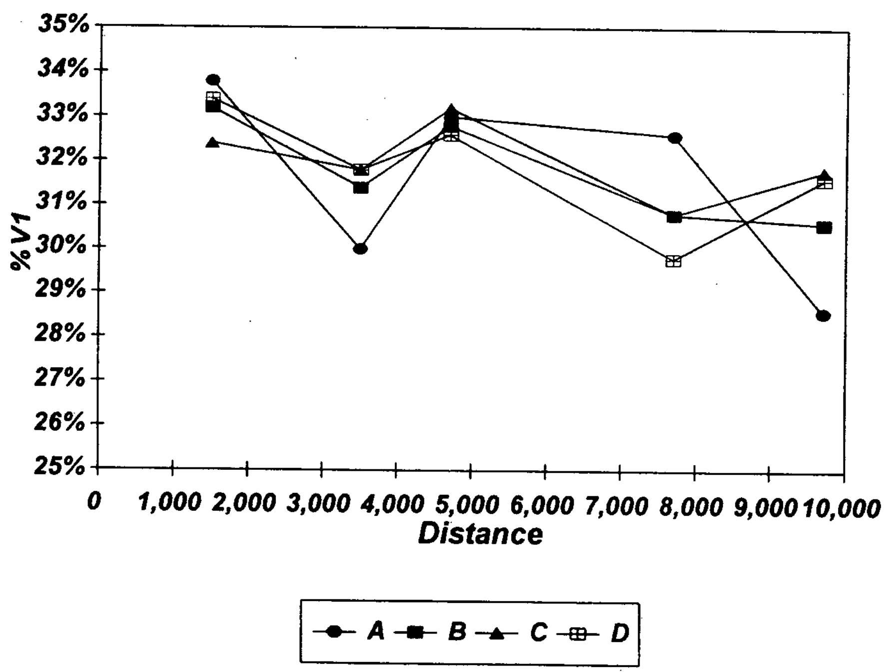


Figure 2-2. Percentage of vehicles in Lane 1 of test section.

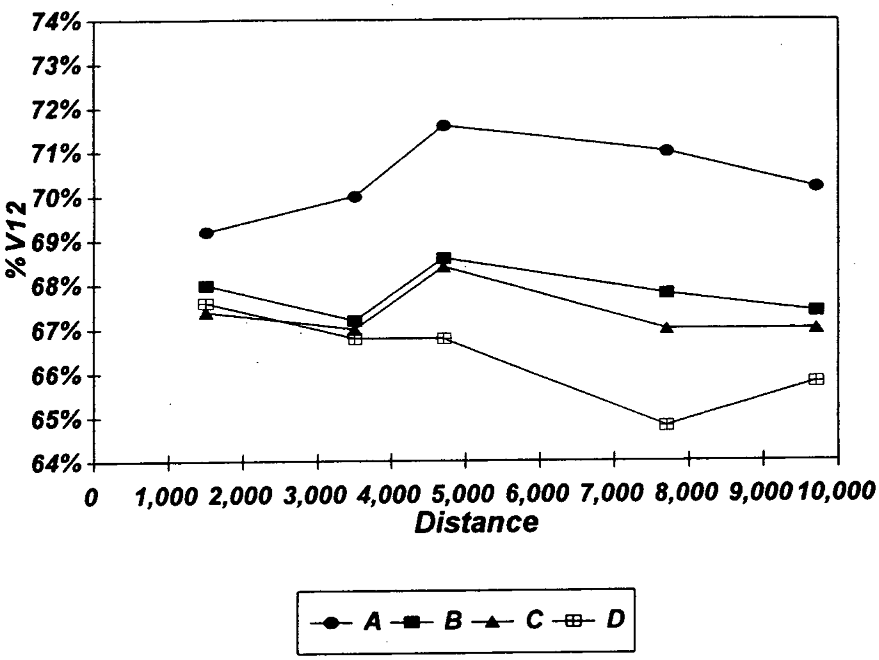


Figure 2-3. Percentage of vehicles in Lanes 1 and 2 of test section.

GENERAL LANE DISTRIBUTION CHARACTERISTICS: FIELD DATA

Figure 2-4 is a plot of lane distribution immediately upstream of the three on-ramp sites of the TES database. The three on-ramps are all on 6-lane freeways, and all are isolated, i.e., at least 1 mi away from adjacent upstream or downstream ramps. For freeway volumes up to 3,500 vph, the heaviest concentration of volume is in lane 2, ranging from over 80 percent for extremely low volumes to about 45 percent for volumes around the 3,500 vph boundary. Except for very low volumes, lane 1 concentration in this range hovers around 20 percent. At volumes over 3,500, the distribution of vehicles among the three lanes moves toward but does not fully achieve equalization. Lane 1 flows rarely exceed 30 percent of the total, with lane 2 continuing to show the highest concentrations in the vicinity of 38 percent.

Figure 2-5 is a similar plot for two off-ramp sites on 6-lane freeways from the TES database. The characteristics are similar, but not as extreme as those for the on-ramp sites. At low volumes (<3,500 vph), lanes 1 and 2 carry the bulk of the traffic, with no strong indication of which dominates. The lane distribution approaches equalization more quickly, and at volumes over 5,000 vph, the lane distribution approaches full equalization (33.3 percent per lane) with little variation.

Figures 2-6 and 2-7 show similar trends for 6-lane freeway data from the NCHRP Project 3-37 database. For merge sites, while lane distribution becomes more equal as total volume increases, the degree of convergence is considerably less than for the TES sites. This may be due to the fact that the NCHRP Project 3-37 sites were not as isolated as the TES sites, and lane distributions may reflect the influence of other nearby ramps. For the NCHRP sites, lane 3 carries the heaviest concentration of vehicles at high volumes. The concentration of vehicles in lane 1 varies widely at volumes over 3,500, from a high of about 34 percent to a low of 9 percent.

Unfortunately, there are no low-volume data for Figure 2-7. No clear trends are evident, with dominant lanes changing for each data set. Lane 1 concentrations vary from 27 percent to 46 percent, with smaller variations for concentrations in lanes 1 and 2.

Examination of the field data for 6-lane freeways suggests that the variation in actual lane distribution is considerably greater than that evident in the FRESIM sensitivity analysis discussed in the previous section. Subsequent analyses comparing the accuracy of FRESIM and the 94HCM method in predicting the volume in lanes 1 and 2 of the freeway will provide further enlightenment on the impact of this apparent lack of sensitivity in FRESIM.

COMPARING THE ACCURACY OF V_{12} PREDICTIONS WITH AN INDEPENDENT DATABASE: TES DATA

Technical Report No. 2, submitted in October 1995, reports in detail on the use of an independent database from the FHWA Traffic Evaluator System (TES) to compare the accuracy of FRESIM and the 94HCM in predicting volumes in lanes 1 and 2. While the entire analysis will not be repeated herein, a summary of the key results and some supporting illustrations are useful in establishing an overall picture of the two procedures.

The TES data base, described in Chapter 1, consists of three isolated on-ramps and two isolated off-ramps on a 6-lane freeway. Actual data were compared to three different

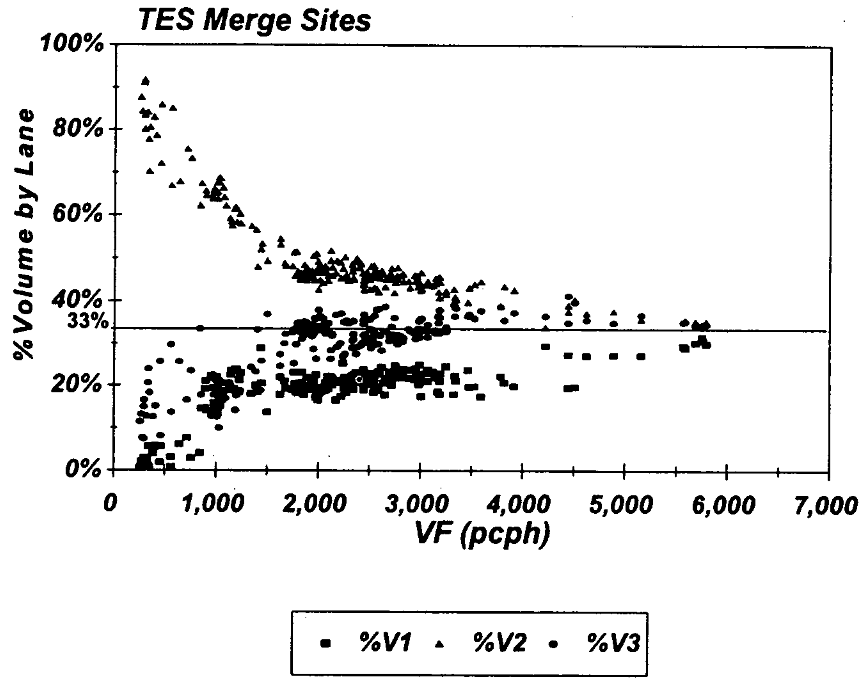


Figure 2-4. Lane distribution for three TES on-ramp sites (on 6-lane freeways).

predictions of V_{12}: (a) 94HCM, (b) FRESIM (unmodified), and (c) FRESIM, modified by placing the actual observed lane distribution in effect at the point of input. The latter was introduced to test the impact of the assumption of uniform lane distribution at the starting point versus the impact of a known distribution based upon the impact of upstream effects (which are not precisely known in the TES database). It was fully expected that the modified FRESIM would produce excellent results (since the modification prespecifies the variable to be predicted, albeit at an upstream point), but its later impact on density predictions was not as easy to anticipate.

Figure 2-8 illustrates the comparison among the three methods in predicting V_{12} for the three merge sites. The results are somewhat mixed:

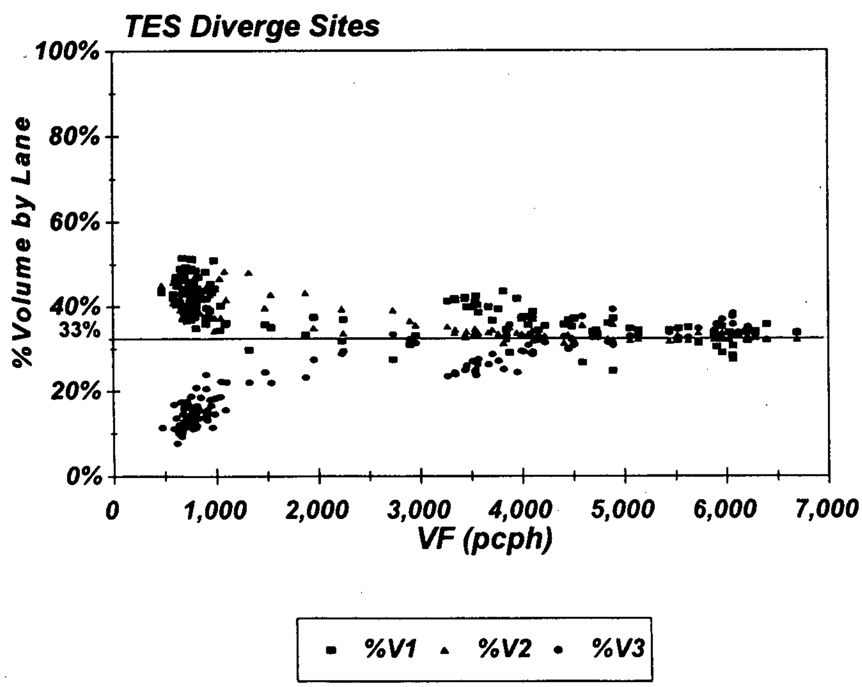


Figure 2-5. Lane distribution for two TES off-ramp sites (on 6-lane freeways).

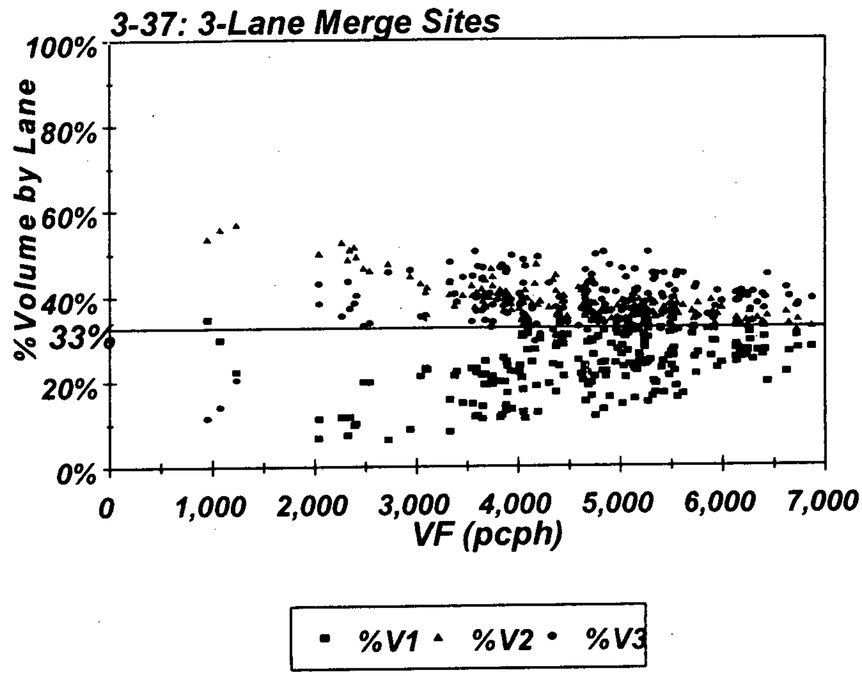


Figure 2-6. Lane distribution for on-ramps on a 6-lane freeway (NCHRP Project 3-37 data).

1. In all cases, the modified FRESIM model yields the best predictions. This is not unexpected, as discussed previously.
2. For Site 1, FRESIM gives slightly better predictions than the 94HCM for freeway volume levels below 1,750 vph. In such cases, the 94HCM tends to under predict V_{12} by about 10 percent. For higher freeway volumes, the 94HCM produces better predictions, with FRESIM yielding predictions that are about 10 percent too high.
3. For Site 2, both FRESIM and the 94HCM tend to under predict V_{12} at lower freeway volumes (<1,750 vph), in this case by as much as 20 percent. At higher volumes,

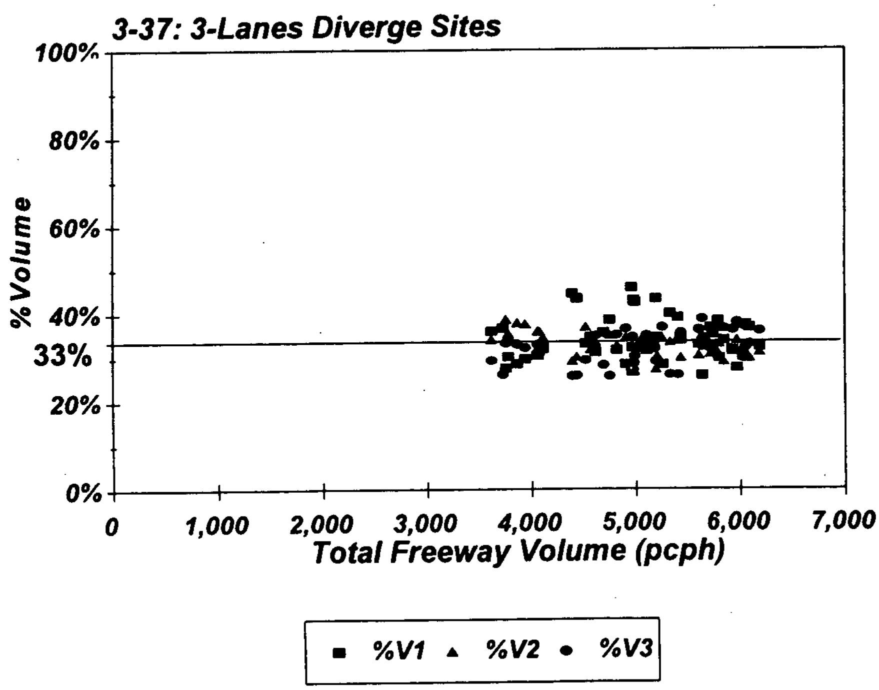


Figure 2-7. Lane distribution for off-ramps on a 6-lane freeway (NCHRP Project 3-37 data).

FRESIM is a better predictor, with the 94HCM continuing to under predict by between 5 percent and 10 percent.

4. For Site 3, FRESIM yields slightly better predictions of V_{12} throughout the range of freeway volumes. Again, the 94HCM under predicts V_{12} by about 10 percent.

While the results are indeed mixed, it is fair to say that for the three merge sites in the TES data, FRESIM does a slightly better job of predicting V_{12} than the 94HCM. The difference is not, however, great, and either model seems to yield reasonable accuracy for the range of data tested.

Figure 2-9 shows similar comparisons for the two TES off-ramp sites. The following conclusions may be drawn:

1. For Site 4, the 94HCM yields better predictions of V_{12} throughout the range of freeway volumes. It even yields better predictions than the modified version of FRESIM, which is surprising. FRESIM tends to underestimate V_{12} at low freeway volumes and overestimate it at high volumes. The variation is in the 10 percent to 15 percent range for FRESIM predictions.

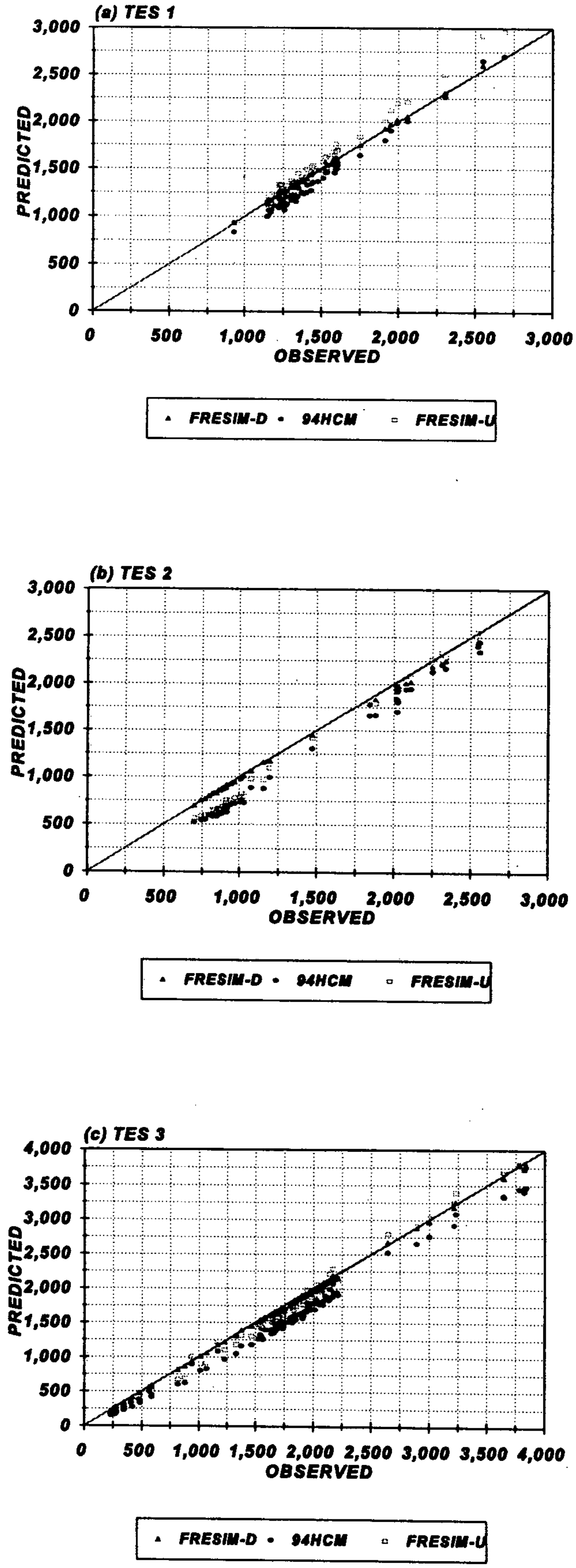


Figure 2-8. FRESIM versus 94HCM predictions of V_{12} for three TES on-ramps on a 6-lane freeway.

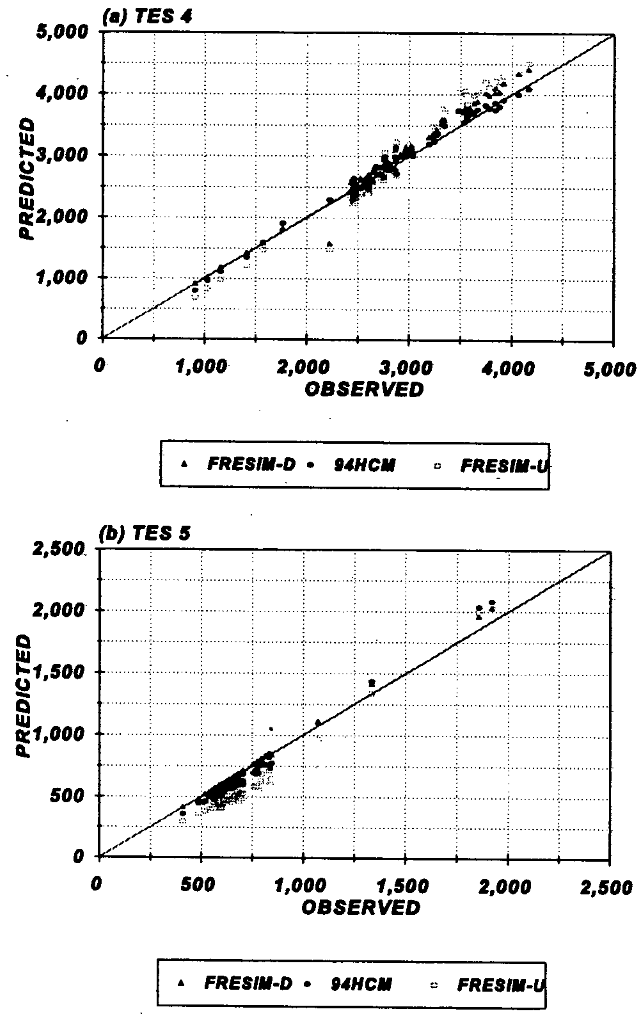


Figure 2-9. FRESIM versus 94HCM predictions of V_{12} for two TES off-ramps on a 6-lane freeway.

2. For Site 5, the modified FRESIM model gives the best overall predictions as expected. At low freeway volumes (<1,500 vph), the 94HCM yields better predictions of V_{12}. At high freeway volumes, both FRESIM and the 94HCM tend to over predict V_{12} by about 10 percent, with FRESIM having a very slight advantage over the 94HCM in accuracy.

These comparisons are relatively important as the TES data represent the only independent data available for study. Data from the NCHRP Project 3-37 is useful, but has been used in calibrating the 94HCM. On the other hand, the TES data represent only isolated ramps and cannot be used to assess the impact of adjoining ramps on the accuracy of the two models.

The comparisons, however, do not yield a clear result. If anything, they verify that both models produce reasonable results. FRESIM seems to do a better job with on-ramps, and the 94HCM seems to do a better job with off-ramp cases. There is nothing, however, in these comparisons that suggests that either model is significantly flawed or inappropriate for use.

COMPARING FRESIM AND THE 94HCM WITH CASES FROM THE NCHRP PROJECT 3-37 DATABASE

The prediction of V_{12} by FRESIM and the 94HCM was compared to field data for 11 sites from the NCHRP Project 3-37 database. No 2-lane sections were chosen for this comparison, as V_{12} is the freeway volume for such cases. The sites represent various configurations of upstream and downstream adjacent ramps. Figures 2-10 through 2-20 illustrate the results of these comparisons.

While this comparison is somewhat biased, as the 11 sites were used in the calibration of the 94HCM model, it allows the assessment of the impact of adjacent ramps on results.

Figures 2-10 and 2-11 illustrate on-ramps on 6-lane freeways. Each has an upstream on-ramp, while one also has a downstream off-ramp. In Figure 2-10, FRESIM overestimates V_{12} by a significant amount, in some cases by as much as 1,000 vph. Even the 94HCM overpredicts V_{12}, but by a considerably smaller margin, in the range of 300–500 vph. In Figure 2-11, FRESIM overpredicts V_{12} by from 200–500 vph, while the 94HCM produces very close estimates. It should be noted that FRESIM, though inferior to the 94HCM in both predictions, is considerably more accurate in Figure 2-11 where the adjacent upstream ramp is farther away.

Figure 2-12 shows an on-ramp with an upstream on-ramp on an 8-lane freeway. FRESIM again overpredicts V_{12} by as much as 1,000 vph, while the 94HCM produces reasonably accurate predictions.

Figures 2-13 through 2-16 depict on-ramps on 6-lane freeways with adjacent upstream off-ramps. A similar pattern begins to emerge. In Figure 2-13, where the distance to the upstream ramp is relatively small, FRESIM again substantially overpredicts V_{12} by as much as 600 vph. The 94HCM is a much better predictor in this case, but still results in overpredictions.

In Figures 2-14 and 2-15, the distance to the upstream ramp is much longer. In both cases, FRESIM does a far better job of predicting V_{12}, although the 94HCM still produces slightly better results. Figure 2-16 is a bit of an anomaly, as the distance to the upstream ramp is in the same range as Figures 2-14 and 2-15. Once again, FRESIM overpredicts V_{12} by 400-500 vph. In this case, however, the 94HCM is only marginally better. This case differs from the others in this group in that the V_{12} values are higher than those included in Figures 2-13 through 2-15. As V_{12} approaches 4,000 vph, FRESIM is actually producing marginally better results than the 94HCM.

Figure 2-17 depicts an on-ramp with an upstream off-ramp on an 8-lane freeway. For this case, FRESIM produces superior estimates of V_{12}. The 94HCM underpredicts V_{12} by as much as 500 vph.

Figures 2-18 through 2-20 show off-ramps on 6-lane freeways, all with adjacent upstream on-ramps. In all cases, FRESIM does a good job of predicting V_{12}. FRESIM and the 94HCM predict V_{12} with similar levels of accuracy.

Figure 2-21 summarizes all results for merge and diverge sites. For merge sites, it is clear that the 94HCM does a considerably better job of predicting V_{12} than FRESIM. For diverge sites, the difference in accuracy is not as pronounced but appears to favor the 94HCM slightly.

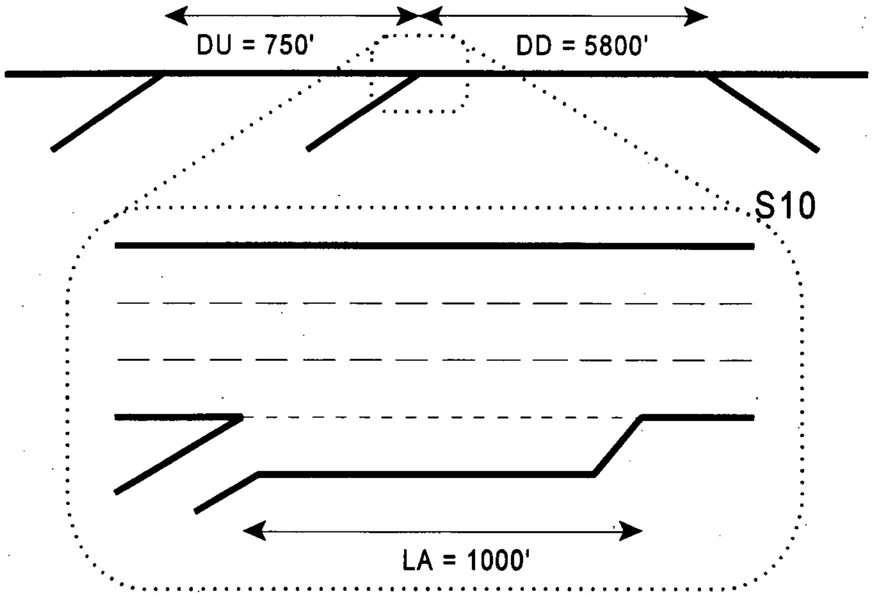
Given that the NCHRP database was used to calibrate the 94HCM model, it is difficult to draw firm conclusions from these comparisons. In general, the following might be concluded:

1. The relative advantage in accuracy of the 94HCM over FRESIM is not surprising, given that the 94HCM was partially calibrated using the test data.
2. There is a strong suggestion that FRESIM is not sensitive enough to the presence of adjacent ramps. Prediction errors tend to increase as the proximity of the adjacent ramp gets smaller.
3. FRESIM predictions of V_{12} tend to be more accurate when the values of V_{12} are high.

The second conclusion supports the sensitivity analysis reported in the first section of this chapter. In that analysis, it was shown that FRESIM's predicted lane distribution did not vary significantly for a four-ramp sequence with four different volume levels.

The accuracy of the 94HCM model can be more precisely compared to that of FRESIM by summarizing the average prediction error in V_{12} for each of the cases previously discussed. The average error is obtained by taking a square root of the sum of squared errors of individual predictions. The results are summarized in Table 2-1. Appendix C provides more detailed statistical data.

In seven of the 11 cases, the 94HCM is the better predictor; in the remaining four, FRESIM yields better predictions of V_{12}. Given the built-in advantage to the 94HCM when using the NCHRP data, this is a fairly good result for FRESIM. Of more



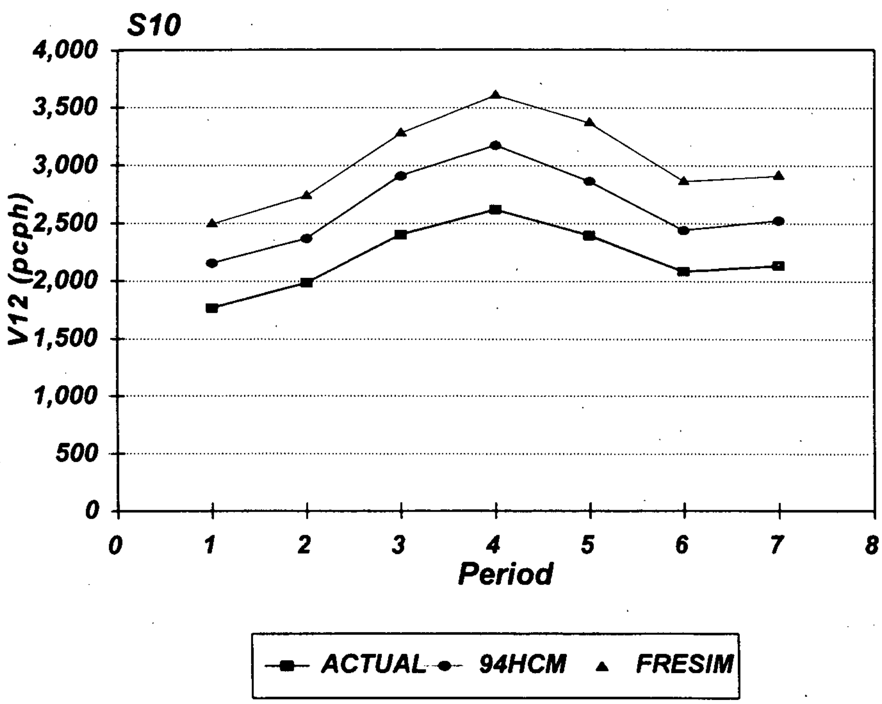
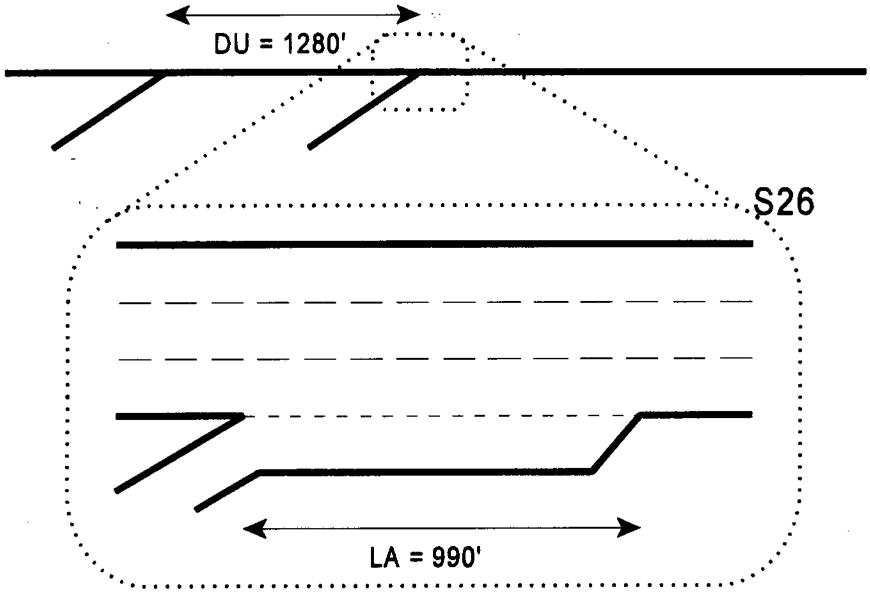


Figure 2-10. Predicted values of V_{12} for NCHRP Site 10.



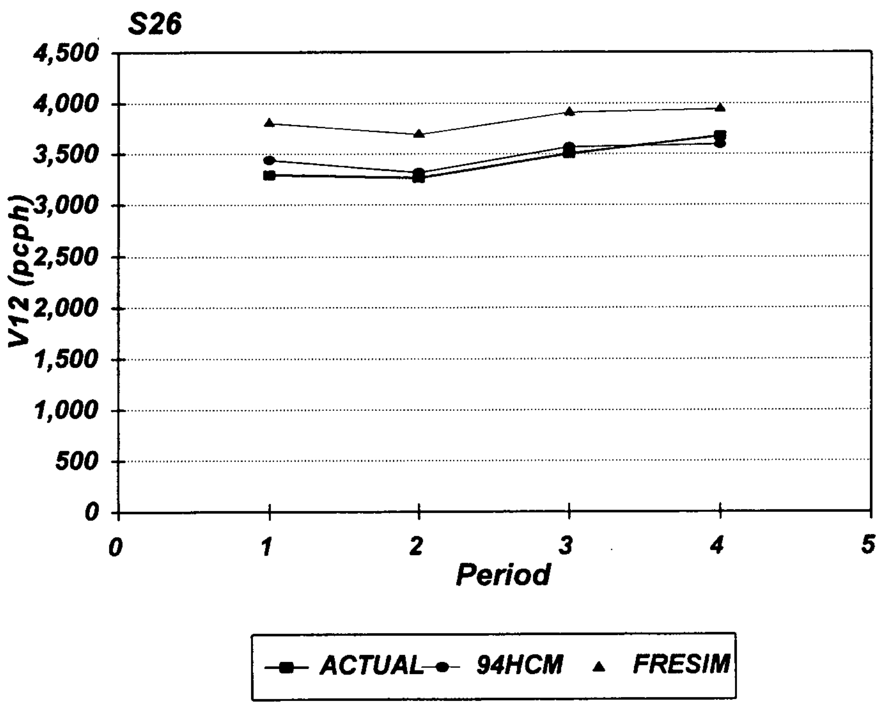


Figure 2-11. Predicted values of V_{12} *for NCHRP Site 26.*

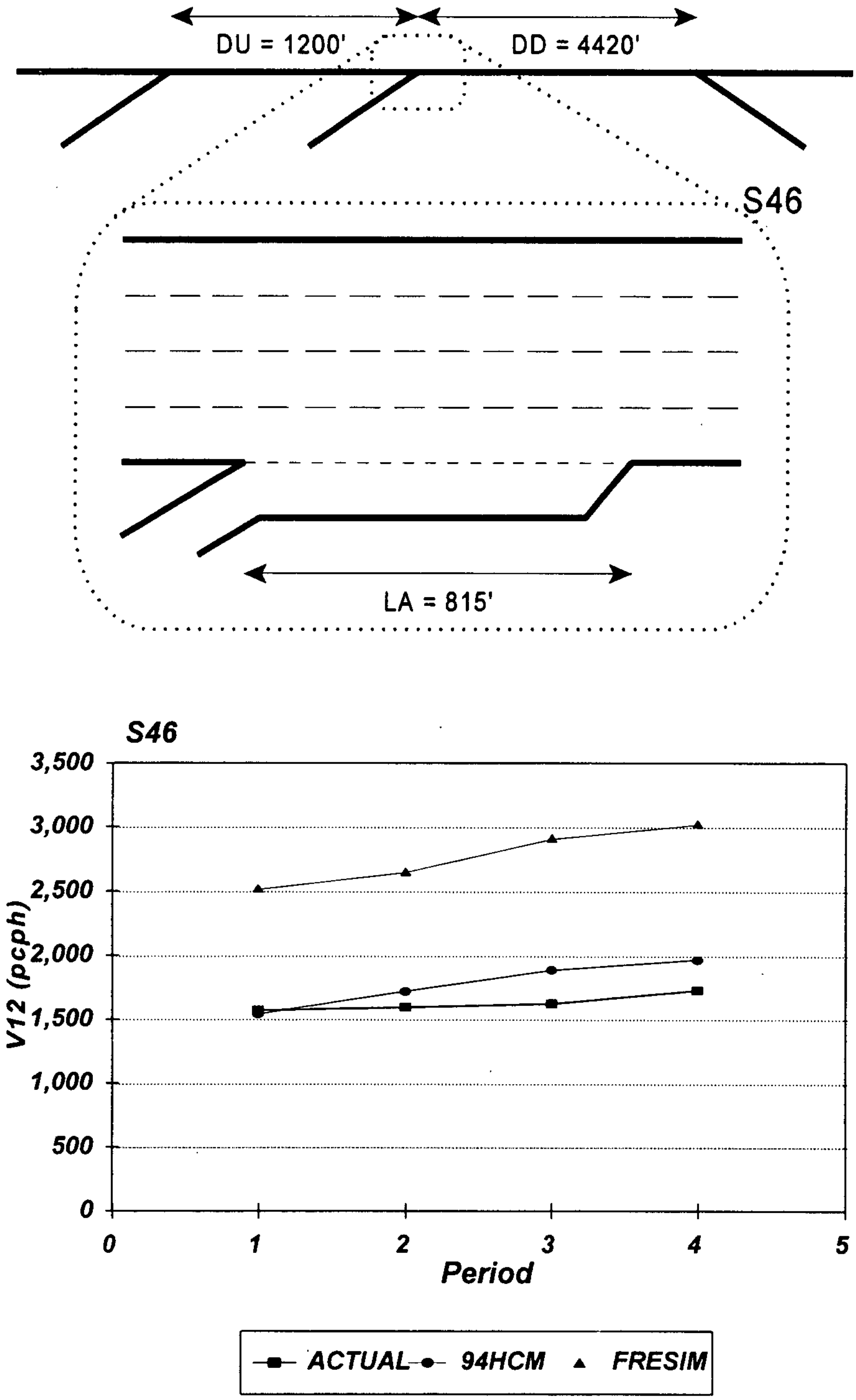
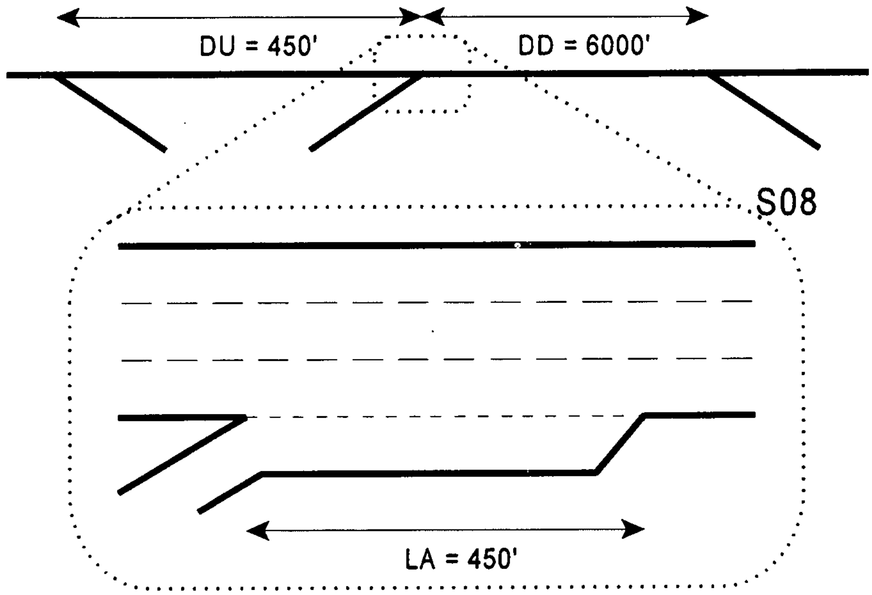


Figure 2-12. Predicted values of V_{12} for NCHRP Site 46.



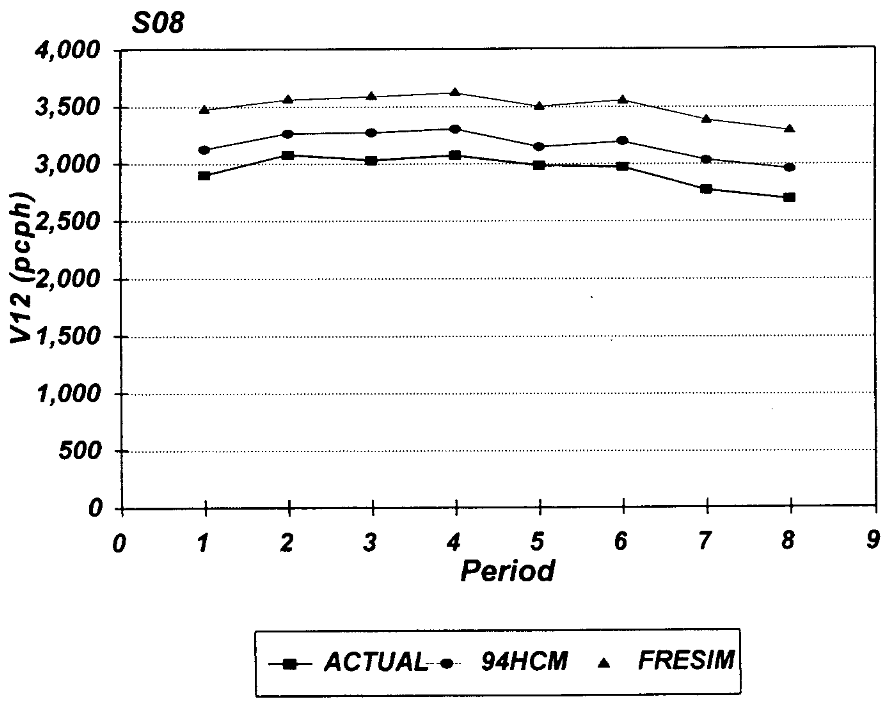
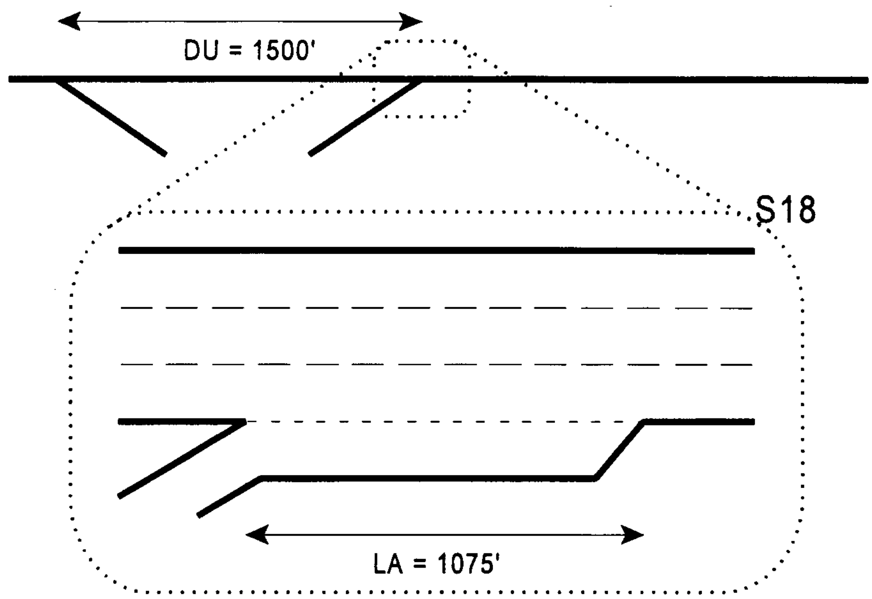


Figure 2-13. Predicted values of V_{12} for NCHRP Site 08.



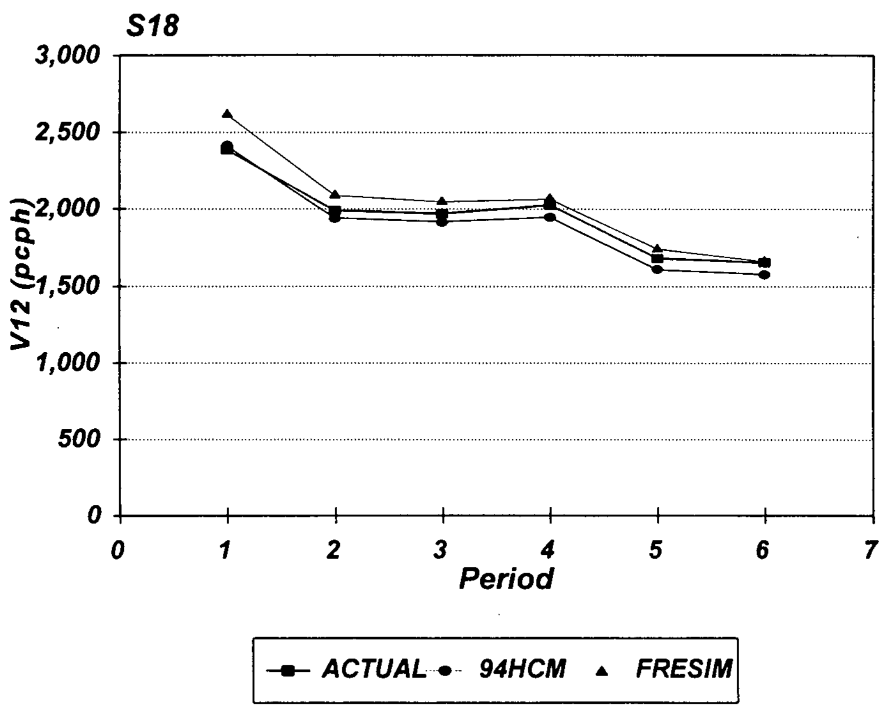


Figure 2-14. Predicted values of V_{12} for NCHRP Site 18.

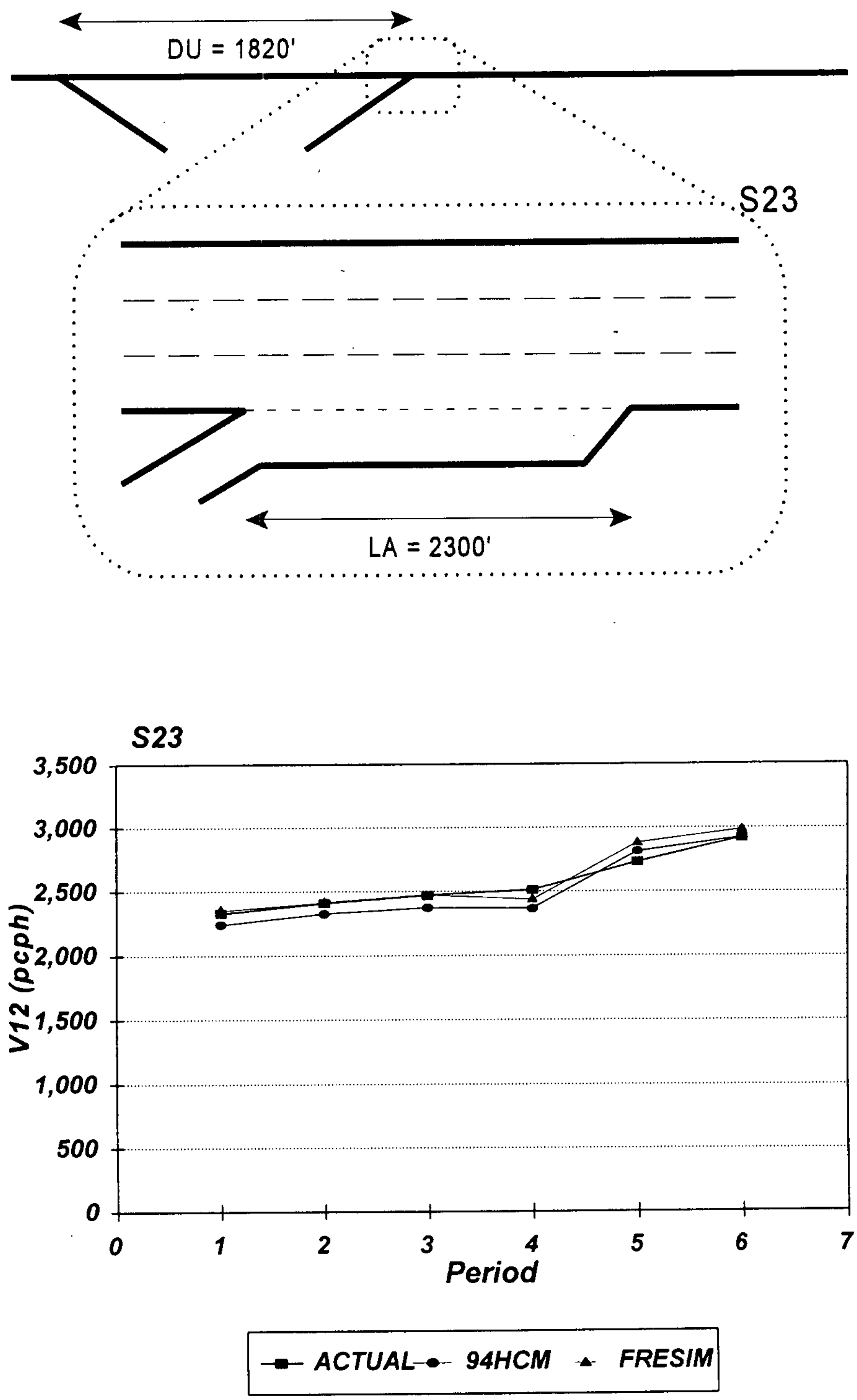
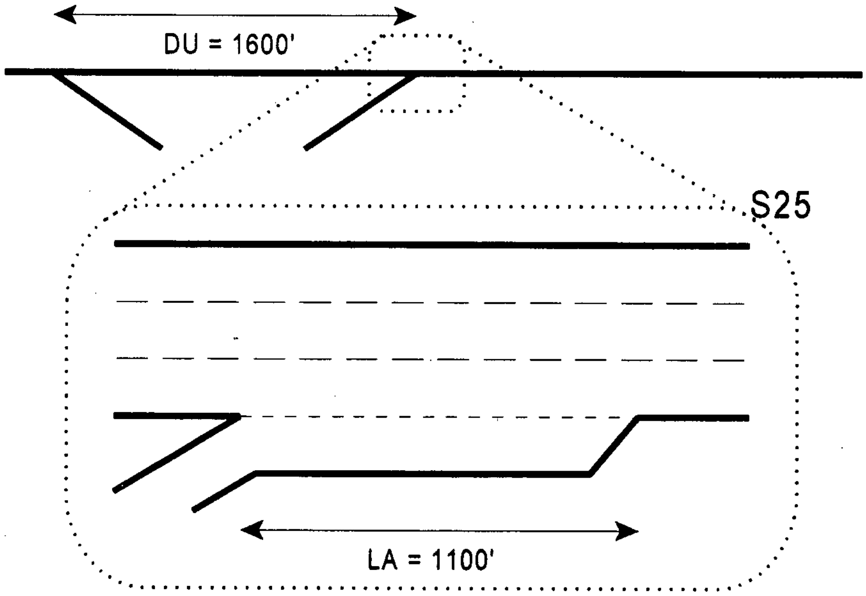


Figure 2-15. Predicted values of V_{12} for NCHRP Site 23.



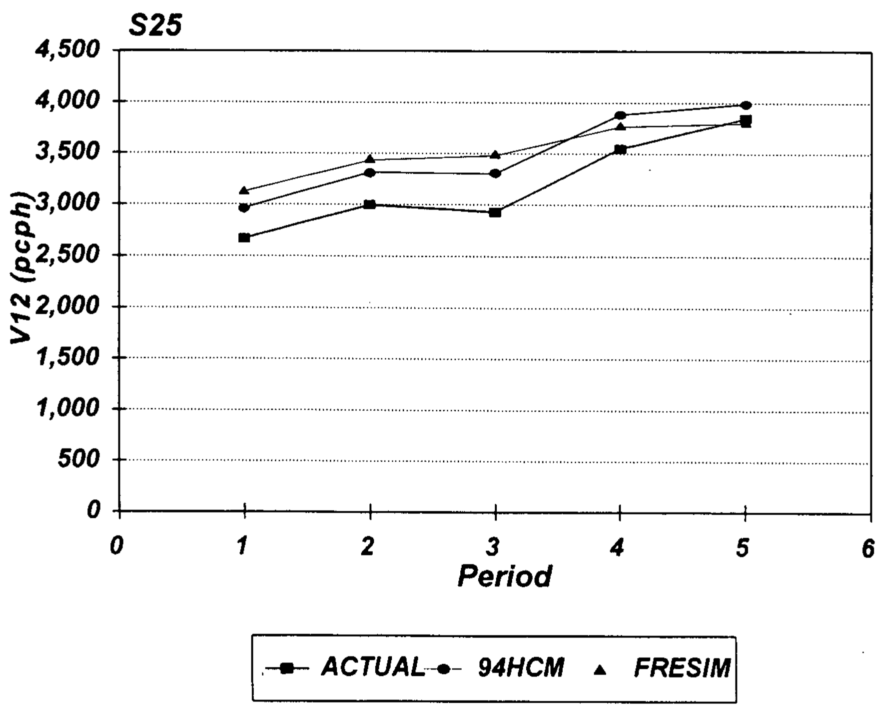


Figure 2-16. Predicted values of V_{12} for NCHRP Site 25.

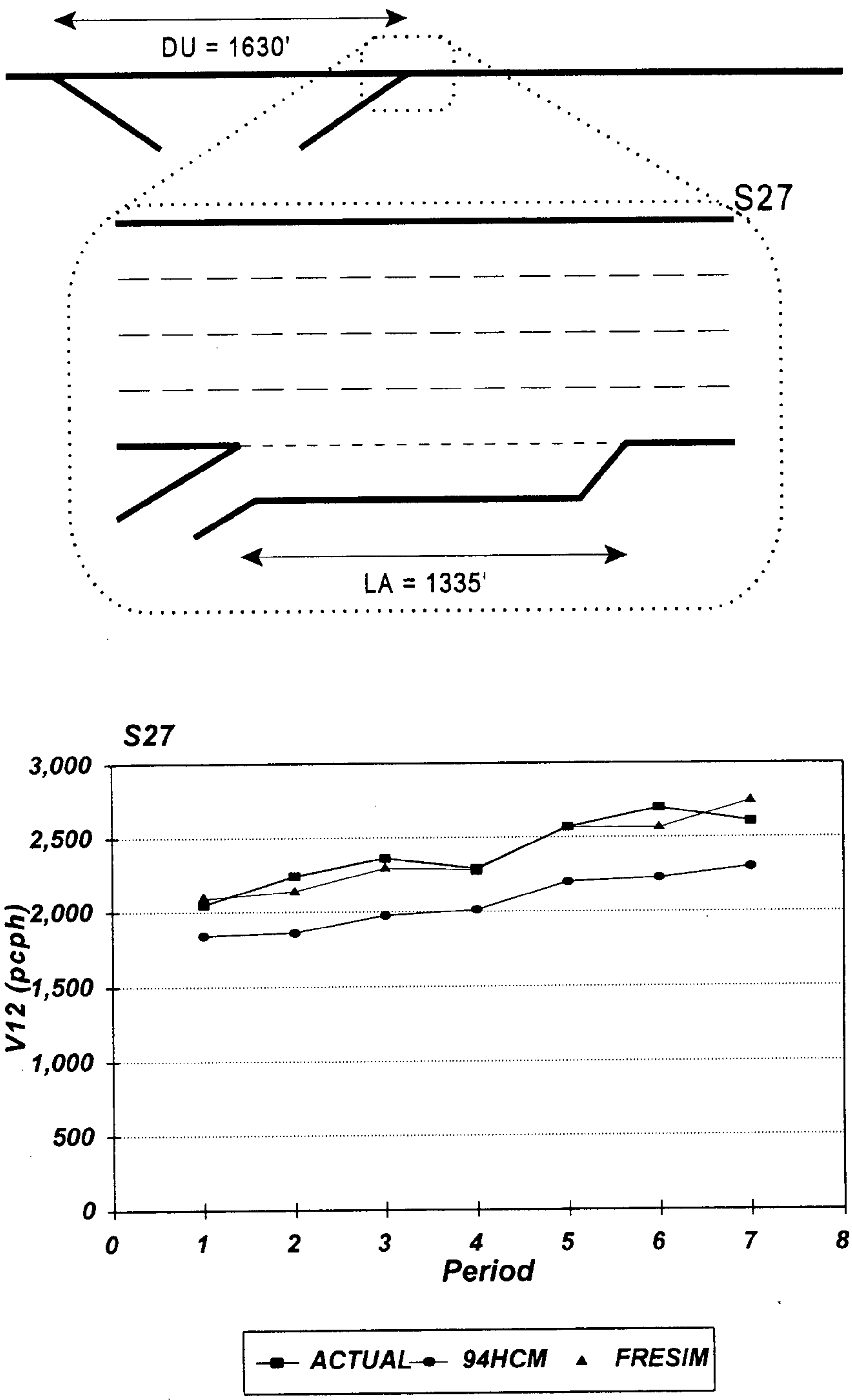
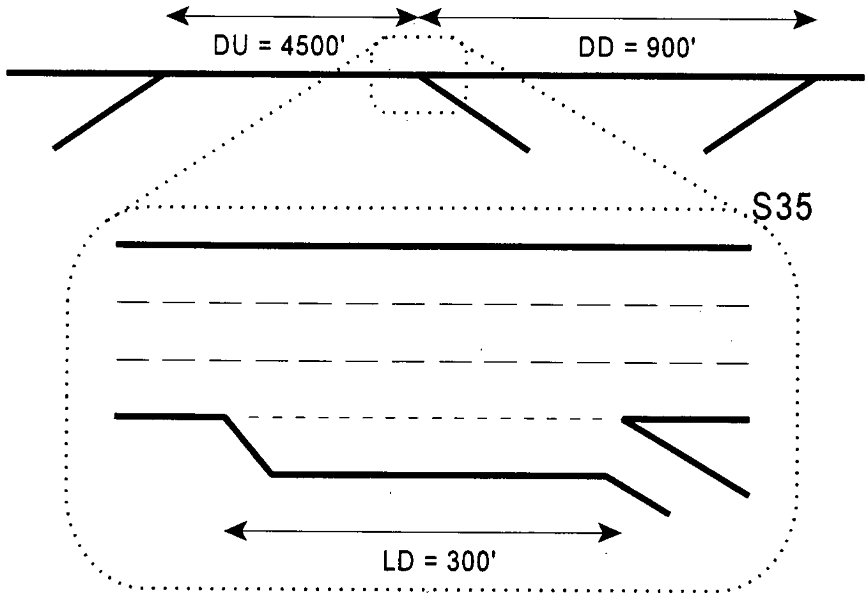


Figure 2-17. Predicted values of V_{12} for NCHRP Site 27.



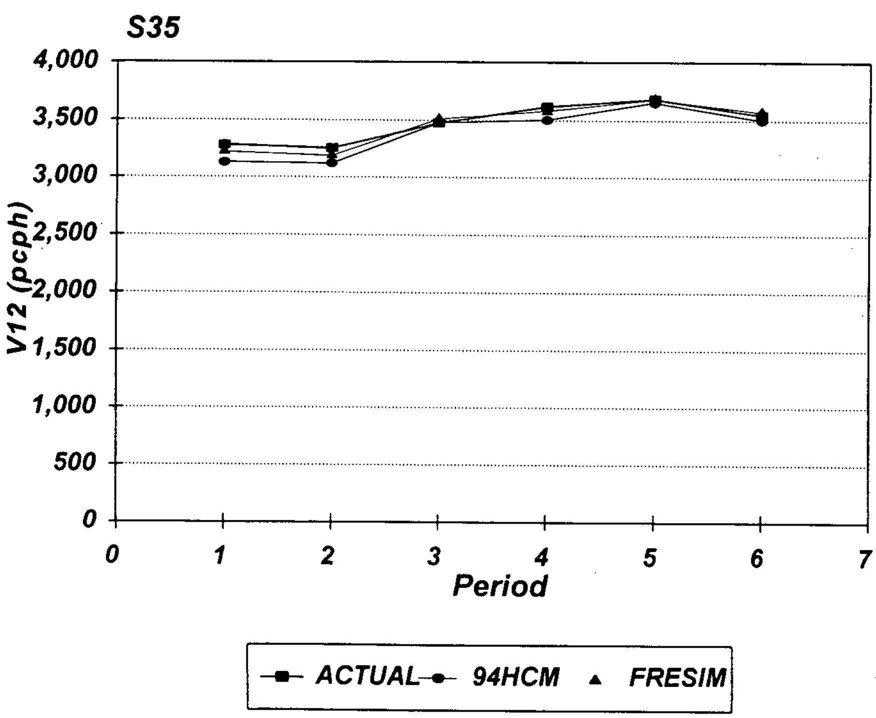


Figure 2-18. Predicted values of V_{12} for NCHRP Site 35.

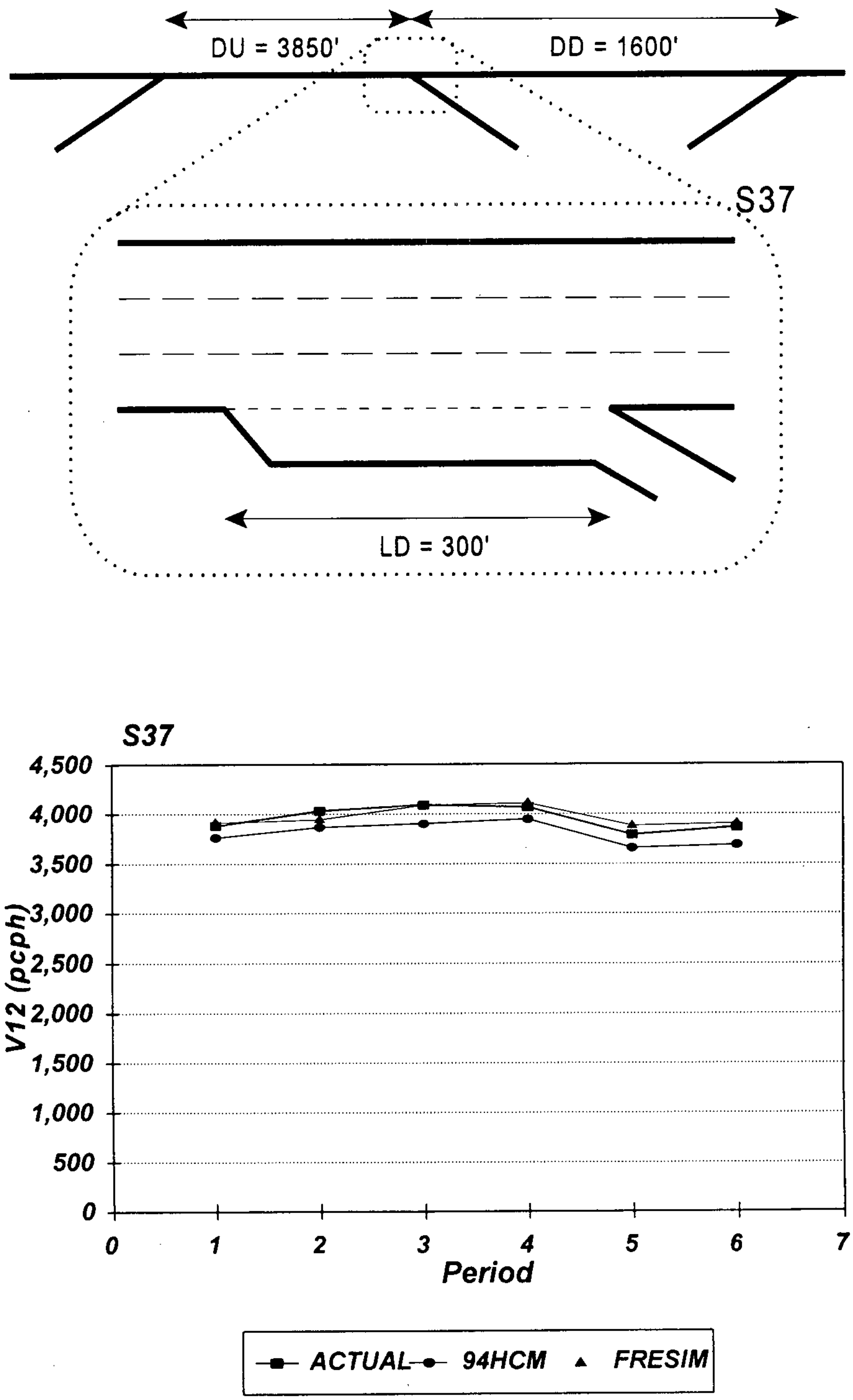
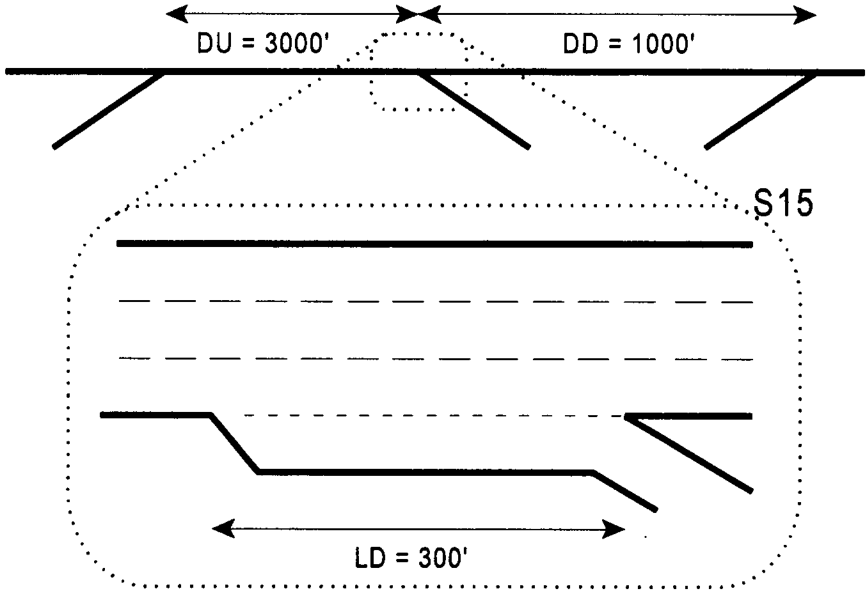


Figure 2-19. Predicted values of V_{12} for NCHRP Site 37.



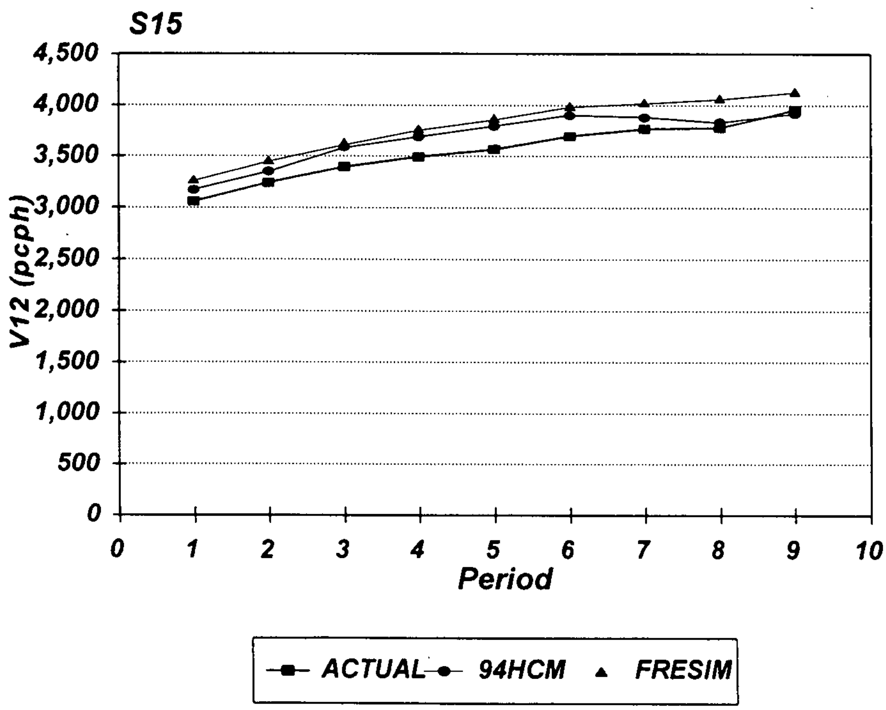


Figure 2-20. Predicted values of V_{12} for NCHRP Site 15.

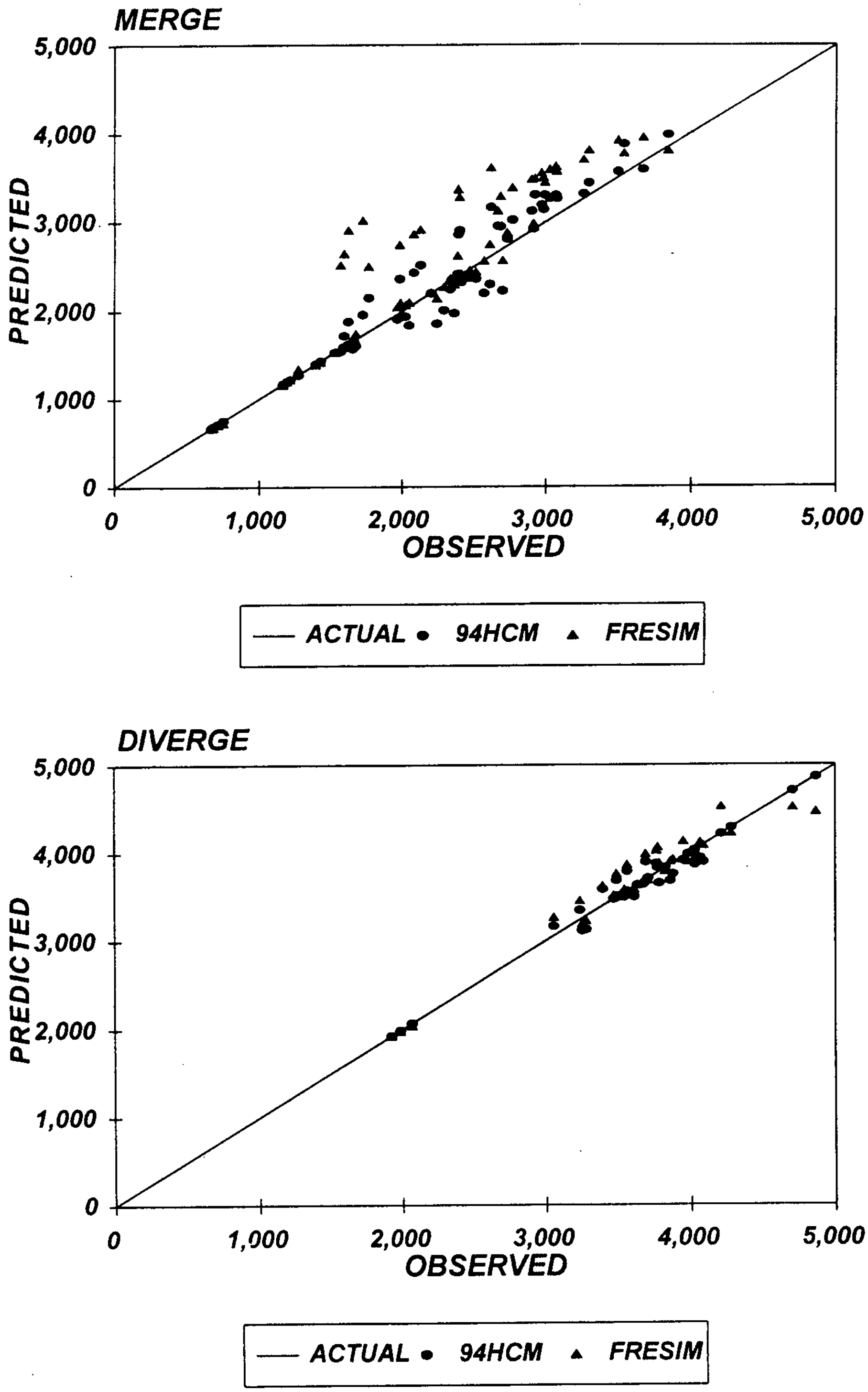


Figure 2-21. Predicted values of V_{12} for all NCHRP merge and diverge sites.

consequence, perhaps, is that in cases where FRESIM is the poorer predictor, the difference in accuracy is more marked. FRESIM inaccuracies, as indicated in Table 2-1, can be quite large. This strengthens the observation that sensitivity of lane distribution to specific ramp configurations and situations is a significant problem in FRESIM.

SENSITIVITY COMPARISONS: FRESIM VERSUS 94HCM IN PREDICTING V_{12}

The 94HCM model focuses on 10 equations calibrated for various configurations that are used to predict V_{12} immediately upstream of an on- or off-ramp. It is useful

TABLE 2-1 Average errors in prediction of V_{12} for the NCHRP data

Site Number	Merge or Diverge	Freeway Lanes	Number of Periods	Absolute Avg. Error FRESIM vph	Absolute Avg. Error 94HCM vph
8	Merge	3	8	569	226
10	Merge	3	7	856	440
18	Merge	3	6	119	64
23	Merge	3	6	76	94
25	Merge	3	5	400	312
26	Merge	3	4	423	94
27	Merge	4	7	86	352
46	Merge	4	4	1159	187
15	Diverge	3	9	257	153
35	Diverge	3	6	41	98
37	Diverge	3	6	63	153

to compare the sensitivity to key variables that are suggested by these equations against similar sensitivities in FRESIM.

This cannot be done with real field data. Unfortunately, field data do not support an analysis in which several variables are held constant while another is systematically varied. In the NCHRP database, this was a particular problem in discerning appropriate ways of incorporating the impact of ramp volume, V_R, on lane distribution. In the database, ramp volume was strongly correlated to freeway volume. This is not hard to understand. In any given area, as traffic intensifies, it is likely that all components of flow intensify together. Thus, it was impossible to directly observe the impact of increasing ramp flow on lane distribution while the freeway volume remained constant.

To better investigate this issue, a series of eight sensitivity analyses were run—one for each equation in the 94HCM (except those applying to 4-lane freeways)—to document how the two models react to such controlled situations.

Figure 2-22 illustrates the sensitivity analysis scenarios conducted for Equation 2, the most frequently used case in the 94HCM. It deals with isolated on-ramps on a 6-lane freeway and all other cases of on-ramps on 6-lane freeways falling outside the calibration range of Equations 3 or 4 (which deal with adjacent ramps). The analysis deals with the reaction of FRESIM and the 94HCM to three key variables: ramp volume, V_R; freeway volume, V_F; and length of acceleration lane, L_A.

Figure 2-23 compares the reaction of FRESIM and the 94HCM to freeway volume. In both cases, the reaction is virtually linear; as freeway volume increases, so does V_{12} at a constant rate. Figure 2-23a shows the analysis for the lowest V_R and shortest L_A, while Figure 2-23b shows the analysis for the highest V_R and longest L_A. While FRESIM predicts higher V_{12} values for all cases, the difference between the two decreases as freeway volume and length of acceleration lane increase. For Equation 2, there appears to be no significant difference in the sensitivity of V_{12} to V_F.

Figure 2-24 illustrates the impact of acceleration lane length on V_{12}. While the 94HCM shows a consistent relationship (where V_{12} increases with increasing length of acceleration lane), FRESIM displays an almost random response to changes in this variable. This makes sense given that one of the underlying difficulties in FRESIM is that almost all merging takes place in the first 100 ft of the acceleration lane, no matter how long it is.

Figure 2-25 shows the comparison in sensitivity to ramp volume. For Equation 2, this is a critical issue, as the equation does not contain V_R as a variable. Thus, Equation 2 has no sensitivity to ramp volume (one of only two lane-distribution equations in the 94HCM with this characteristic). Again, two cases are shown for the extreme values of L_A. Both are for a freeway volume of 3,000 vph. No significant differences in runs for higher freeway volumes were apparent. For the short acceleration lane (400 ft), V_{12} drops significantly as V_R goes from 300 to 600 vph, but only slightly as V_R increases again to 900 vph.

For the longer acceleration lane (1400 ft), the drop in V_{12} is slight as V_R goes from 300 to 600 vph, but increases between 600 and 900 vph. In FRESIM, the longer acceleration lane of the second case shown allows for higher ramp volumes before the lane distribution becomes significantly sensitive to this factor.

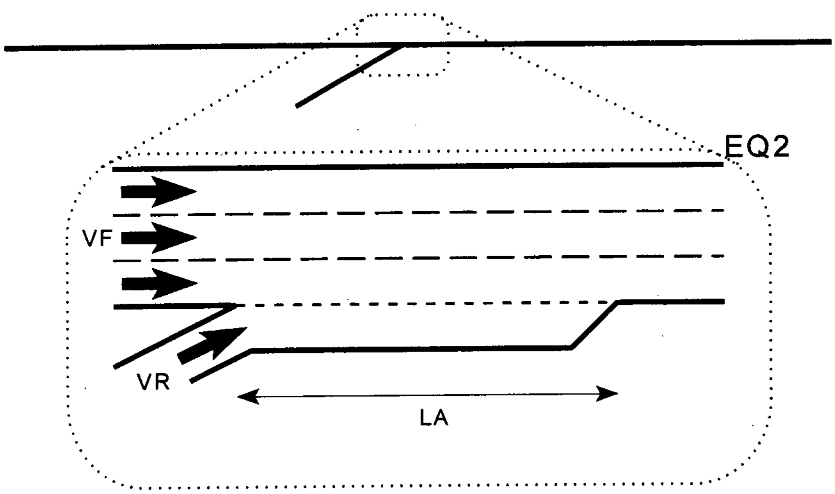
Equation 3 of the 94HCM includes independent variables V_F, V_R, D_U, and S_{FR}. It covers on-ramps with an adjacent upstream off-ramp on 6-lane freeways. Figure 2-26 shows the sensitivity analyses set up for this case.

Figure 2-27 illustrates the critical results of this analysis. Three different values of D_U are depicted in Figures 2-27a, b, and c. Within each graph, three different values of S_{FR} are shown. In all cases, V_R is the independent variable. The 94HCM model shows three distinctly different sensitivities that are not well represented by FRESIM:

1. As ramp volume increases, V_{12} decreases slowly but at a steady rate. The response of FRESIM to ramp volume is mixed and inconsistent.
2. The free-flow speed of the ramp has a significant impact on V_{12} in the 94HCM; there is little indication of such an impact in FRESIM.
3. As D_U increases, V_{12} increases significantly in the 94HCM; again, FRESIM is not very sensitive to changes in D_U.

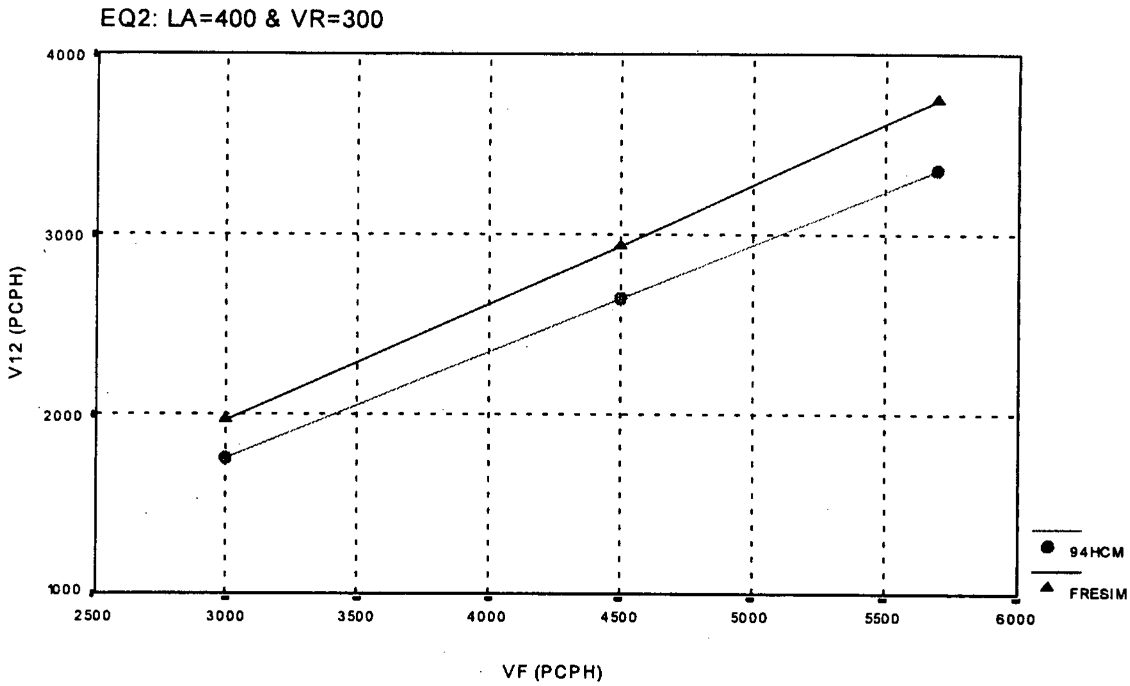
Figure 2-28 illustrates the sensitivity analysis scenarios for the 94HCM Equation 4. This equation is for on-ramps on 6-lane freeways with a downstream adjacent off-ramp. The equation is dependent upon the ratio of V_D/D_D and the freeway volume. This is the second equation from the 94HCM that is not sensitive to changes in ramp volume.

Figure 2-29 illustrates the key results. Figure 2-29a shows the variation in V_{12} versus V_D/D_D for three different freeway volume levels. In all cases, the 94HCM shows a significantly higher sensitivity to V_D/D_D than FRESIM. For both models, V_{12} increases similarly with increasing freeway volume. Figure 2-29b shows the proportion of

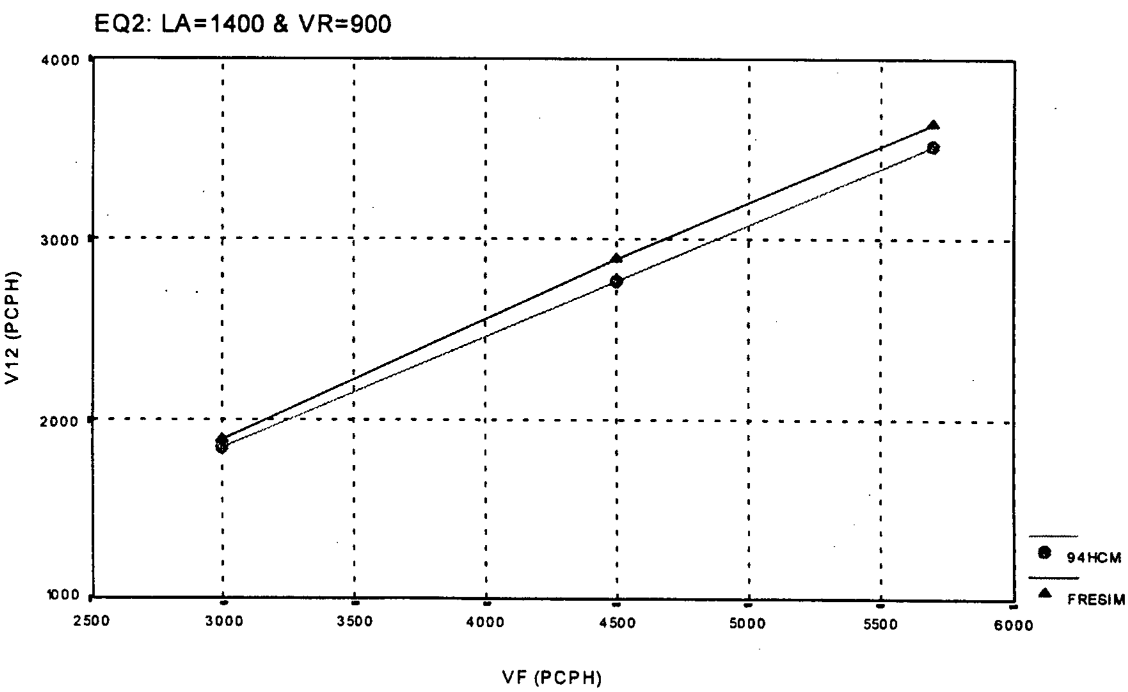


94HCM Equation 2			
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Ramp Free-Flow Speed = 45 mph No Trucks Level Grade			
Lanes	**V_R (pcph)**	**V_F (pcph)**	**L_A (feet)**
3	300 600 900	3,000 4,500 5,700	400 600 800 1,000 1,200 1,400

Figure 2-22. Sensitivity cases for 94HCM Equation 2.

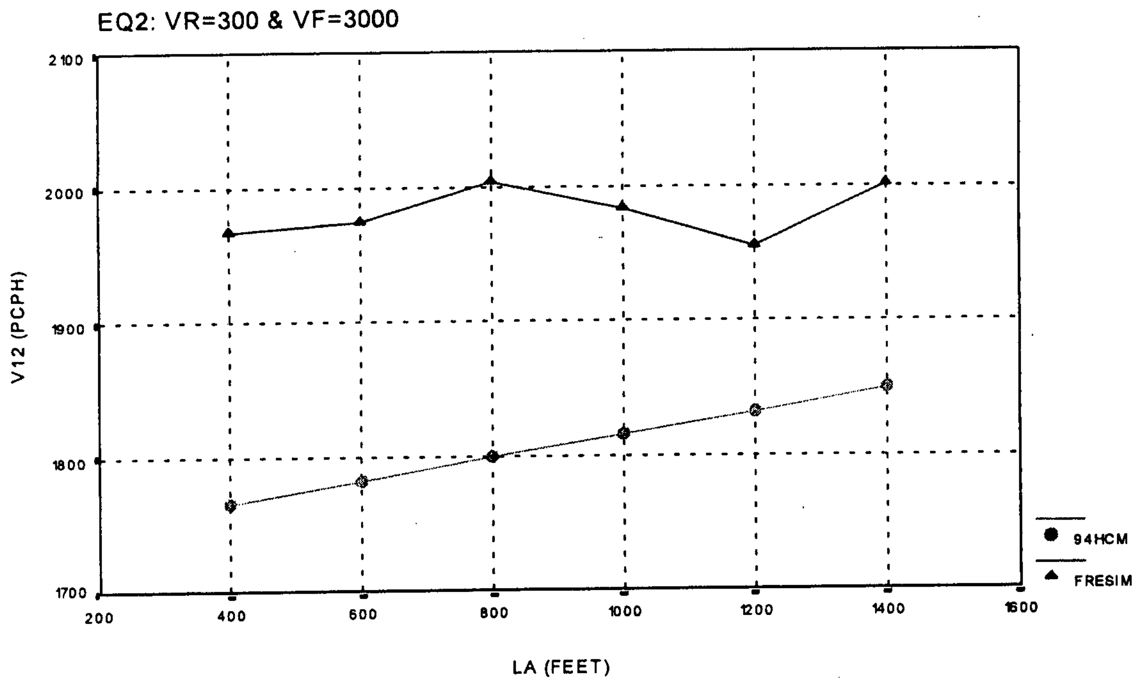


(a) $L_A = 400$ ft; $V_R = 300$ vph

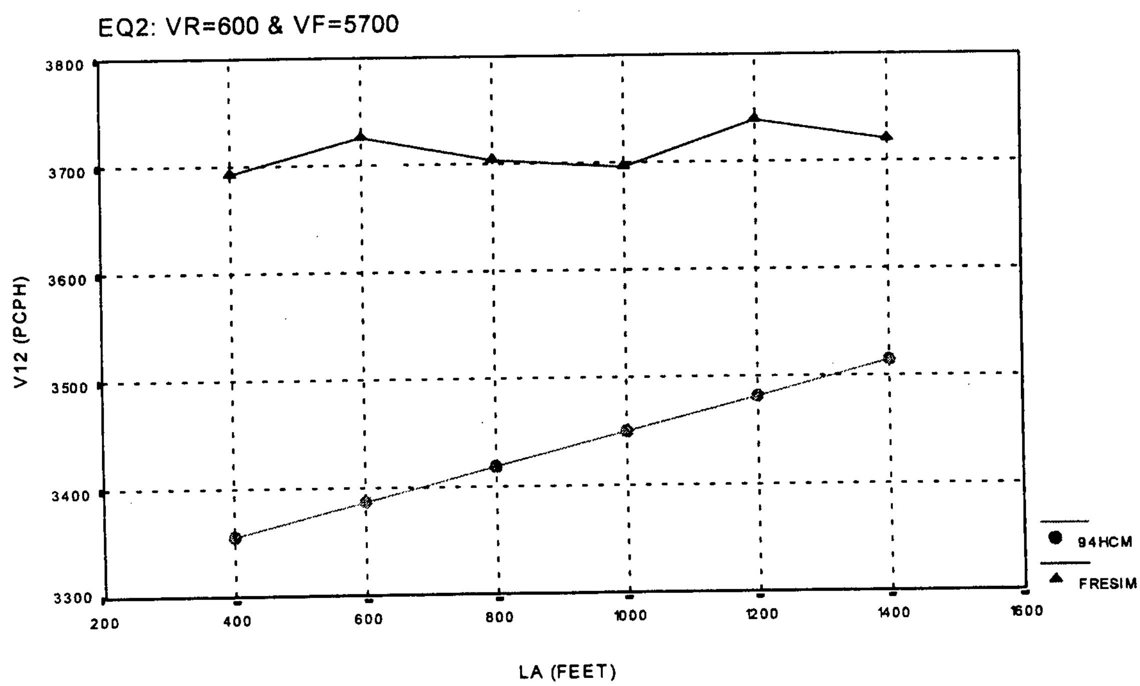


(b) $L_A = 1400$ ft, $V_R = 900$ vph

Figure 2-23. Sensitivity to freeway volume—94HCM Equation 2.

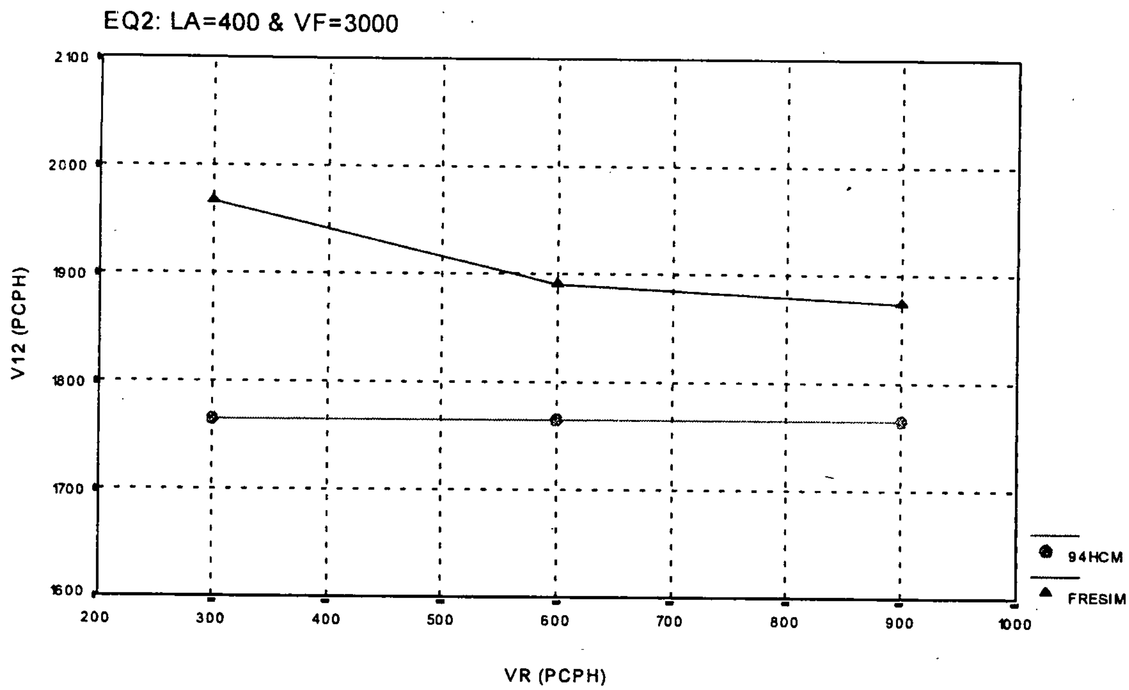


(a) V_R = 300 vph, V_F = 3,000 vph

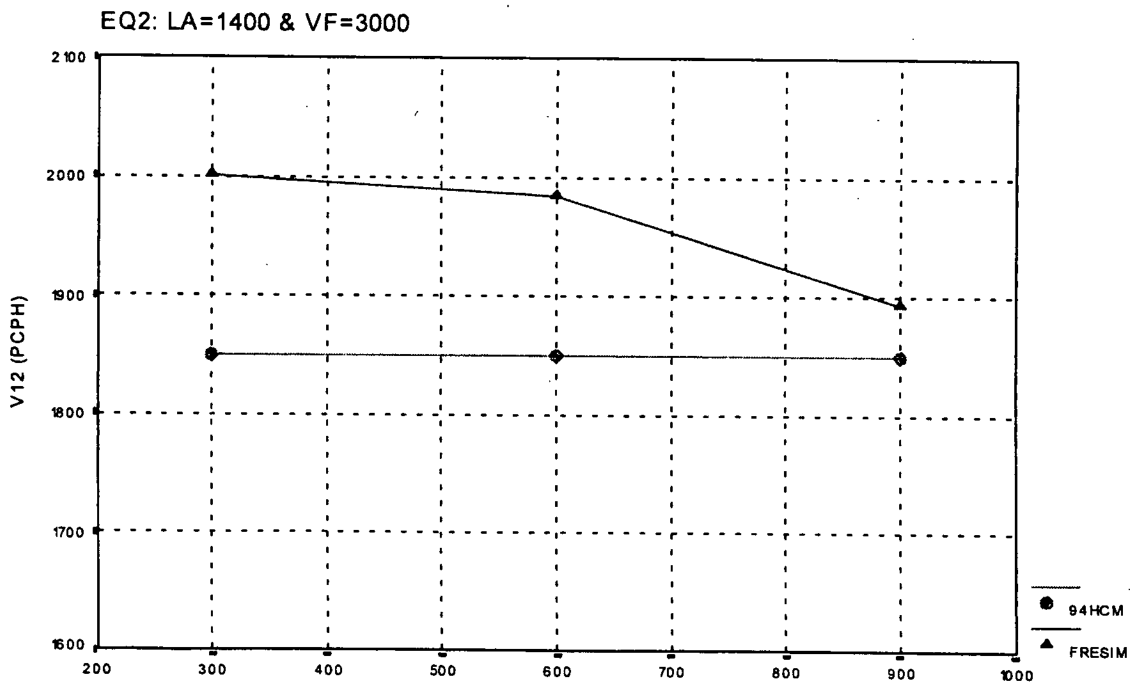


(b) V_R = 600 vph, V_F = 5,700 vph

Figure 2-24. Sensitivity to acceleration lane length—94HCM Equation 2.

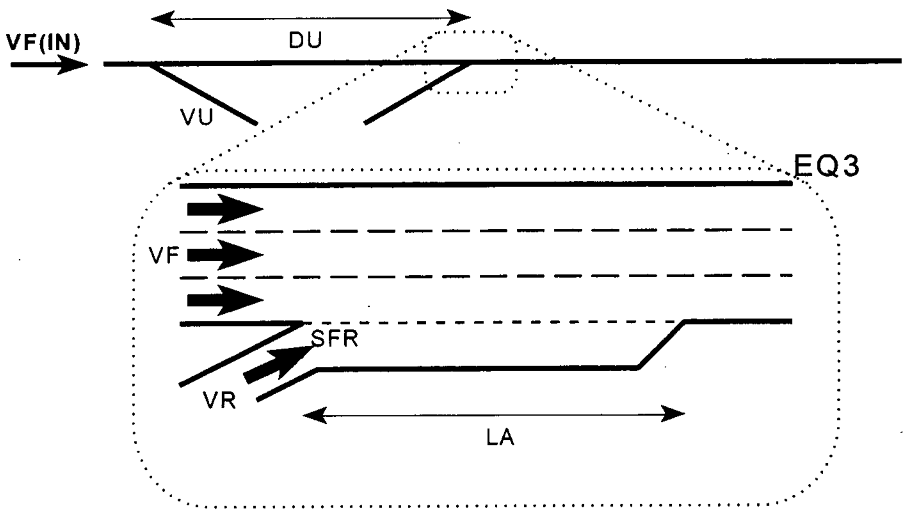


(a) L_A = 400 ft, V_F = 3,000 vph



(b) L_A = 1400 ft, V_F = 3,000 vph

Figure 2-25. Sensitivity to ramp volume—94HCM Equation 2.



94HCM Equation 3				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Upstream Ramp Free-Flow Speed = 55 mph Main Ramp Acceleration Lane Length (L_A) = 750 ft Upstream Ramp Deceleration Lane Length = 500 ft Exiting Upstream Ramp Volume = 10% of $V_{F(IN)}$ No Trucks Level Grade				
Lanes	**V_R (pcph)**	**$V_{F(IN)}/V_F$ (pcph)**	**S_{FR} (mph)**	**D_U (feet)**
3	300 600 900	3,333/3,000 5,000/4,500 6,000/5,400	35 45 55	500 1,500 2,500

Figure 2-26. Sensitivity cases for 94HCM Equation 3.

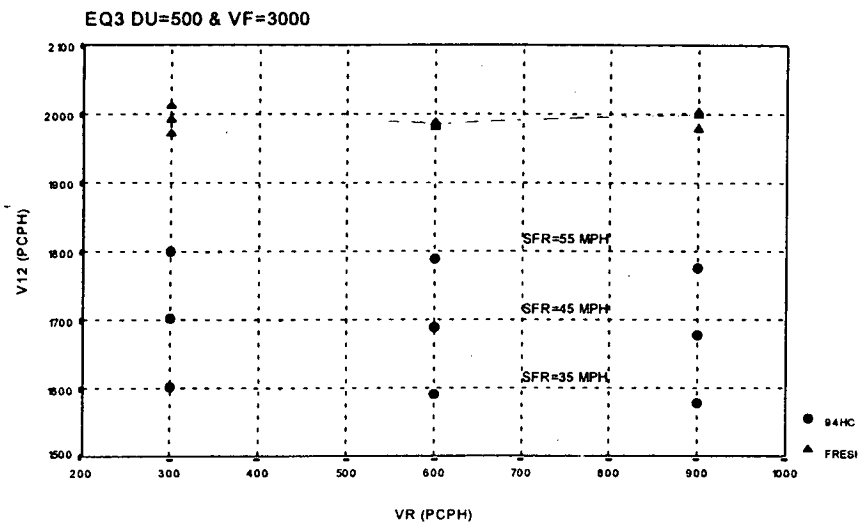
vehicles in lanes 1 and 2 as a function of V_D/D_D. Again, FRESIM is seen to be far less sensitive to the ratio than the 94HCM.

Figure 2-30 illustrates the sensitivity scenarios for Equation 5, which deals with on-ramps on an 8-lane freeway. The equation includes the variables V_F, V_R, and the ratio L_A/S_{FR}. Figure 2-31 depicts the principal results. Once again, FRESIM is seen to be far less sensitive to the geometric variables L_A and S_{FR} than the 94HCM, which reacts linearly to the ratio of the two. The response of the 94HCM to ramp volume is also more uniform and consistent than that of FRESIM.

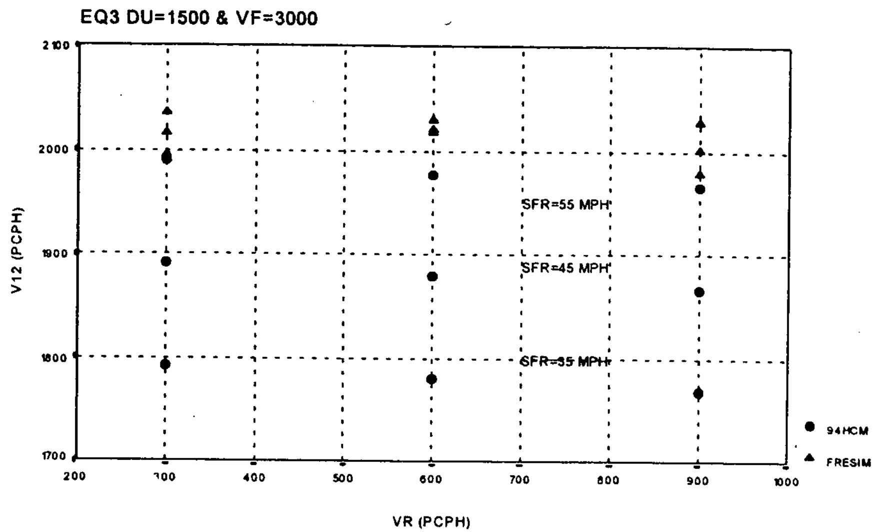
To illustrate sensitivities in predicting V_{12} immediately upstream of an on-ramp, variables V_{12} and V_{12}/V_F have been used more or less interchangeably, based on whichever produced the clearest graphical presentation. This is logical since the form of the equation $V_{12} = V_F P_{FM}$ suggests that the two will have similar properties, except for the obvious relationship between V_{12} and V_F.

Where off-ramps are concerned, this is not the case. The general form of the equation for off-ramps is $V_{12} = V_R + (V_F - V_R) P_{FD}$. Thus, for cases of off-ramps, all plots are shown versus V_{12} for consistency.

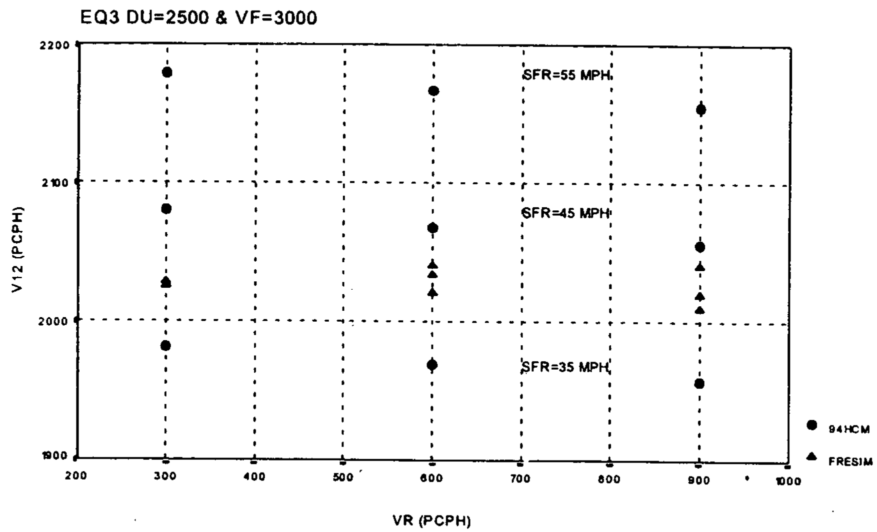
Figure 2-32 shows the sensitivity cases created for Equation 7. V_R is established as a percentage of V_F at four different levels, while three basic freeway volume levels are used. A new variable ($LINK_{UP}$) is introduced to test the impact of upstream input distance on lane distribution. This is an issue which impacts only FRESIM predictions. As discussed in Chapter 1, FRESIM has a basic flaw that complicates off-ramp analysis. Because of the probability-based nature of the model, it is impossible to specify an exact off-ramp volume



(a) D_U = 500 ft, V_F = 3,000 vph

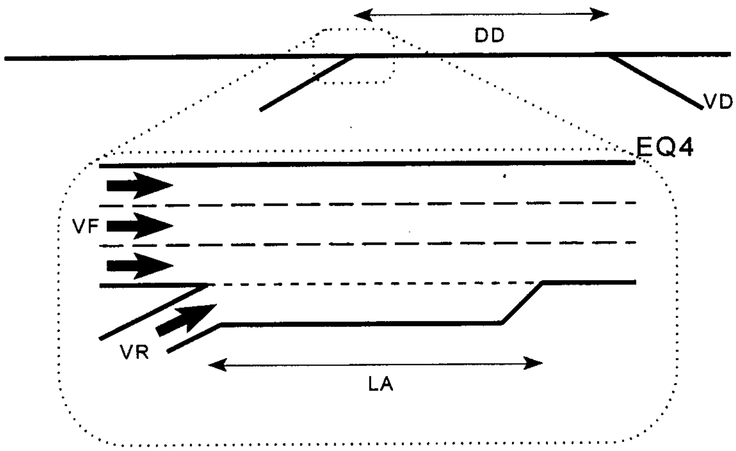


(b) D_U = 1,500 ft, V_F = 3,000 vph



(c) D_U =2,500 ft, V_F = 3,000 vph

Figure 2-27. Sensitivity to V_R, D_U, and S_{FR} in 94HCM Equation 3.



94HCM Equation 4				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Main Ramp Free-Flow Speed = 45 mph Downstream Ramp Free-Flow Speed = 55 mph Main Ramp Acceleration Lane Length (L_A) = 500 ft Downstream Ramp Deceleration Lane Length = 500 ft No Trucks Level Grade				
Lanes	**V_R (pcph)**	**V_F (pcph)**	**V_D (% of V_F+V_R)**	**D_D (feet)**
3	600	3,000 4,500 5,700	10% 20% 30%	1,200 3,600 6,000

Figure 2-28. Sensitivity cases for 94HCM Equation 4.

as in the case of on-ramps. Thus, off-ramp volume will vary in FRESIM around the intended value, which is entered as a proportion of freeway volume.

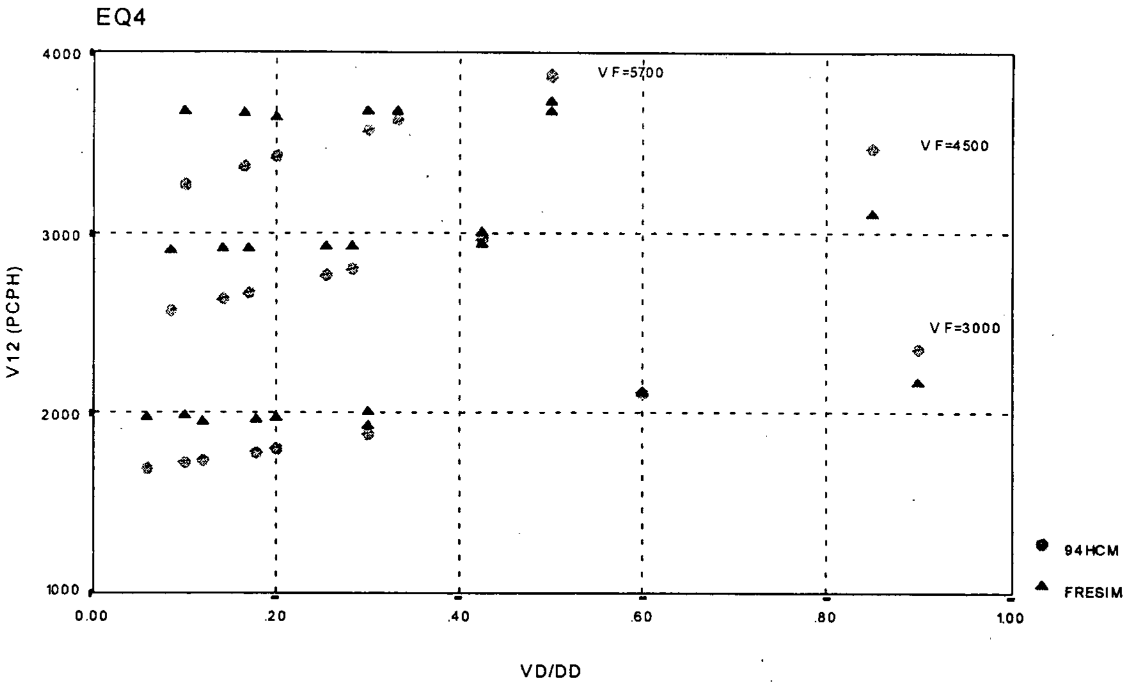
Figure 2-33 illustrates the results. The 94HCM model gives almost linear results, with V_{12} increasing as the ramp volume increases (as would be expected). As freeway volume increases, V_{12} increases as well. FRESIM produces the same general trends, although the trend is not linear and not always consistent in direction. In all cases, FRESIM tends to estimate higher V_{12} levels than the 94HCM. The difference becomes larger as freeway volume increases.

The differences in FRESIM lane distribution, depending on the input distance from the ramp junction, are inconsistent and only seem to make a significant difference at lower freeway volumes. This highlights the relative insensitivity of FRESIM lane distribution predictions to adjacent ramp junctions.

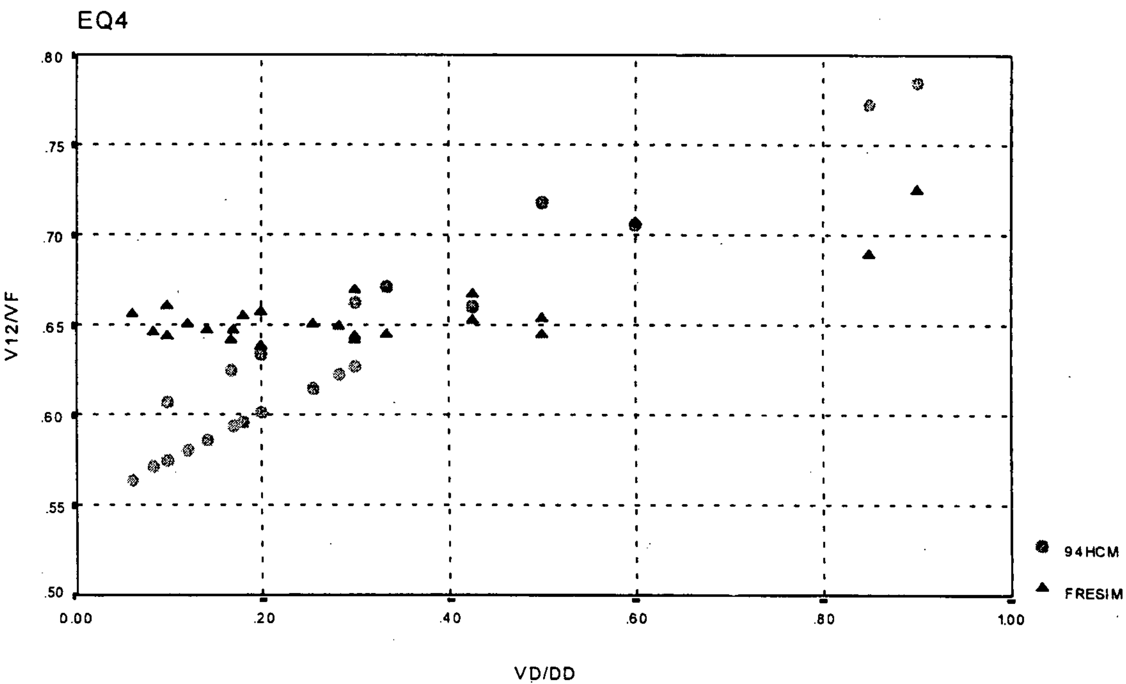
No runs were made with varying L_D or S_{FR} values. Equation 7 contains neither of these variables and is therefore insensitive to both. FRESIM is insensitive to L_D, as its logic forces most vehicles to merge in the first 100 ft of the acceleration lane, regardless of its total length. FRESIM is also relatively insensitive to the free-flow speed of the ramp, as has been demonstrated previously.

Figure 2-34 illustrates the sensitivity cases undertaken to study HCM Equation 8. This equation deals with an adjacent upstream on-ramp on a 6-lane freeway. Figure 2-35 shows some of the critical results of the analysis. Figures 2-35 a, b, and c each represent increasing values of V_U and V_R. In looking at these figures, the following points are clearly made:

1. As V_U and V_R increase, V_{12} also increases. The sensitivity of FRESIM to these factors, however, is far more limited than that of the 94HCM.
2. While the 94HCM model is very sensitive to changes in D_U, FRESIM displays very little sensitivity to this variable.

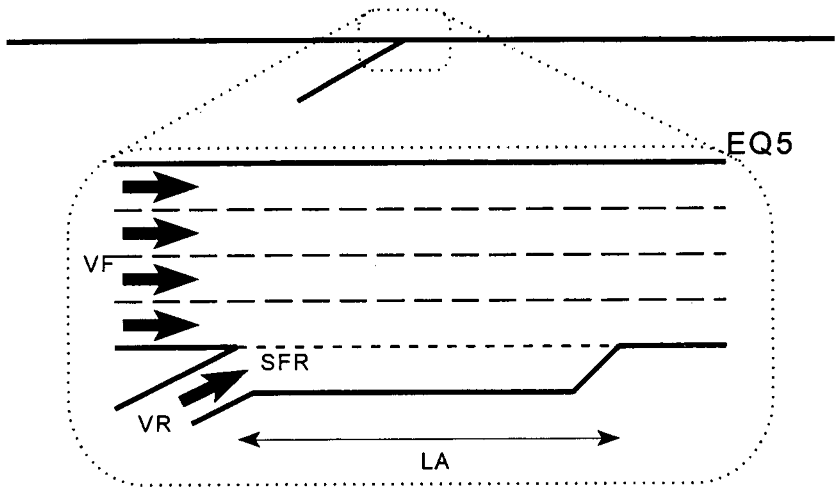


(a) V_{12} vs. V_D/D_D



(b) V_{12}/V_F vs. V_D/D_D

Figure 2-29. Sensitivity to V_D/D_D and V_F in 94HCM Equation 4.



94HCM Equation 5				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph No Trucks Level Grade				
Lanes	**V_R (pcph)**	**V_F (pcph)**	**L_A (feet)**	**S_{FR} (mph)**
4	300 600 900	4,000 6,000 7,600	400 800 1200	35 45 55

Figure 2-30. Sensitivity cases for 94HCM Equation 5.

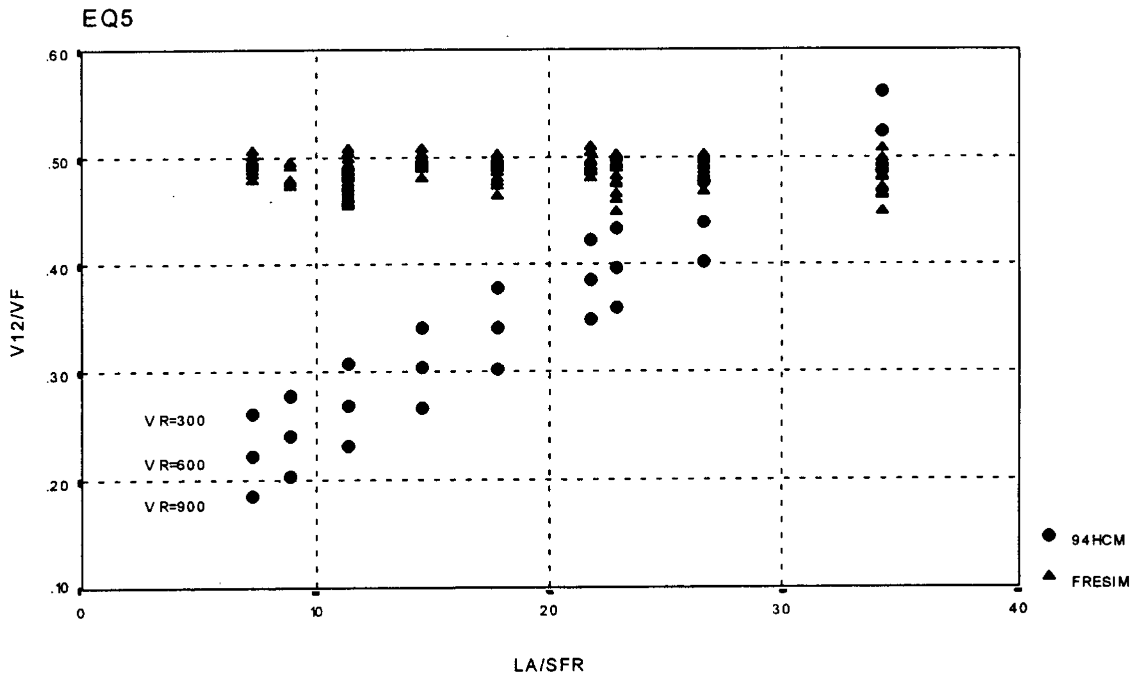
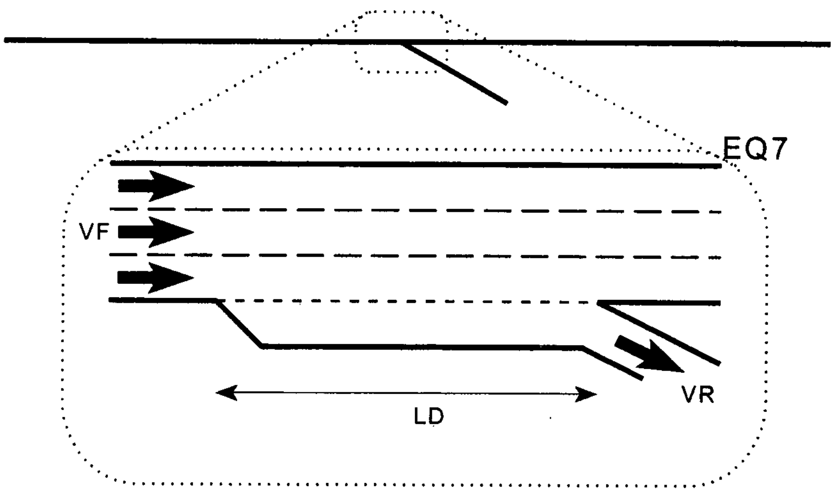
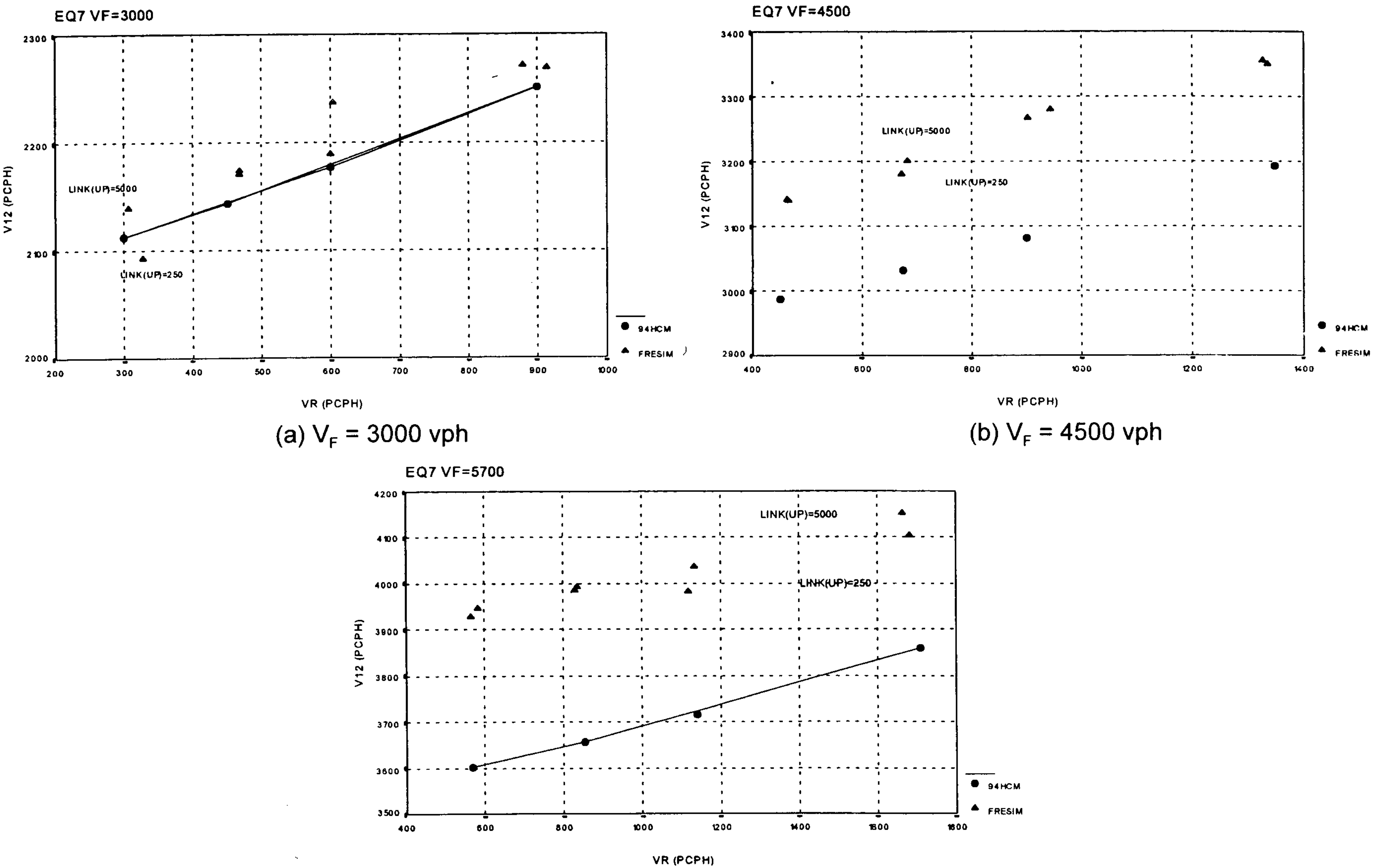


Figure 2-31. Sensitivity of V_{12}/V_F to V_R And L_A/S_{FR}—94HCM Equation 5.



94HCM Equation 7			
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Main Ramp Free-Flow Speed = 45 mph Main Ramp Deceleration Lane Length (L_D) = 600 feet No Trucks Level Grade $LINK_{UP}$ represent length of link in the upstream direction from the main ramp			
Lanes	**V_R (% of V_F)**	**V_F (pcph)**	**$LINK_{UP}$ (feet)**
3	10% 15% 20% 30%	3,000 4,500 5,700	250 5,000

Figure 2-32. Sensitivity cases for 94HCM Equation 7.

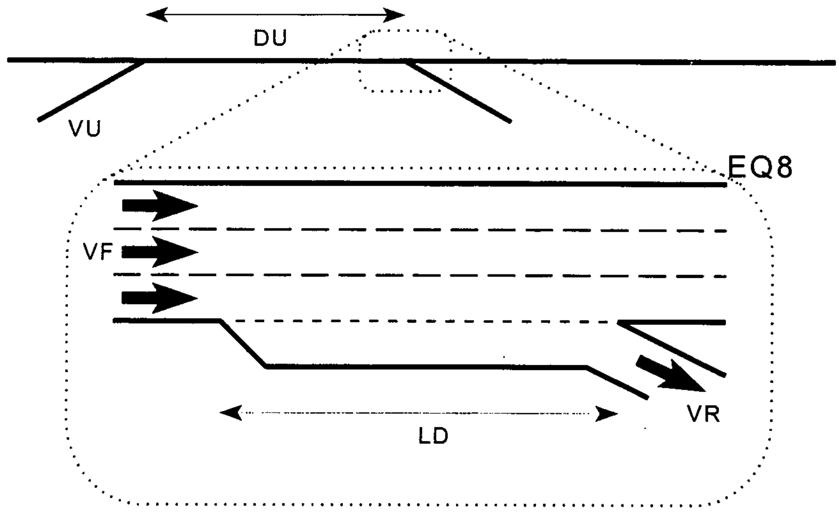


(a) V_F = 3000 vph

(b) V_F = 4500 vph

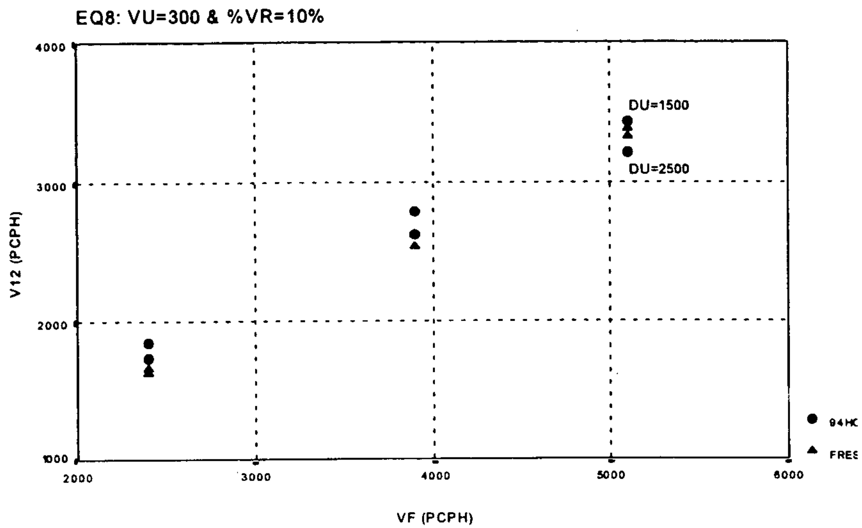
(c) V_F = 5700 vph

Figure 2-33. Sensitivity of V_{12} to V_R, V_F, and $LINK_{UP}$—94HCM Equation 7.

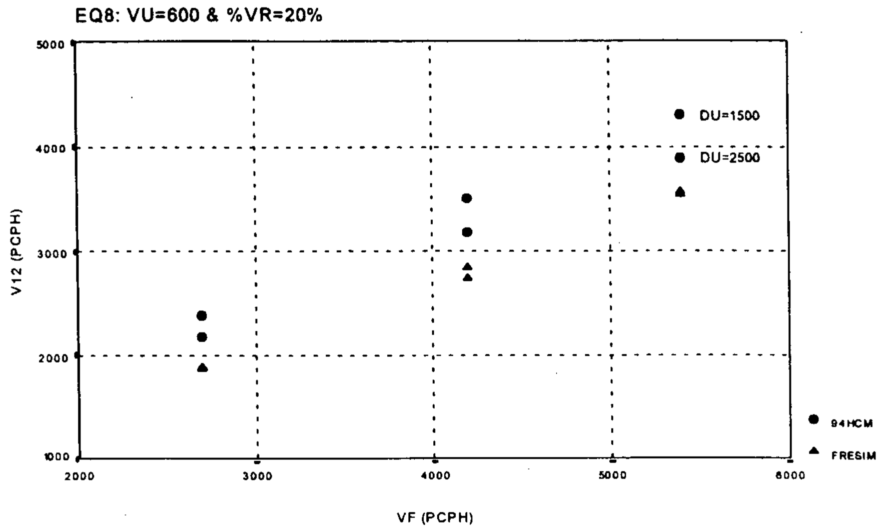


94HCM Equation 8				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Main Ramp Free-Flow Speed = 55 mph Upstream Ramp Free-Flow Speed = 45 mph Main Ramp Deceleration Lane Length (L_D) = 500 feet Upstream Ramp Acceleration Lane Length (L_A) = 500 feet No Trucks Level Grade				
Lanes	**V_R (% of V_F)**	**V_F (pcph)**	**D_U (feet)**	**V_U (pcph)**
3	10% 20% 30%	3,000 4,500 5,700	500 5,000	300 600 900

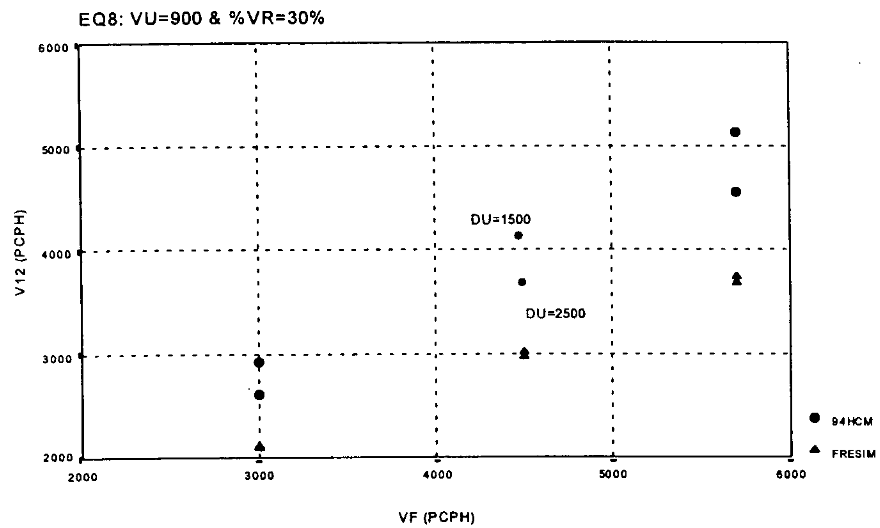
Figure 2-34. Sensitivity cases for 94HCM Equation 8.



(a) V_U = 300 vph; V_R = 10%



(b) V_U = 600 vph, V_R = 20%



(c) V_U = 900 vph; V_R = 30%

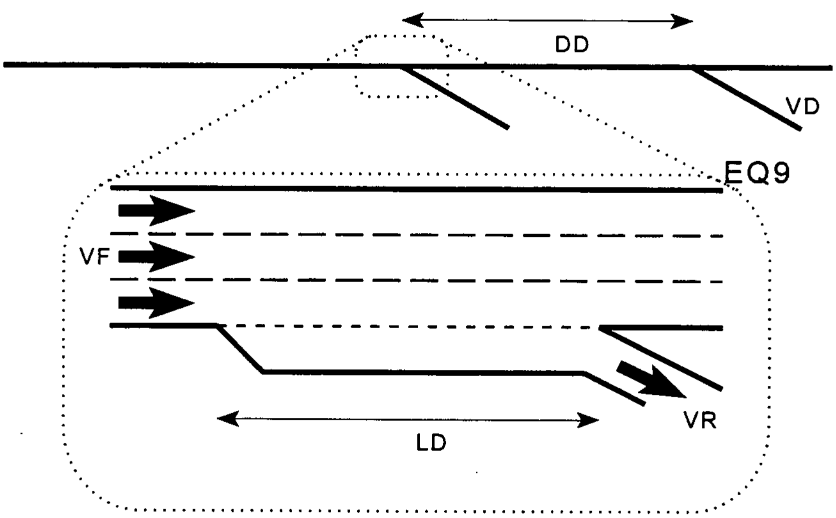
Figure 2-35. Sensitivity of V_{12} to V_F, V_U, V_R, and D_U—94HCM Equation 8.

3. For this configuration, FRESIM tends to predict lower values of V_{12} than the 94HCM.

Figure 2-36 illustrates similar sensitivity cases for Equation 9, which deals with a downstream adjacent off-ramp on a 6-lane freeway. Figure 2-37 shows the critical results, which are remarkably similar to those for Equation 8. Again, FRESIM is seen to be considerably less sensitive than the 94HCM to critical variables such as distance to the downstream ramp, D_U, and to increases in the ramp and downstream ramp volume levels.

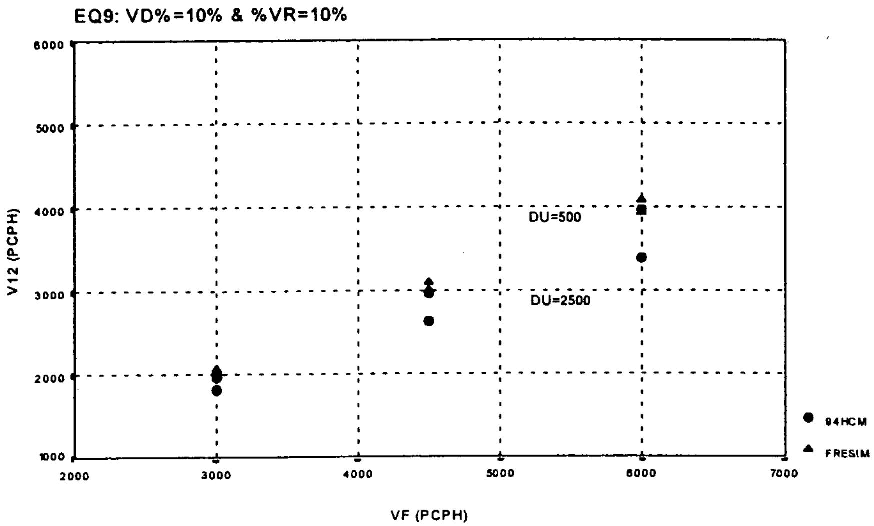
Figure 2-38 shows sensitivity cases for Equation 10, which deals with all off-ramps on 8-lane freeways. Because this equation is virtually a constant "$V_{12} = V_R + 0.435\ (V_F - V_R)$," the 94HCM model has no sensitivity to variables other than the ramp and freeway volumes. FRESIM cases were run for two different input distances. Again, the results show that this is not a significant factor influencing FRESIM results.

Figure 2-39 summarizes the important results. As ramp flow increases, V_{12} increases for both FRESIM and the 94HCM, with exception of the FRESIM results for 30 percent exiting vehicles in Figure 2-39c. FRESIM now behaves in a strange way by not allowing the intended off-ramp vehicles to exit. Many vehicles in FRESIM do not successfully exit for high freeway volumes. This anomaly is an irrational result. Other sensitivities appear to be reasonable.

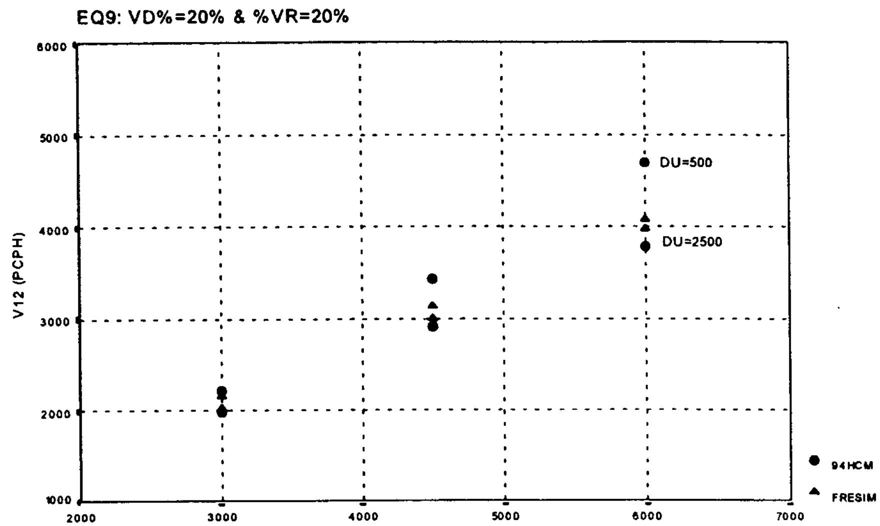


94HCM Equation 9				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Main Ramp Free-Flow Speed = 55 mph Downstream Ramp Free-Flow Speed = 55 mph Main Ramp Deceleration Lane Length (L_D) = 500 feet Downstream Ramp Deceleration Lane Length (L_D) = 500 feet No Trucks Level Grade				
Lanes	**V_R (% of V_F)**	**V_F (pcph)**	**$LINK_{UP}$ (feet)**	**D_D (feet)**
3	10% 20% 30%	3,000 4,500 6,000	250 5,000	500 5,000

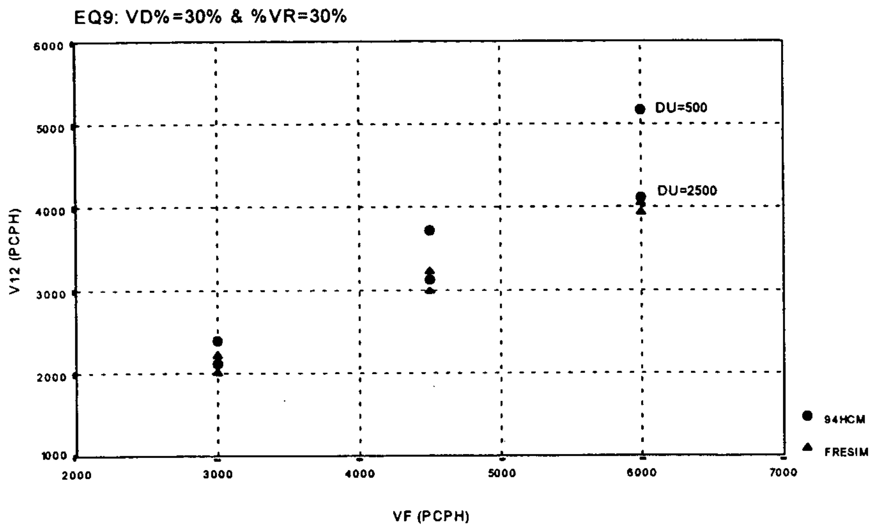
Figure 2-36. Sensitivity cases for 94HCM Equation 9.



(a) V_R = 10% & V_D = 10%

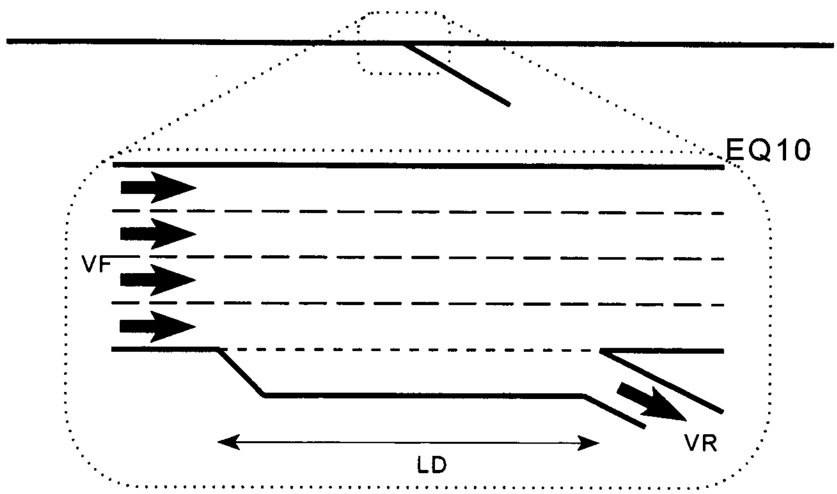


(b) V_R = 20% & V_D = 20%



(c) V_R = 30% & V_D = 30%

Figure 2-37. Sensitivity of V_{12} to V_R and V_D—94HCM Equation 9.



94HCM Equation 10				
In addition to the variables listed below, the following variables were held constant for all runs: Freeway Free-Flow Speed = 65 mph Main Ramp Free-Flow Speed = 45 mph Main Ramp Deceleration Lane Length (L_D) = 600 feet No Trucks Level Grade				
Lanes	**V_R (% of V_F)**	**V_F (pcph)**	**$LINK_{UP}$ (feet)**	**$LINK_{DWN}$ (feet)**
4	**10%** **20%** **30%**	**4,000** **6,000** **7,600**	**250** **5,000**	**250** **5,000**

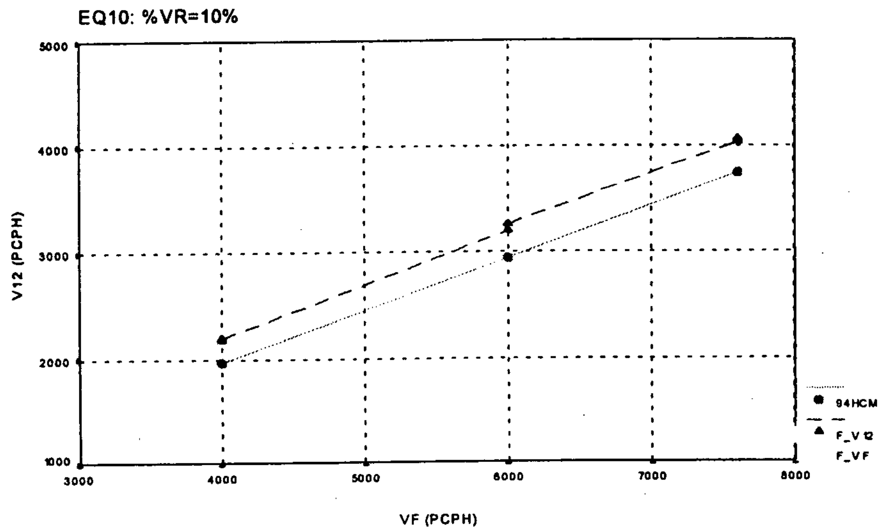
Figure 2-38. Sensitivity cases for 94HCM Equation 10.

SUMMARY AND CONCLUSIONS

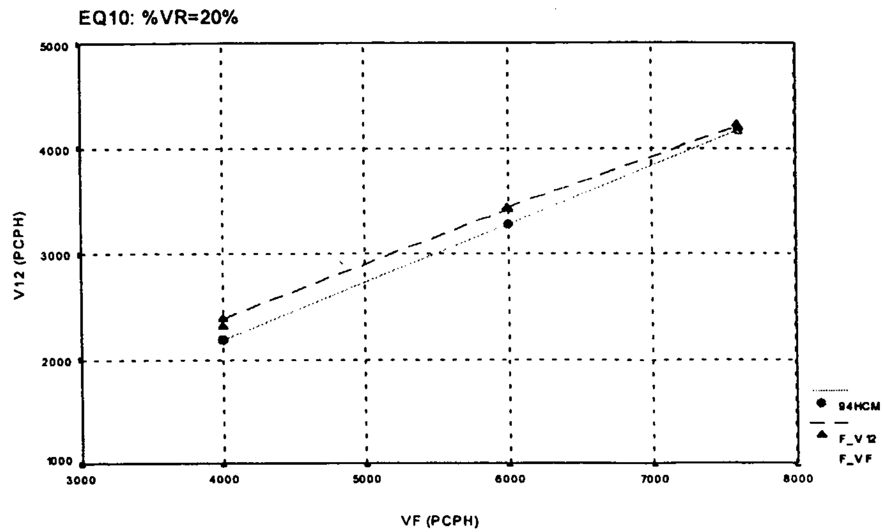
The principal difficulty with FRESIM in its predictions of V_{12} is the relative insensitivity of the model to important variables. The lack of sensitivity to specific geometric variables, such as length of acceleration or deceleration lane and free-flow speed of the ramp, limits the ability of analysts to examine the impact of design changes. As both sensitivities were evident in the NCHRP database, the lack of sensitivity in FRESIM must be considered a flaw.

It is also clear that the sensitivity of FRESIM to the existence and proximity of upstream and/or downstream adjacent ramps and to the volume on these ramps is not substantial and is well below that of the 94HCM models.

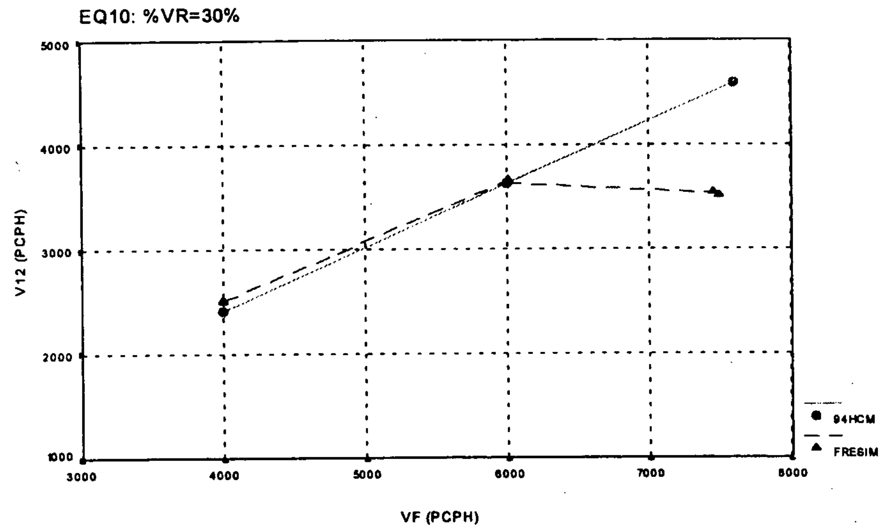
It is this lack of sensitivity that remains the primary obstacle in applying FRESIM directly to the analysis of ramp merge and diverge areas. The lane distribution resulting from a FRESIM analysis is simply too static and unresponsive to a variety of specific variables, all of which have been deemed important by the 94HCM. The fact that they are considered important reflects strong correlations in a substantial field database [NCHRP Project 3-37 (1)]. The fact that FRESIM does not replicate these sensitivities seriously affects its use for ramp analysis.



(a) V_R = 10%



(b) V_R = 20%



(c) V_R = 30%

Figure 2-39. Sensitivity of V_{12} to V_R and V_F—94HCM Equation 10.

CHAPTER 3

COMPARING PREDICTIONS OF DENSITY AND SPEED

The 1994 *Highway Capacity Manual* (94HCM) methodology for analysis of ramp junctions bases level of service on density in the "ramp influence area." The ramp influence area covers a 1,500-ft section of roadway (upstream of an off-ramp and downstream of an on-ramp) that includes the acceleration or deceleration lane and lanes 1 and 2 of the freeway. For stable operations, an algorithm is also provided that allows for the estimation of speed (i.e., space mean speed) of vehicles within this section.

In this chapter, several means of comparing density and speed predictions of both the 94HCM and FRESIM are reported and discussed.

COMPARISONS WITH AN INDEPENDENT DATABASE: TES DATA

Technical Report No. 2, submitted in October 1995, discusses the comparisons among the 94HCM, FRESIM, and TES data in great detail. Some of the results are repeated here for completeness, but not all are reproduced.

Figure 3-1 shows the comparisons among actual TES density data, 94HCM data, FRESIM data (unmodified), and FRESIM data (modified to reflect actual V_{12} entering the area) for on-ramps on 6-lane freeways. It is clear that for all three sites, FRESIM is a better predictor of density (whether modified or unmodified) than the 94HCM. The 94HCM is more likely to overestimate density than underestimate it, but both appear to be possible. For Site 3, all three models yield good predictions. For Sites 1 and 2, prediction errors can be substantial for the effective range of densities covered.

Figure 3-2 shows speed comparisons for the same three on-ramp cases. The 94HCM model predicts a more constant speed than FRESIM and does not predict small perturbations evident in the data. However, the 94HCM generally is a better predictor of speed than FRESIM. FRESIM tends to overpredict speed, sometimes substantially. None of the models is able to predict short-term spikes in the field data, which might be due to some form of disruption to flow, such as a lane blockage.

Figures 3-3 and 3-4 show similar data for the two off-ramp cases included in the TES data set. Again, both are isolated ramps on 6-lane freeways. Again, FRESIM is seen to be a better predictor of density. The 94HCM is a better predictor of speed for Site 4, while FRESIM is a better predictor of speed for Site 5.

The TES site results are interesting. The 94HCM gives better predictions of both V_{12} and speed, yet FRESIM gives better density estimates. This may indicate one area in which FRESIM is more sensitive than the 94HCM. The 94HCM essentially assumes that V_{12} remains relatively constant throughout the 1,500-ft length of the influence area. This means that as vehicles move from the acceleration ramp to lane 1, more or less equal numbers of vehicles are moving from lane 2 to lane 3. The reverse would occur for an off-ramp. FRESIM may be allowing for more variance in the occupancy of lanes 1 and 2 along the length of the influence area, resulting in a different density estimate.

The results may also have something to do with the way density is estimated from both field and simulation data. It is not measured exactly in either case, but inferred from speed and flow data at 500-ft trap boundaries throughout the influence area. There are four such traps in each lane, including the acceleration or deceleration lane.

It is also interesting that FRESIM yields fairly accurate density predictions given that the lane-changing regime forces on-ramp vehicles to merge in the first 100 ft of the acceleration lane and off-ramp vehicles to enter the deceleration lane quickly.

COMPARISONS USING THE NCHRP DATABASE

Similar comparisons were made using the NCHRP Project 3-37(1) database, as described in Chapter 1. Figures 3-5 and 3-6 show the results of these analyses for prediction of density and speed for merge and diverge cases.

In predicting densities, the results illustrated in Figure 3-5 are considerably more favorable to the 94HCM methodology. This might be expected, given that the data was used, at least in part, to calibrate the 94HCM algorithms. For most merge cases, the 94HCM gives better predictions of density than FRESIM. Results for diverge cases are more mixed, with the 94HCM yielding better density estimates for high density values, and FRESIM giving better estimates for lower densities (with the dividing line at approximately 35 veh/hr/lane).

The results of these analyses are more precisely presented in Table 3-1. Appendix C contains more detailed statistical data. Average errors in the prediction of density and speed are compared for each NCHRP site included in the compar-

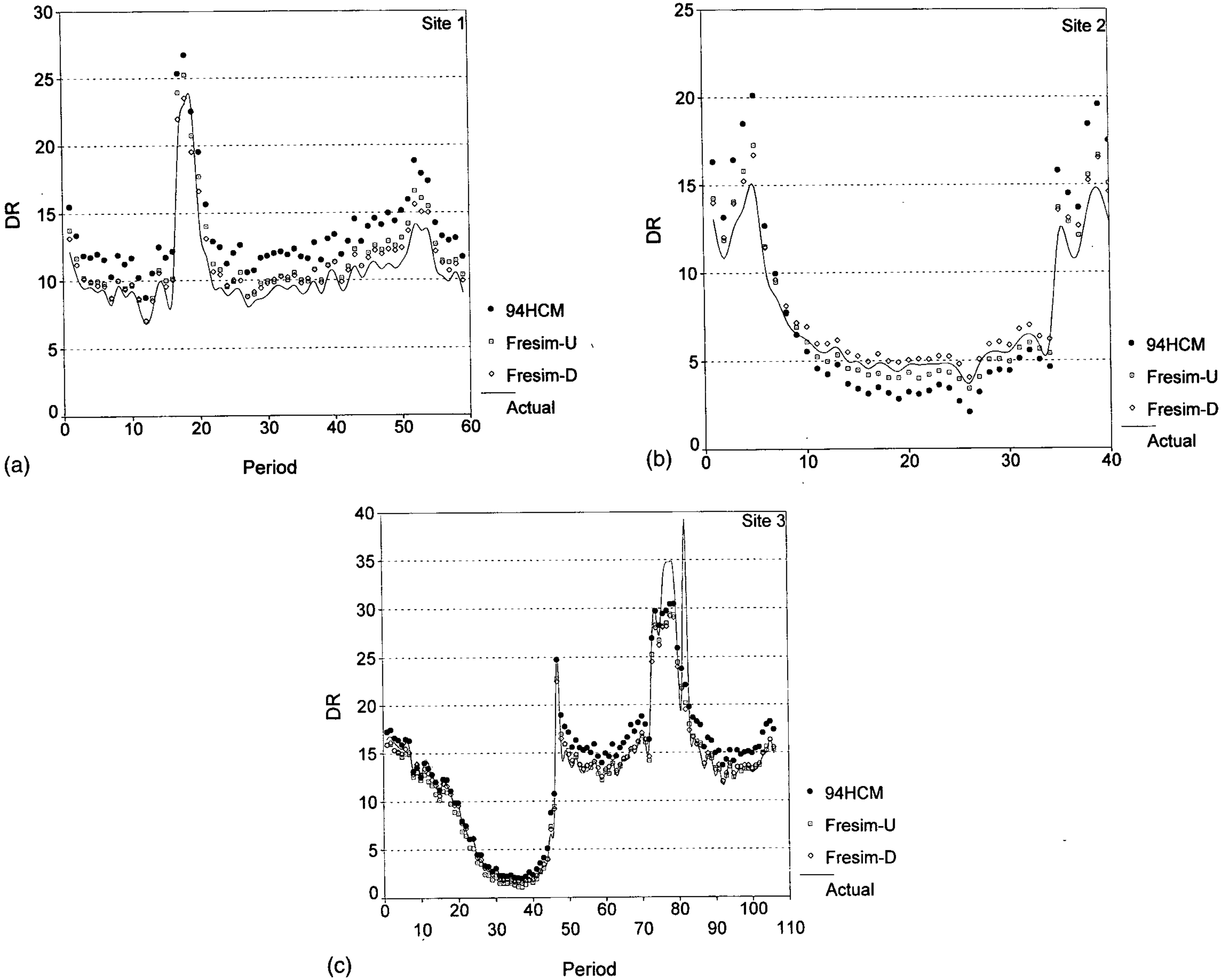


Figure 3-1. Predicted values of density for on-ramps—TES data.

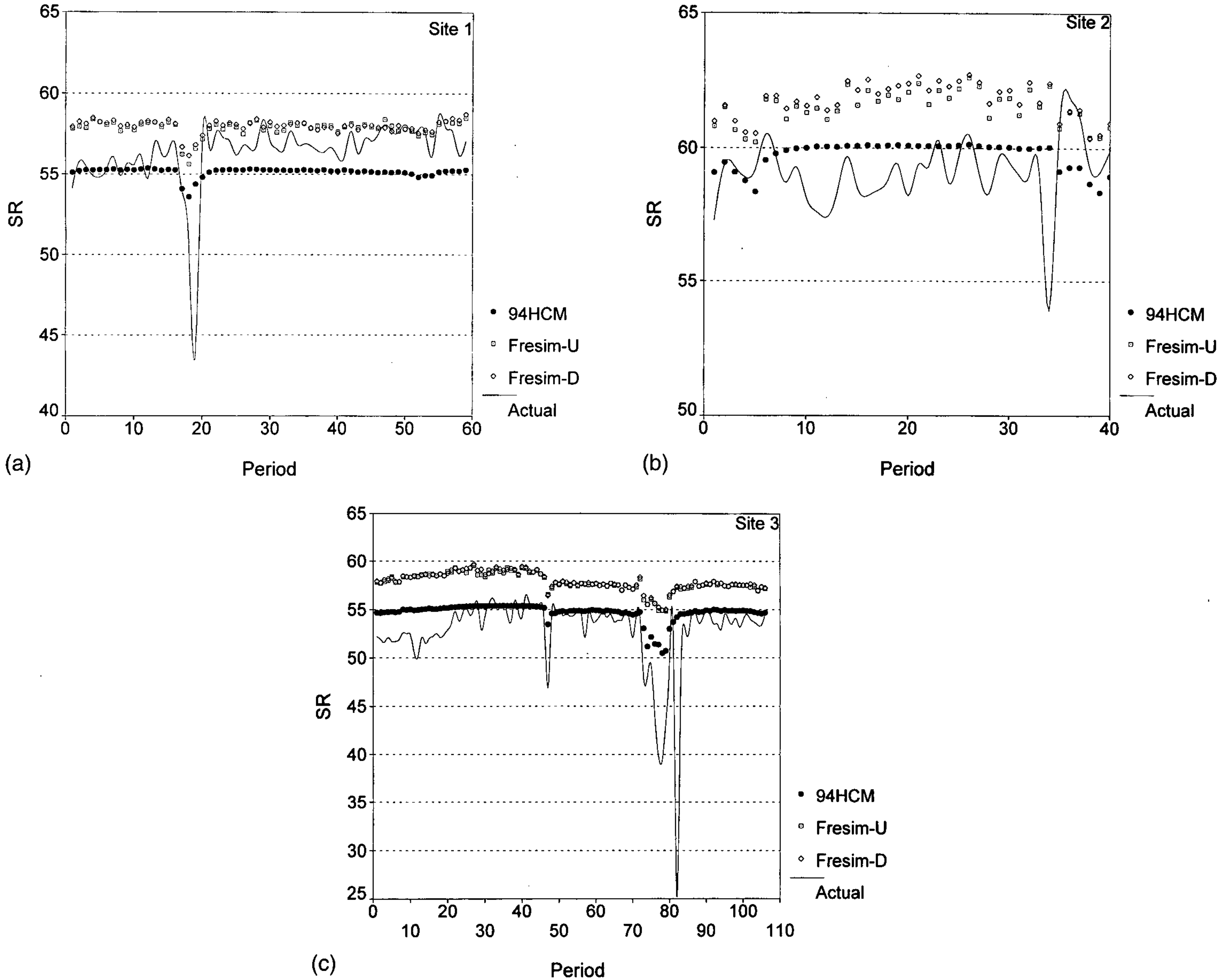


Figure 3-2. Predicted values of speed for on-ramps—TES data.

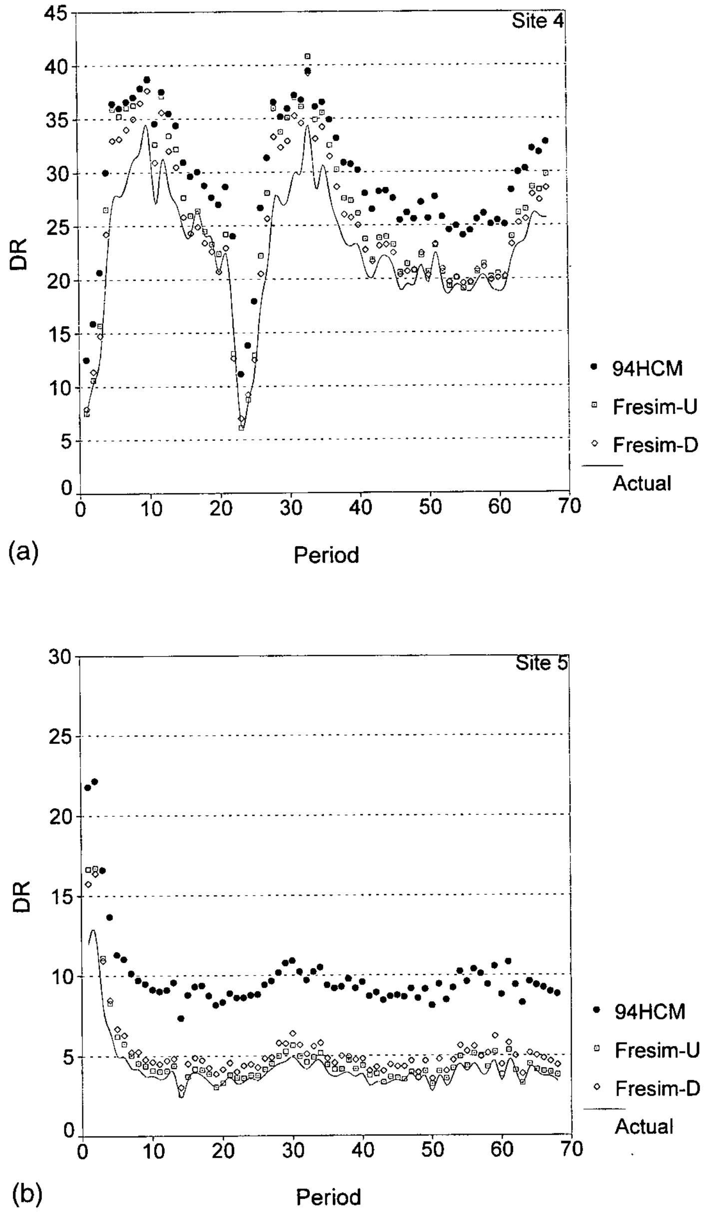


Figure 3-3. Predicted values of density for off-ramps—TES data.

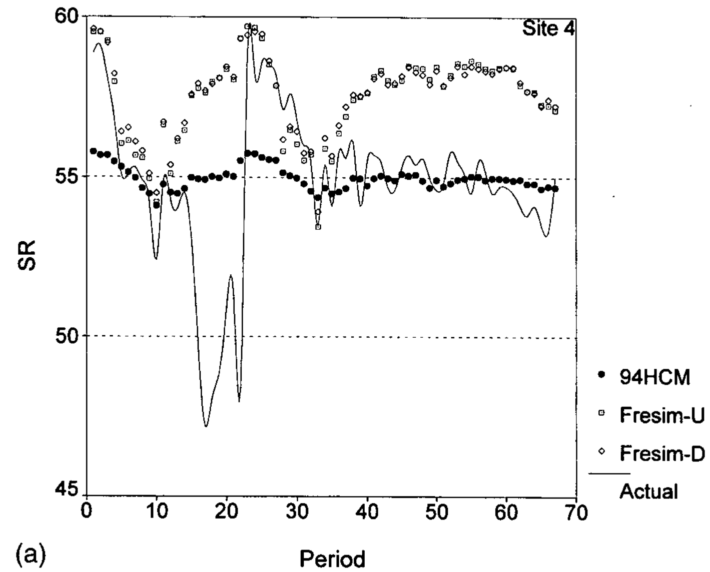
ison. The "average error" is computed as the square root of the average squared error.

The results are interesting. For eight out of 11 on-ramp cases, the 94HCM produces better density estimates than FRESIM. For the same 11 sites, however, the 94HCM produces better speed estimates in only four cases. For six off-ramp cases, FRESIM and the 94HCM produce better estimates of density in three cases each. The 94HCM produces better speed estimates than FRESIM in four out of six cases.

Even more interesting is the fact that in seven of the 17 cases, one model produces better density predictions and the other better speed predictions. This suggests that neither model has the relationship between the two very well defined.

This could be a result of the way in which density and speed were observed in the field and extracted from the simulation runs. It could also be a result of underlying assumptions in the models themselves. As noted, the 94HCM assumes a relatively constant volume along the length of the "ramp influence area" and FRESIM is insensitive to many variables thought to have a substantial influence on merge and diverge area operations.

Figure 3-7 illustrates the relationship between S_R and D_R for actual data, and for FRESIM and 94HCM predictions.



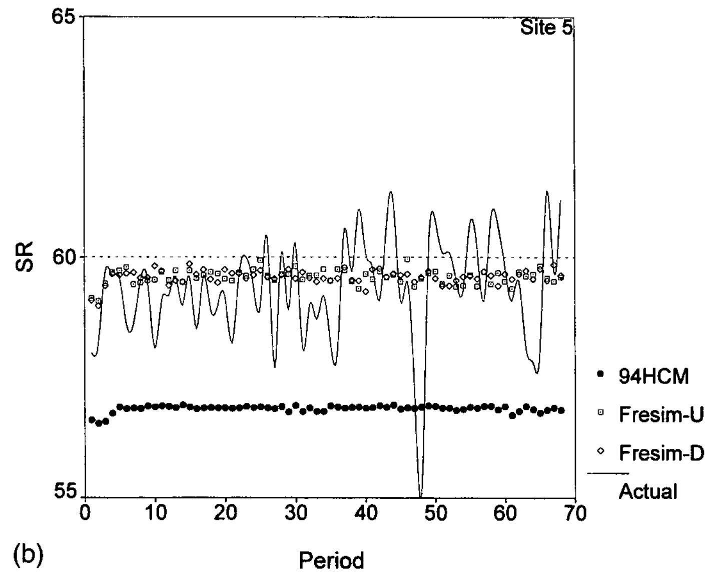


Figure 3-4. Predicted values of speed for off-ramps—TES data.

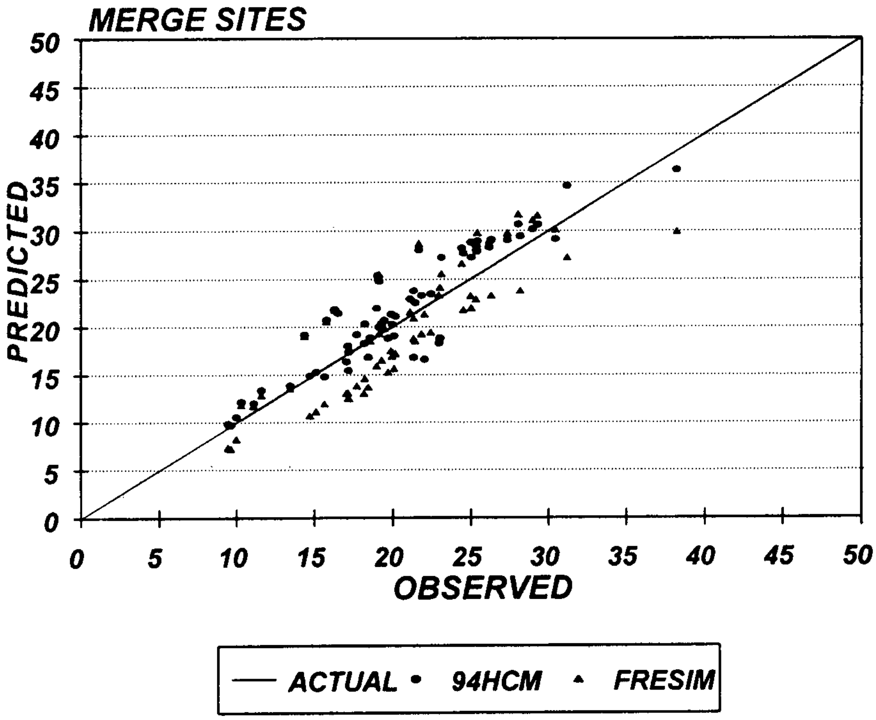
Interestingly, all three yield similar relationships. The actual data appear to have a slightly higher slope, i.e., sensitivity of speed to density, than either the 94HCM or FRESIM. In all cases, the relationship is flatter than might have been expected, even for densities in excess of 36 pc/mi/ln. There is nothing in this data, however, to suggest that either model is projecting a grossly unreasonable speed-density relationship.

SENSITIVITY ANALYSES ON DENSITY AND SPEED

The density model of the 94HCM is sensitive to ramp volume, the volume in lanes 1 and 2, and the length of the acceleration or deceleration lane. Thus, most of the differences in sensitivity of FRESIM and the 94HCM in predicting V_{12} will at least partially carry over to the prediction of density and speed.

Nevertheless, all of the sensitivity cases described in Chapter 2 were also run to compare predictions of density and speed. These cases were further examined for differences in these predictions and for the speed versus density relationships that their results implied.

Figures 3-8 and 3-9 illustrate the results of sensitivity analyses for 94HCM Equation 2, dealing with isolated 6-lane ramps. In Figure 3-8a, it is seen that for densities under 30 pc/mi/ln, the 94HCM produces somewhat higher esti-



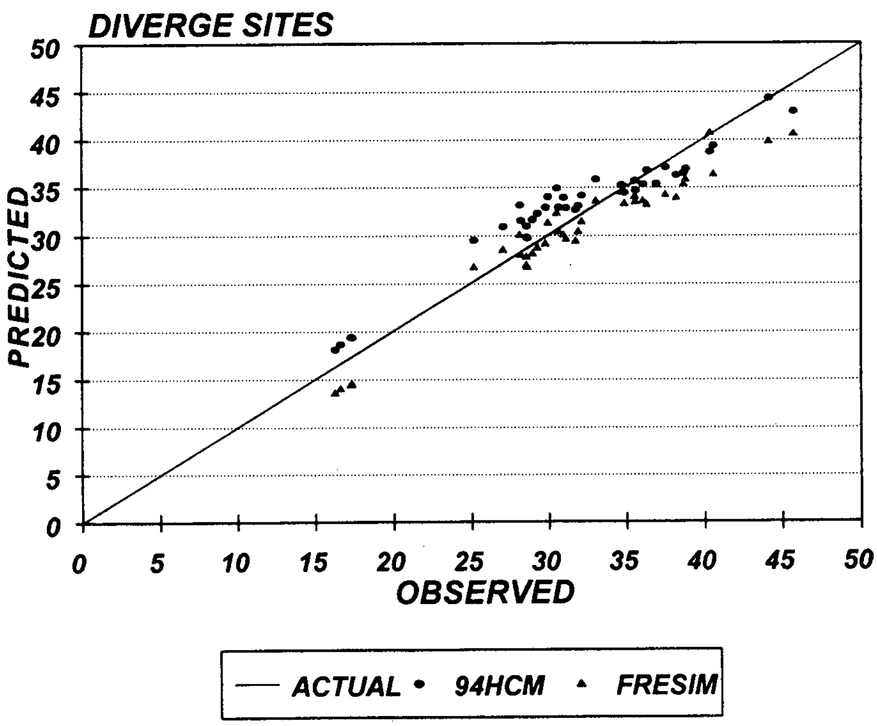
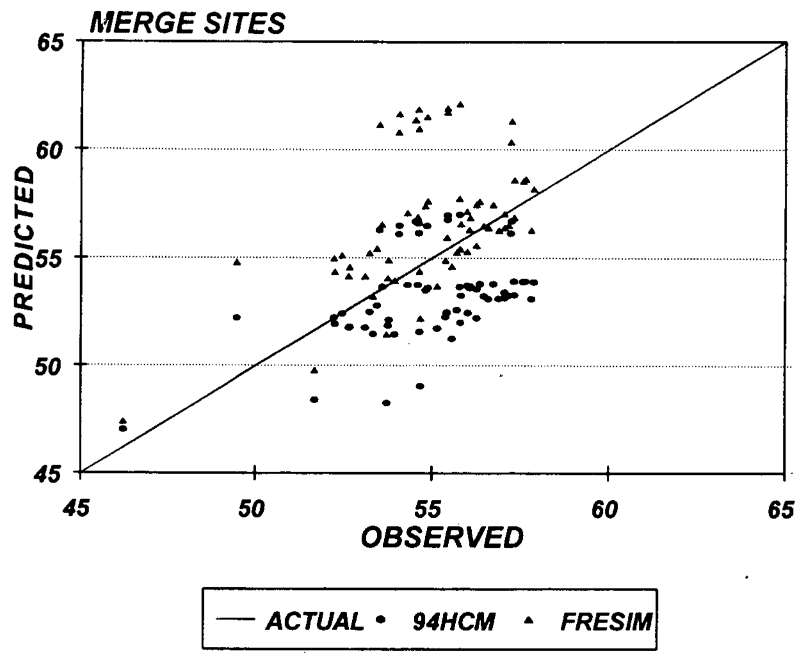


Figure 3-5. Predicted values of density for merge and diverge sites—NCHRP data.

mates of D_R than FRESIM. At higher densities, however, FRESIM produces significantly larger D_R estimates than the 94HCM. A similar trend is evident in speed predictions. For speeds of 55 mph or lower, the 94HCM produces higher estimates than FRESIM; for higher speeds, FRESIM is producing slightly higher speed estimates.

Figure 3-9 shows the speed-density relationship that results from the sensitivity cases for Equation 2. FRESIM displays a wider range of both speeds and flows, while the 94HCM produces a much more limited range. The 94HCM results form a clearer trend, but the range of results appears to be too limited.



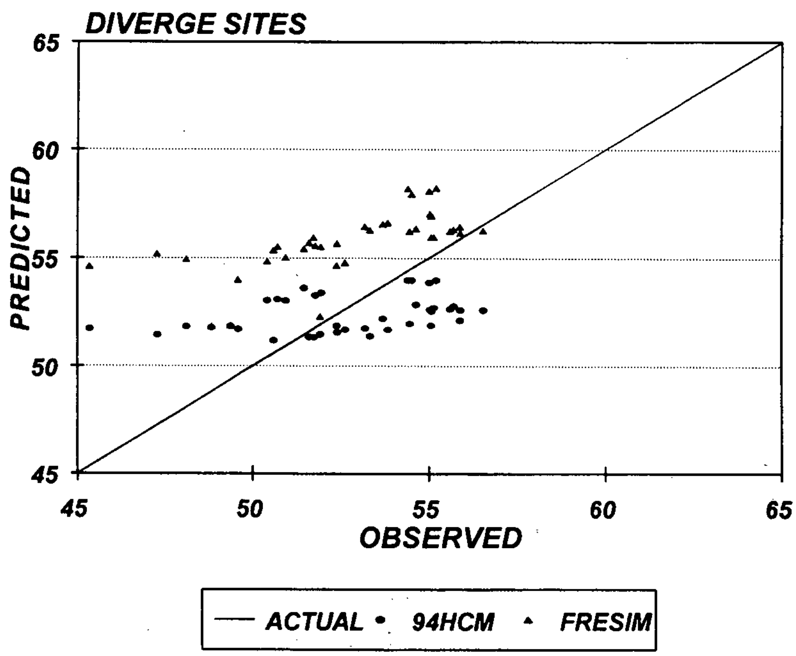


Figure 3-6. Predicted values of speed for merge and diverge sites—NCHRP data.

Similar comparisons are made for each of the 94HCM equations, except for those applying to 4-lane freeways. Figures 3-10 and 3-11 illustrate the comparisons for 94HCM Equation 3, which deals with adjacent upstream off-ramps and an on-ramp on a 6-lane freeway. For this case, the 94HCM appears to generally predict higher densities, while FRESIM predicts higher speeds. The scatter of points is more random than for Equation 2. The speed-density curves of Figure 3-11 result in a well-defined curve for 94HCM results and a more linear trend for FRESIM. FRESIM produces higher speeds at the upper end of the speed scale.

Figures 3-12 and 3-13 show the results for the 94HCM Equation 4, dealing with a downstream adjacent off-ramp and an on-ramp on a 6-lane freeway. As illustrated in Figure 3-12, the 94HCM once again predicts higher densities and lower speeds than FRESIM consistently. The resulting speed-density curves of Figure 3-13 are virtually the same for both models.

TABLE 3-1 Comparative prediction errors—density and speed (NCHRP data)

Site	Type of Ramp	No. of Lanes on Fwy	No. of Data Periods	Absolute Average Error			
				Density pc/mi/ln		Speed mph	
				94HCM	FRESIM	94HCM	FRESIM
9	On	2	6	1.2*	2.7	2.1*	7.1
16	On	2	6	1.1*	2.7	3.7	0.9*
40	On	2	4	1.4	1.1*	2.5	1.0*
8	On	3	8	2.2*	2.9	1.6*	2.6
10	On	3	7	5.5*	5.8	3.4	0.6*
18	On	3	6	1.6*	4.2	1.4*	5.7
23	On	3	6	2.5	1.4*	4.4	1.6*
25	On	3	5	3.6*	4.5	2.0	1.3*
26	On	3	4	2.4*	3.3	2.2	1.1*
27	On	4	7	1.1*	4.1	2.9	1.8*
46	On	4	4	4.7	0.7*	1.3*	2.3
36	Off	2	4	2.0*	2.7	0.9*	3.3
54	Off	2	6	2.9	0.6*	3.0	0.9*
56	Off	2	7	1.4*	3.5	1.8*	2.8
15	Off	3	9	3.4	1.5*	3.0*	5.6
35	Off	3	6	1.7	1.3*	2.7	1.8*
37	Off	3	6	1.6*	2.9	2.0*	4.1

*better estimate

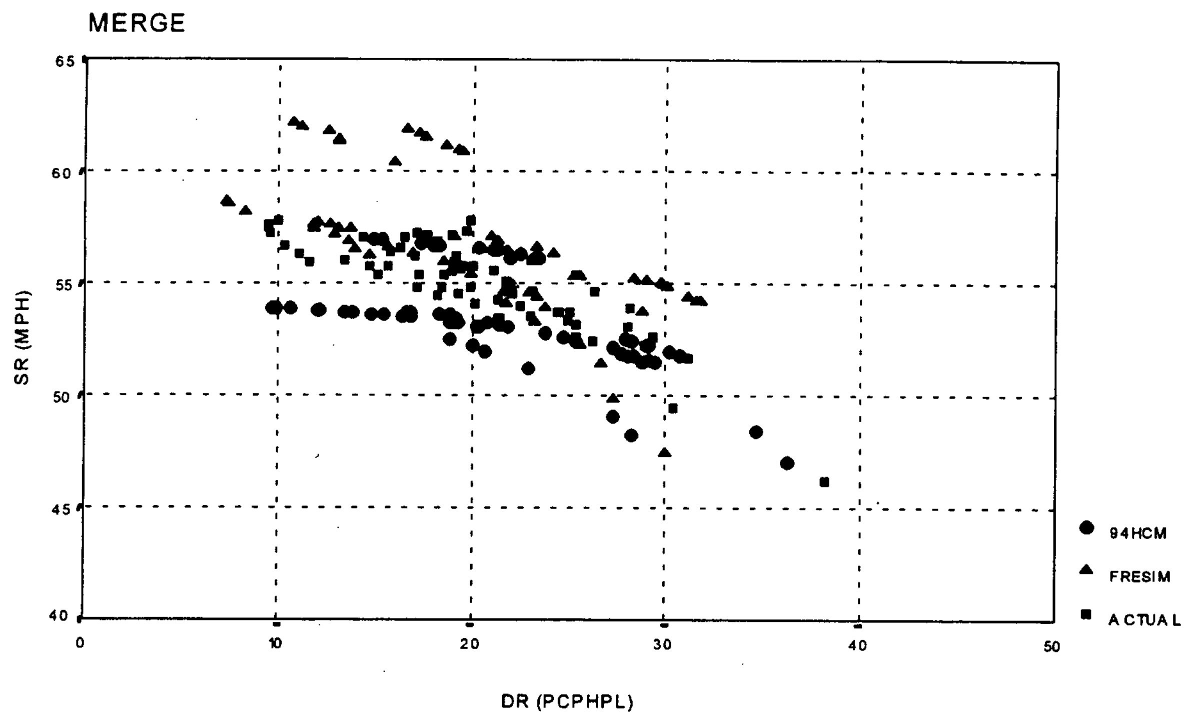
Figures 3-14 and 3-15 show the results for the 94HCM Equation 5, which deals with all cases of on-ramps on an 8-lane freeway. Figure 3-14 shows that, unlike in Equations 3 and 4, FRESIM predicts higher density values than the 94HCM for this case. The speed predictions are more mixed, with FRESIM tending to give lower speed estimates. However, the range of the difference between the 94HCM and FRESIM predictions is very large for this case and is possibly related to the fact that there is only one general 94HCM model for 8-lane freeways, not a series of models dealing with different adjacencies.

The density-speed curves of Figure 3-15 show similar trends for both the 94HCM and FRESIM. Again, FRESIM shows a wider variance and a greater range of both speeds and densities across the sensitivity cases.

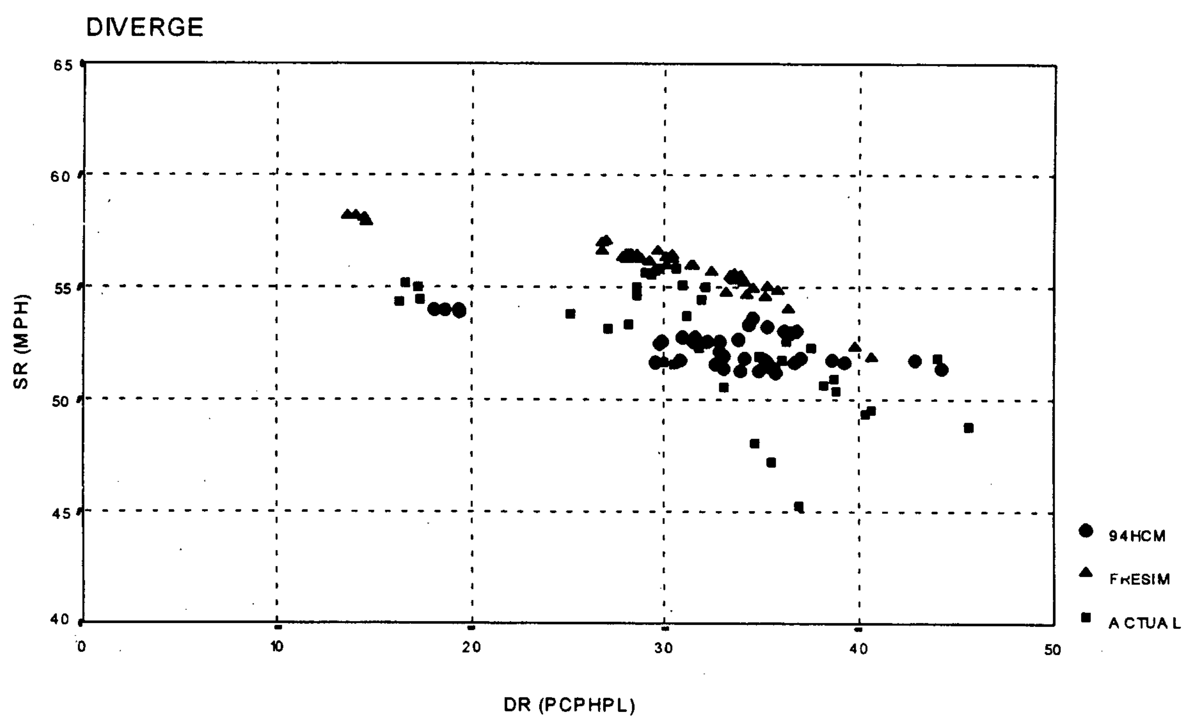
The next set of illustrations deals with off-ramps. In these cases, some startling and consistent trends are evident. Therefore, figures are organized somewhat differently to emphasize this. Figures 3-16 through 3-19 show comparisons in the prediction of density for Equations 7, 8, 9 and 10 respectively, all of which are off-ramp cases. For all these cases, the figures show that the 94HCM predicts consistently, and often significantly, higher densities than FRESIM. The only points for which this is not true involve two high-density points using Equation 10; these cases involve off-ramp vehicles not successfully leaving the freeway at the desired point.

One possible explanation of this phenomenon is that the 94HCM model forces all off-ramp vehicles into lane 1 at the gore area, which adds to density. As noted previously, a serious flaw in FRESIM is the inability to absolutely control off-ramp volumes. These are left to a probability-based process, and the actual ramp volume may vary considerably from the intended volume, even when averaged over a series of runs.

Figures 3-20 through 3-23 show speed prediction comparisons for the same cases. Here, the 94HCM consistently, and often significantly, predicts lower speeds than FRESIM. The prediction of higher densities and lower speeds is entirely consistent, as one will lead to the other. The reasons for the differences are the same as those cited for density predictions. However, the scatter of speed predictions is very wide, showing little consistency between the two models.

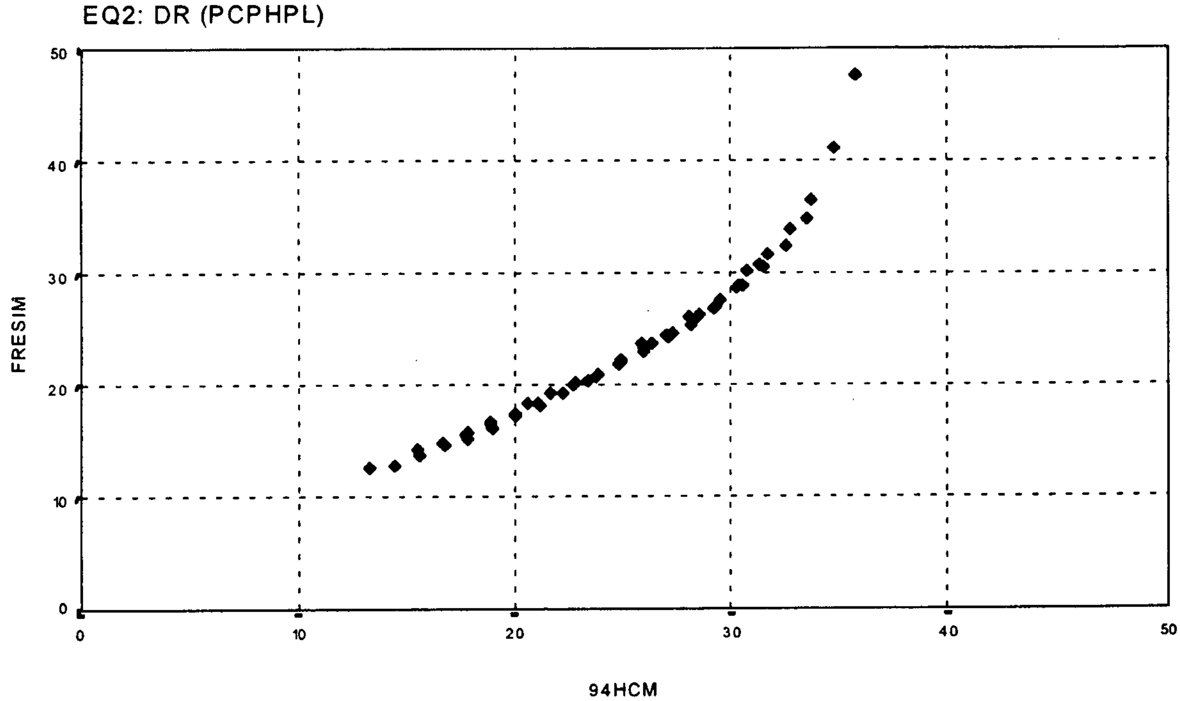


(a) On-Ramps

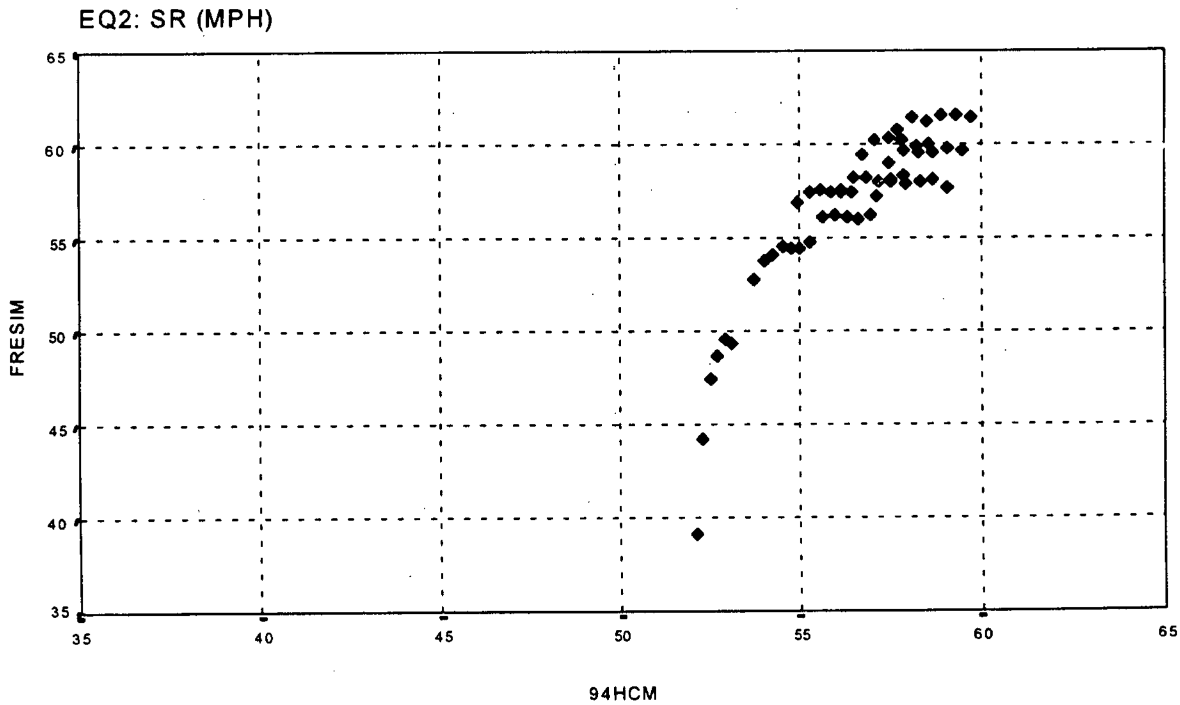


(b) Off-Ramps

Figure 3-7. Speed versus density in ramp influence areas—NCHRP data.



(a) Density



(b) Speed

Figure 3-8. Comparing density and speed predictions—94HCM Equation 2.

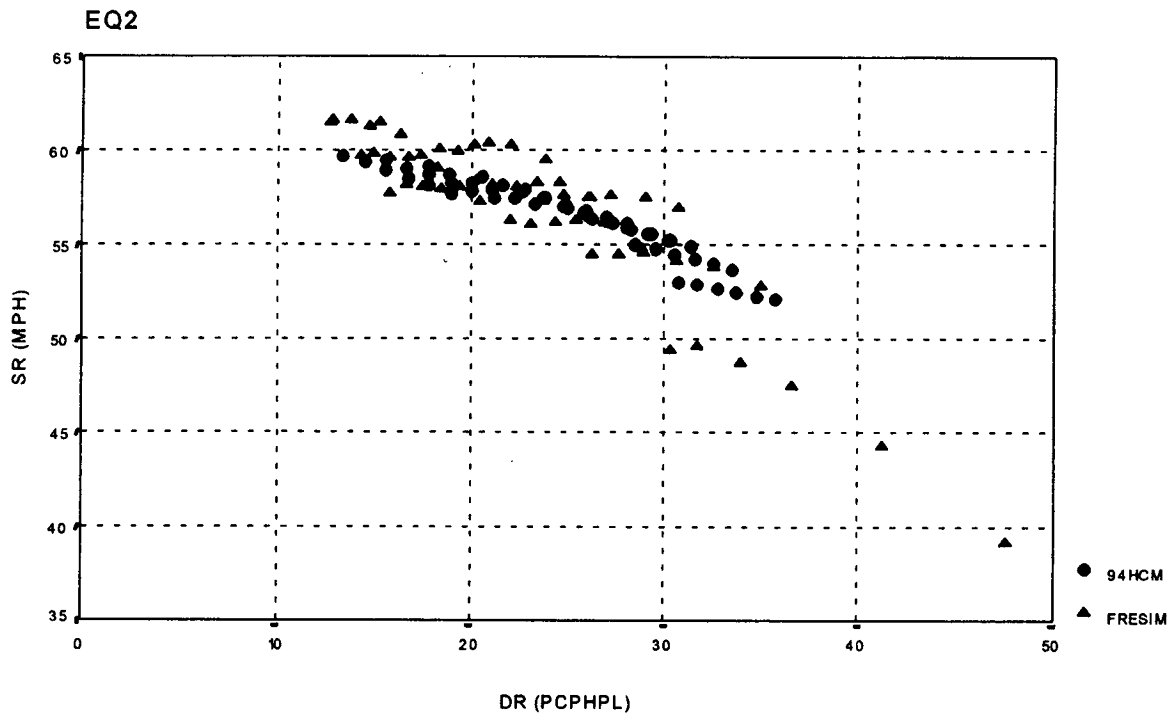
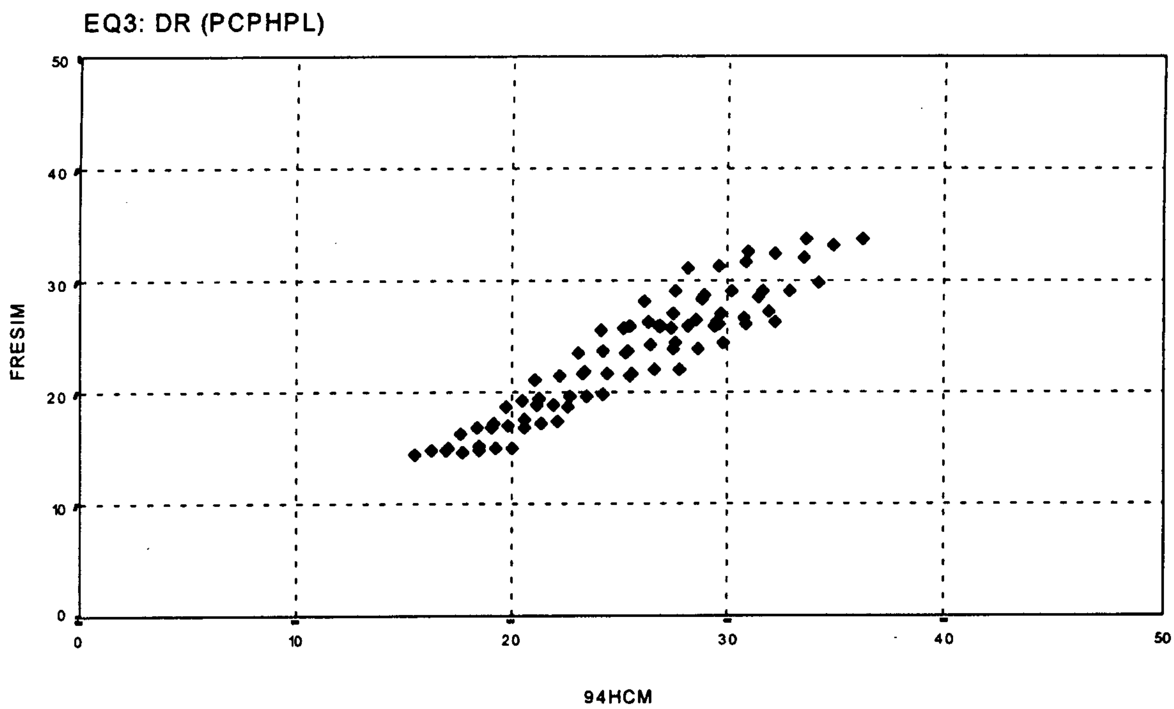
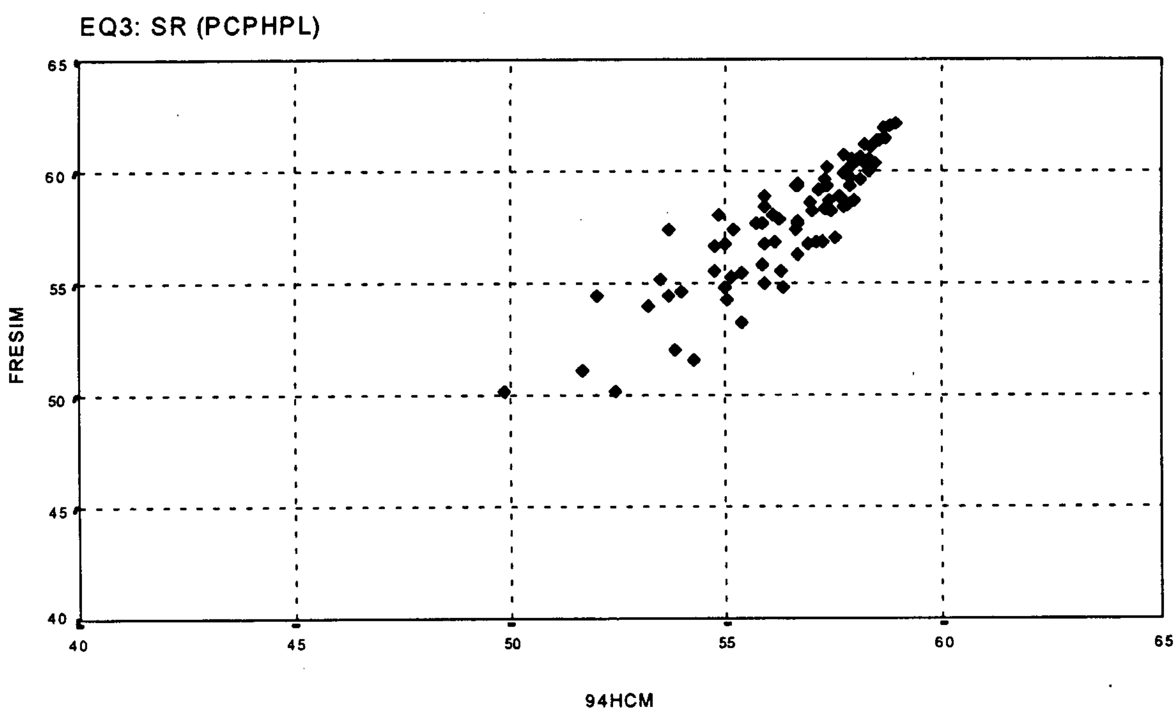


Figure 3-9. Speed versus density curves—94HCM Equation 2.



(a) Density



(b) Speed

Figure 3-10. Comparing density and speed predictions—94HCM Equation 3.

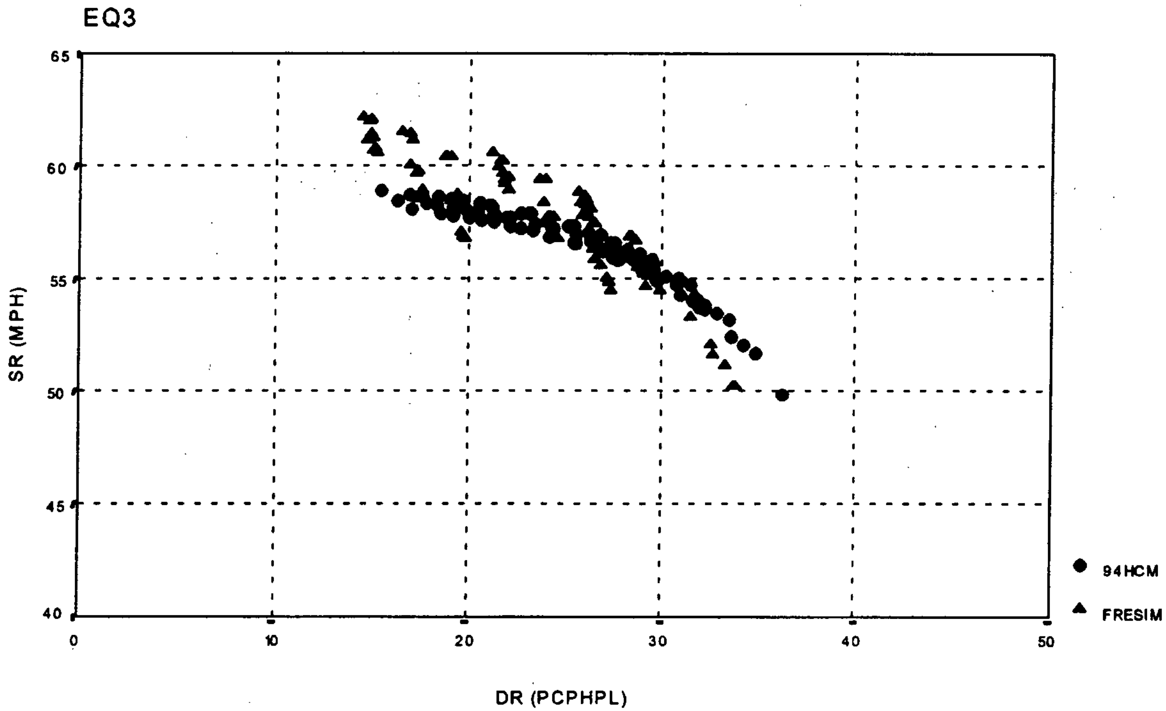
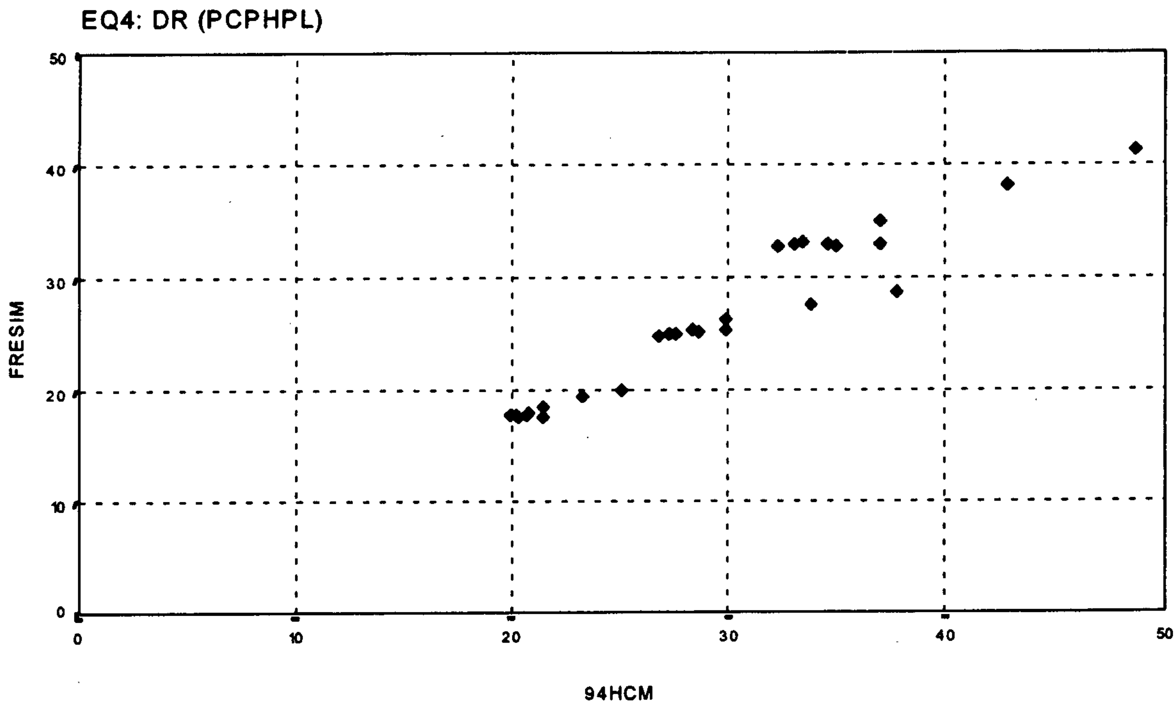
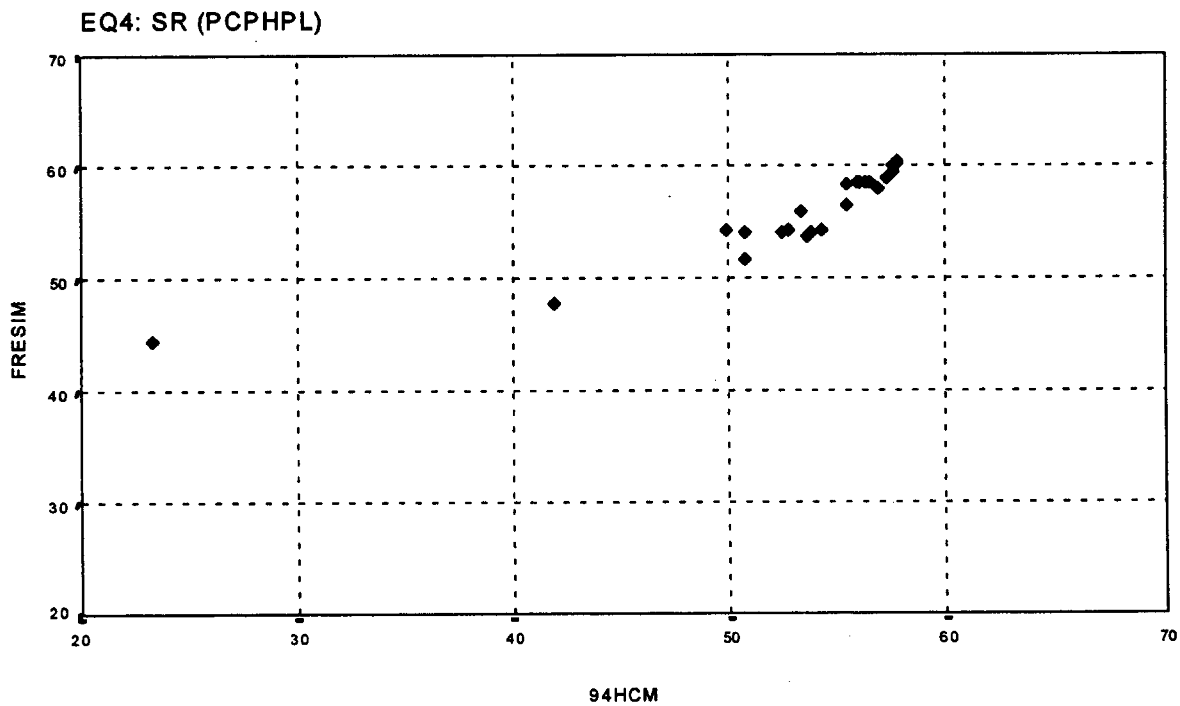


Figure 3-11. Speed versus density curves—94HCM Equation 3.



(a) Density



(b) Speed

Figure 3-12. Comparing density and speed predictions—94HCM Equation 4.

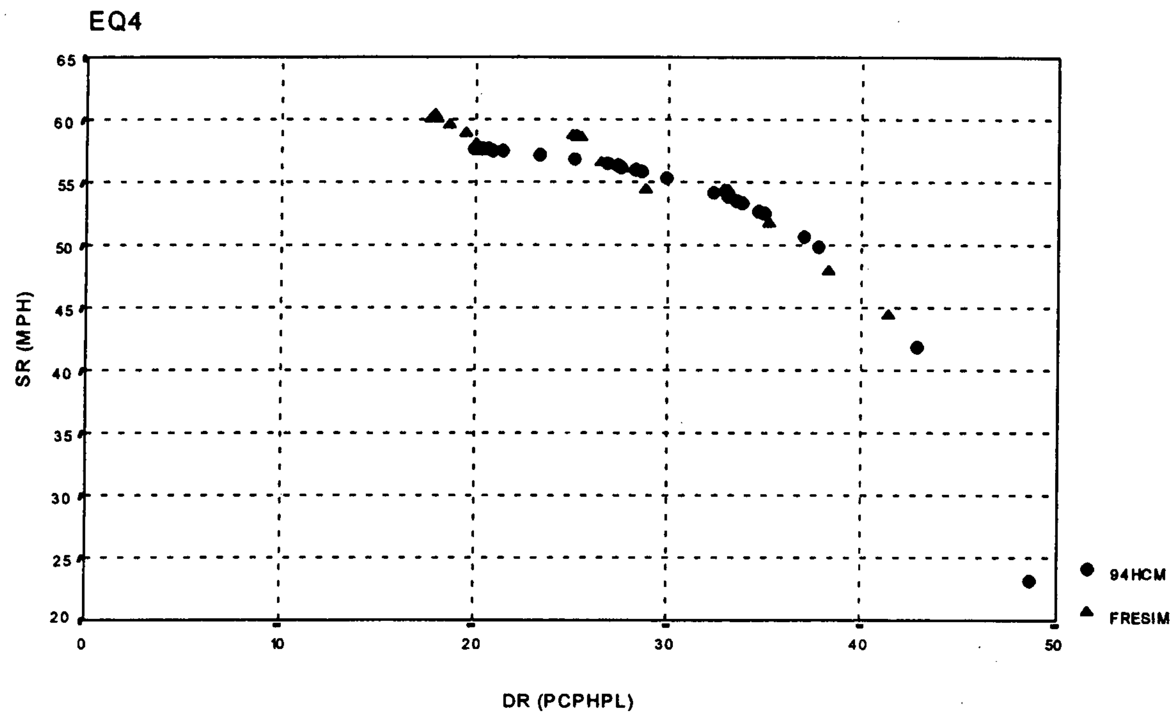
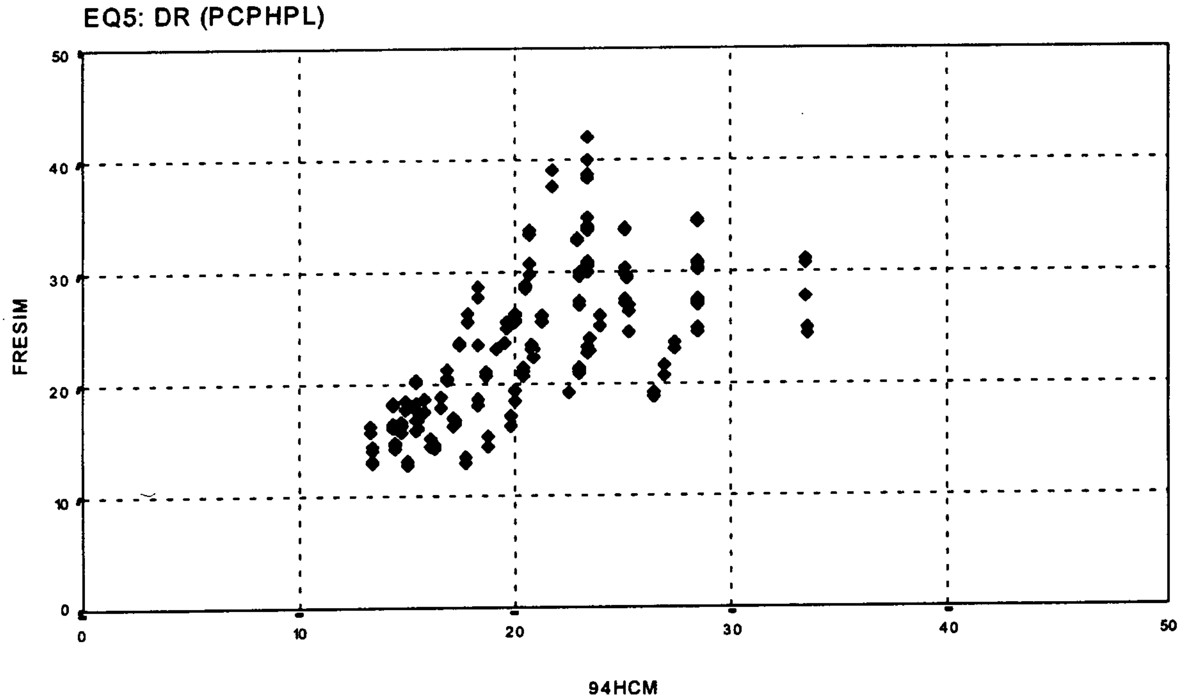
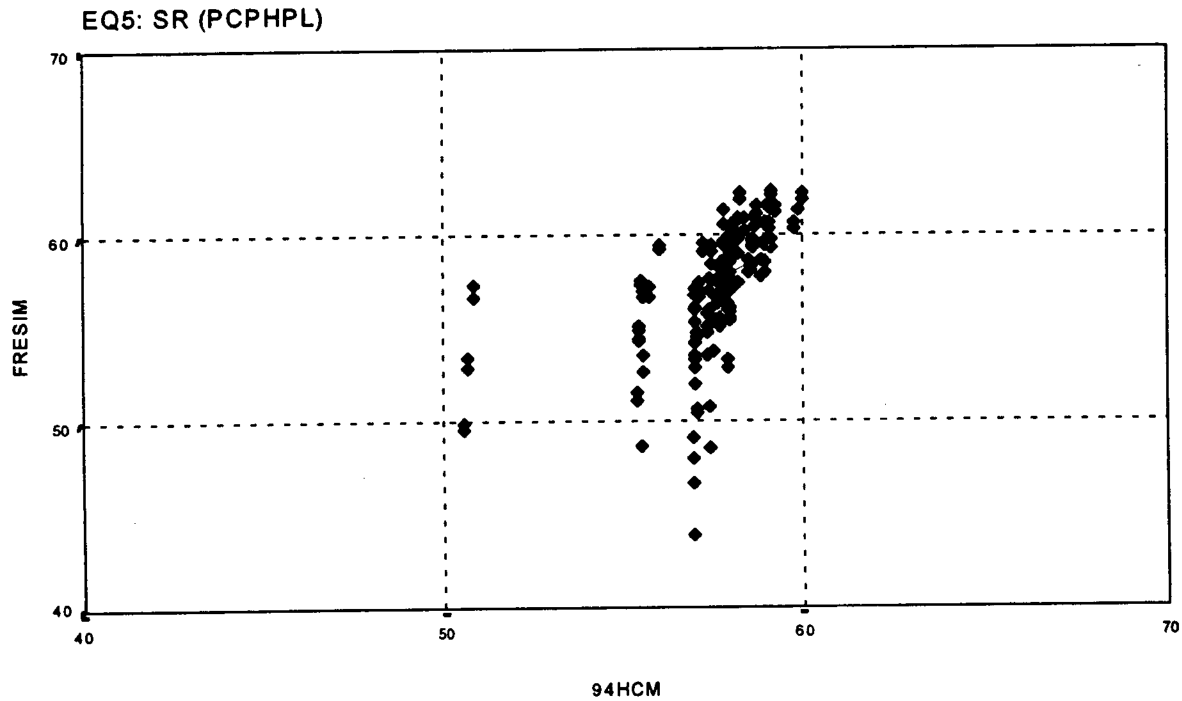


Figure 3-13. Speed versus density curves—94HCM Equation 4.



(a) Density



(b) Speed

Figure 3-14. Comparing density and speed predictions—94HCM Equation 5.

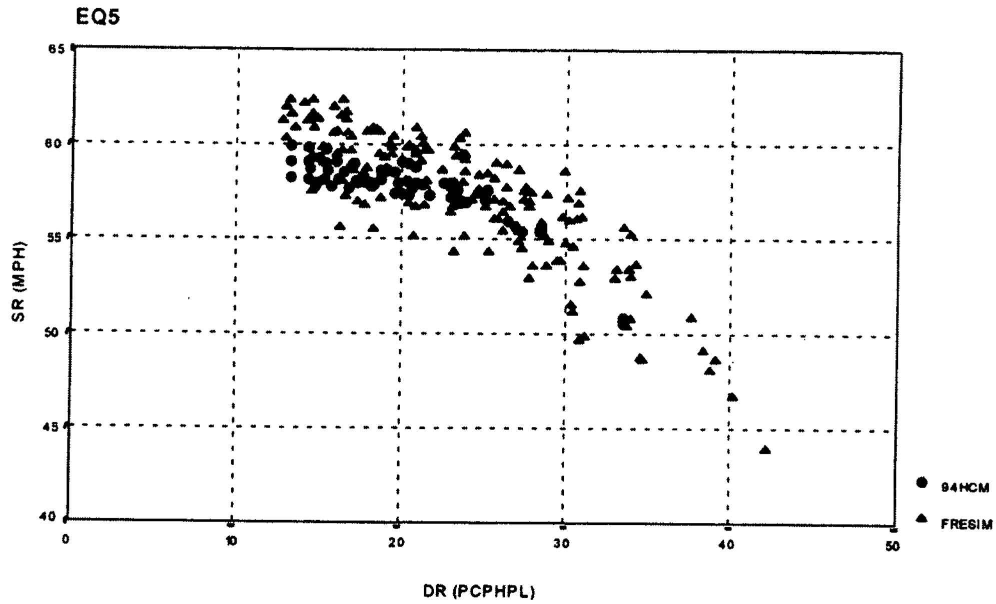


Figure 3-15. Speed versus density curves—94HCM Equation 5.

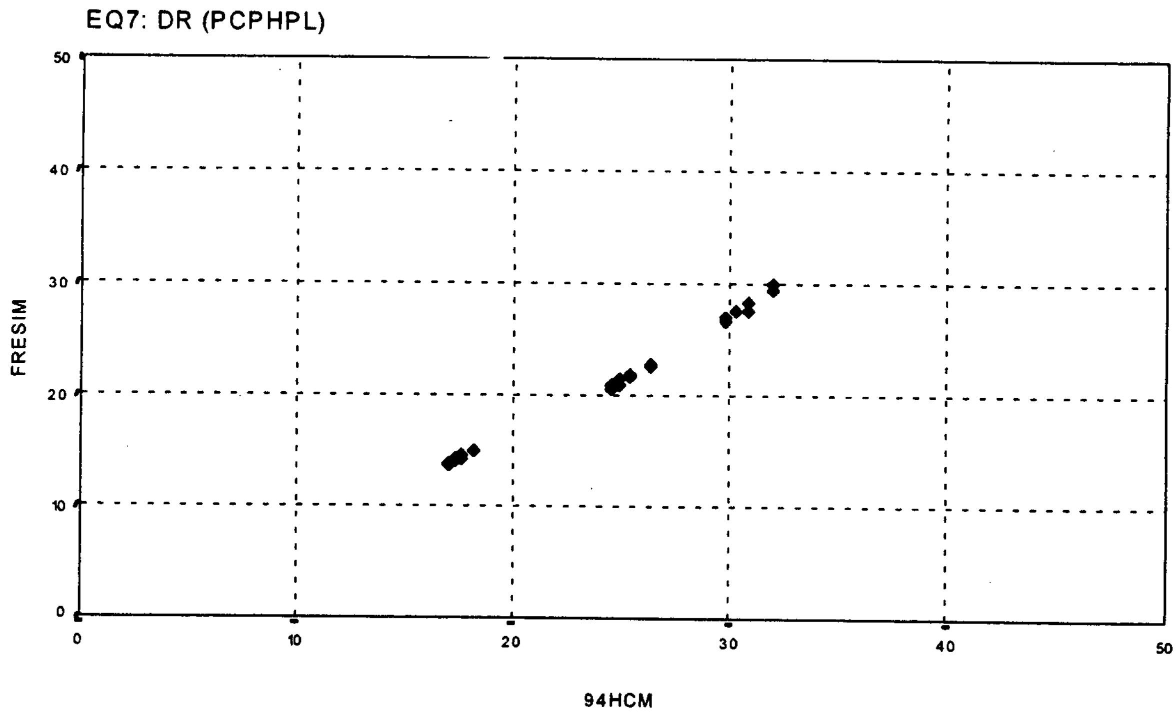


Figure 3-16. Density predictions—94HCM Equation 7.

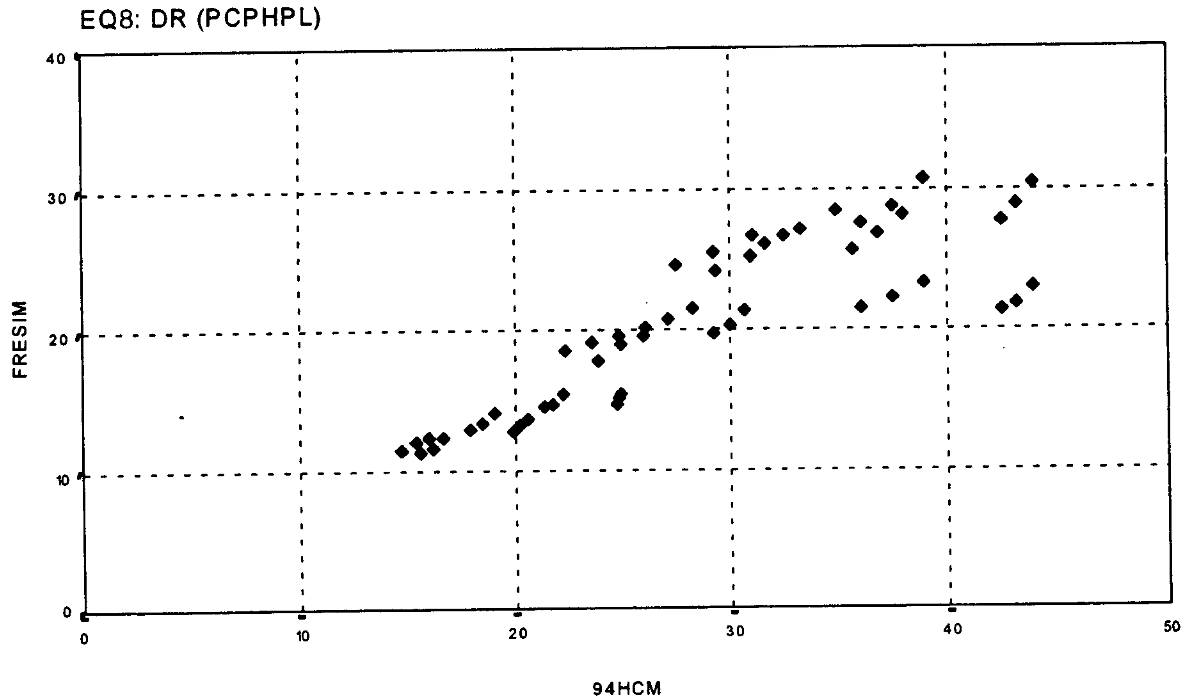


Figure 3-17. *Density predictions—94HCM Equation 8.*

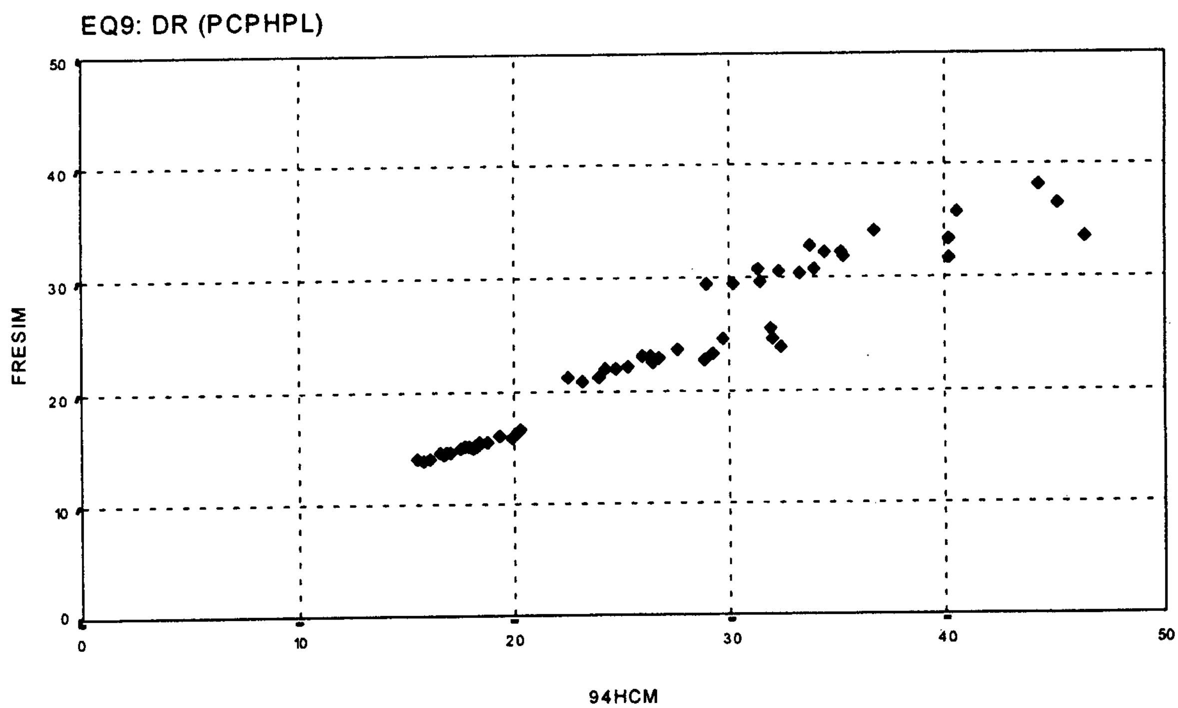


Figure 3-18. *Density predictions—94HCM Equation 9.*

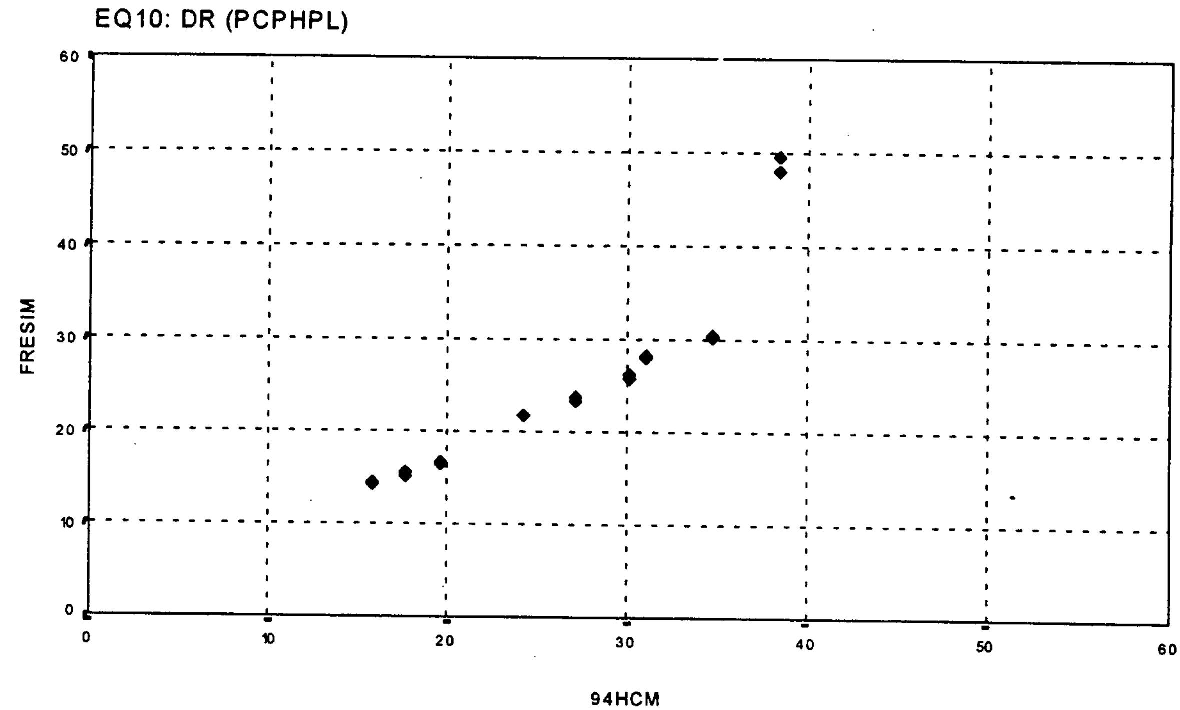


Figure 3-19. *Density predictions—94HCM Equation 10.*

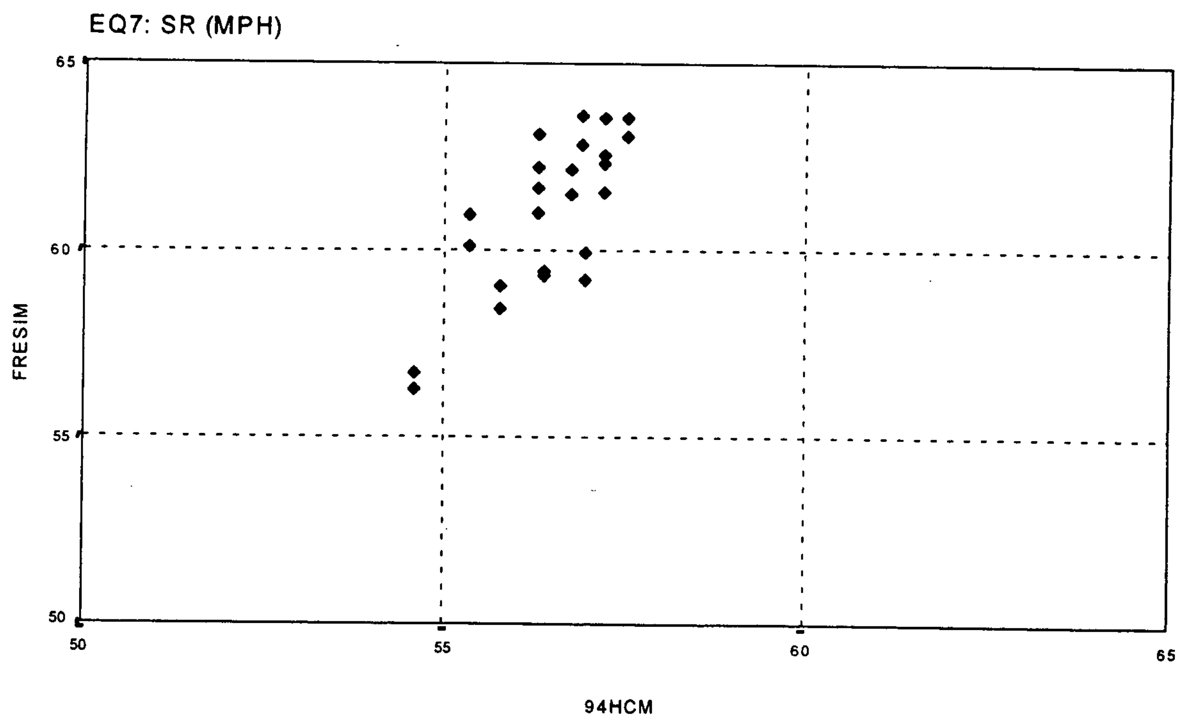


Figure 3-20. *Speed predictions—94HCM Equation 7.*

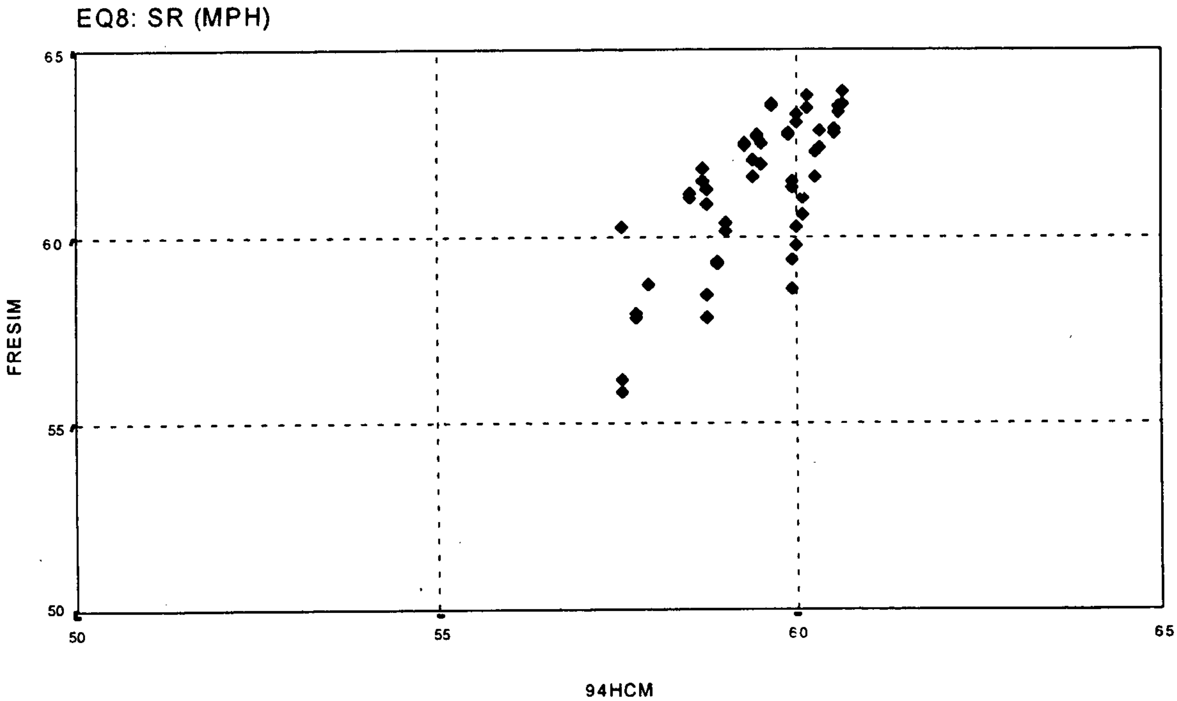


Figure 3-21. Speed predictions—94HCM Equation 8.

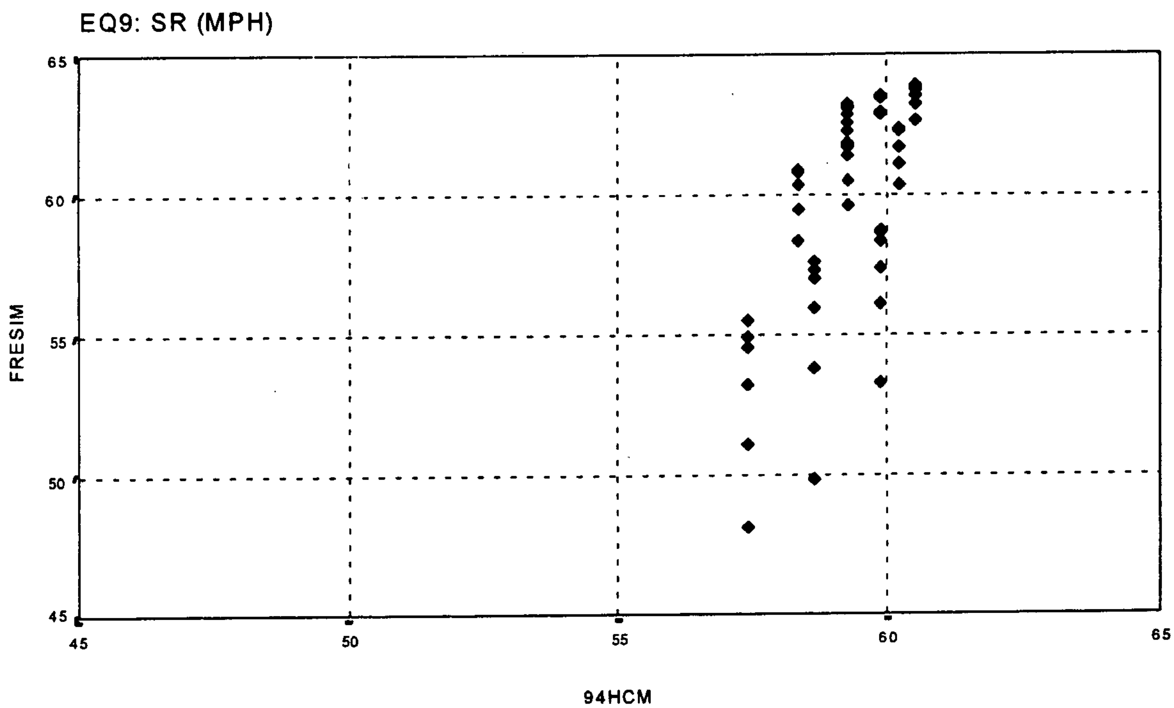


Figure 3-22. Speed predictions—94HCM Equation 9.

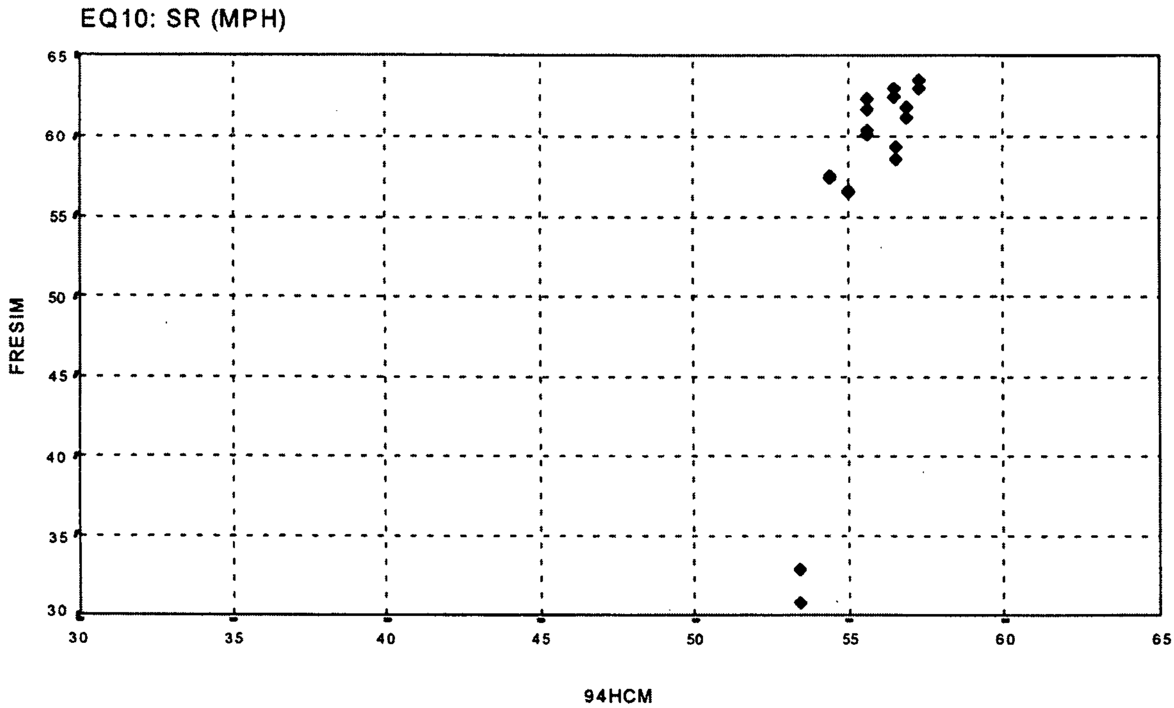


Figure 3-23. Speed predictions—94HCM Equation 10.

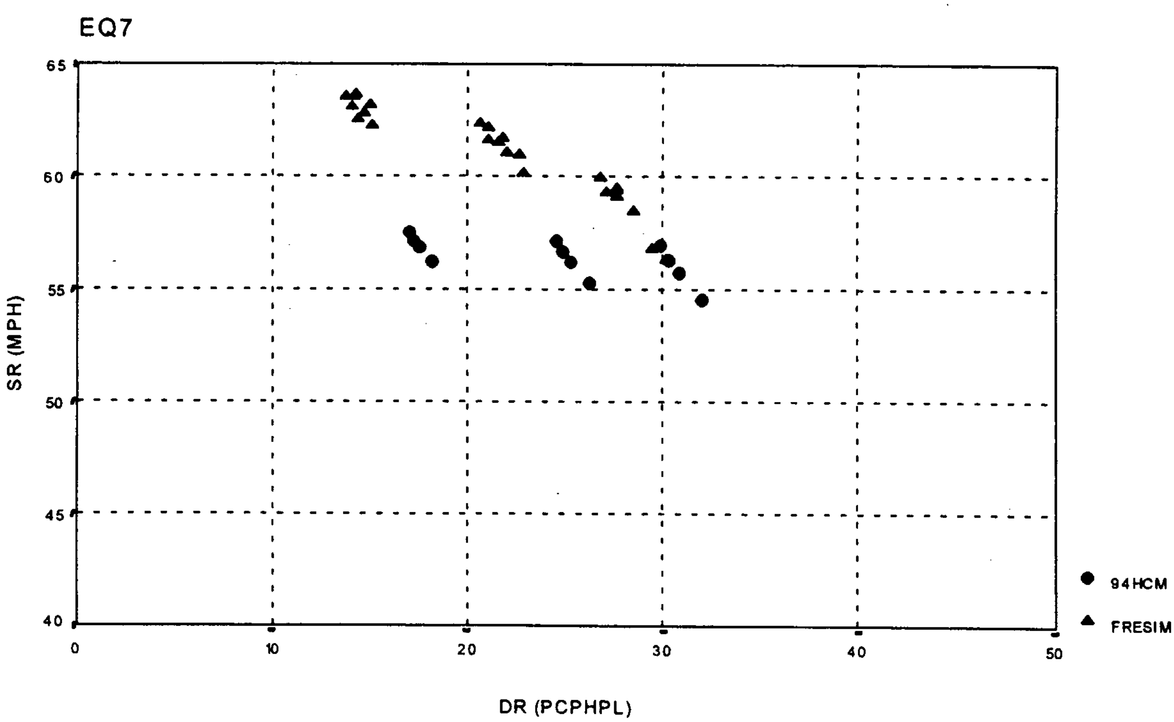


Figure 3-24. Speed versus density curves—94HCM Equation 7.

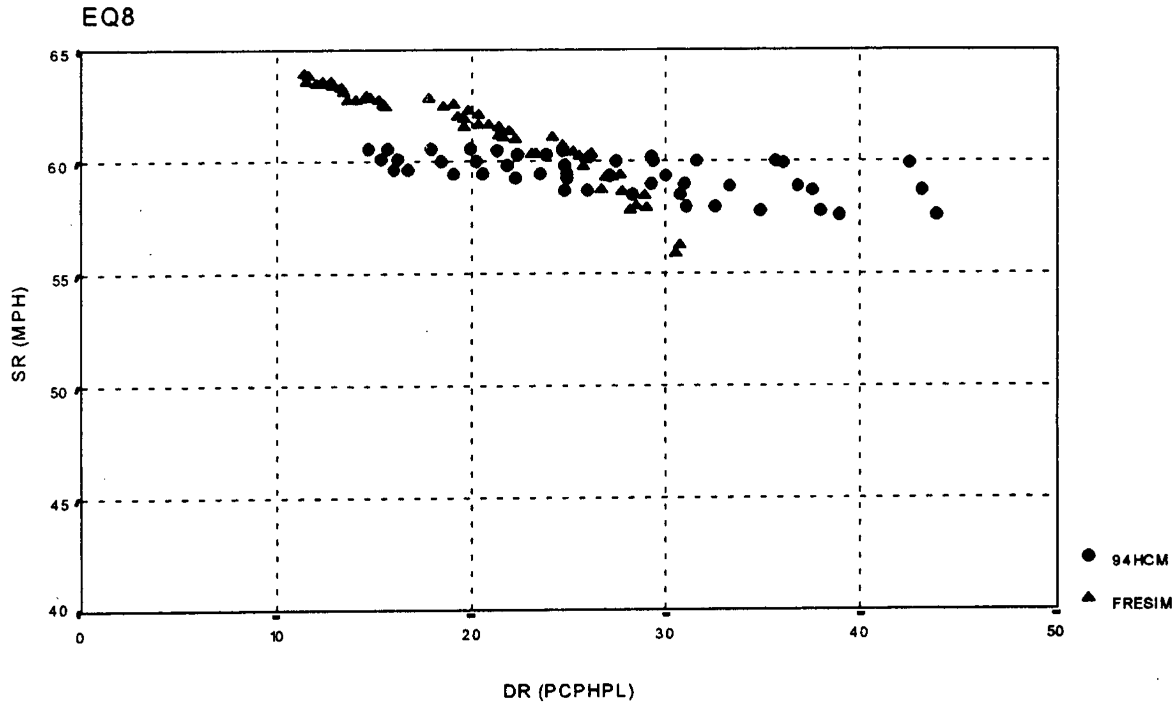


Figure 3-25. Speed versus density curves—94HCM Equation 8.

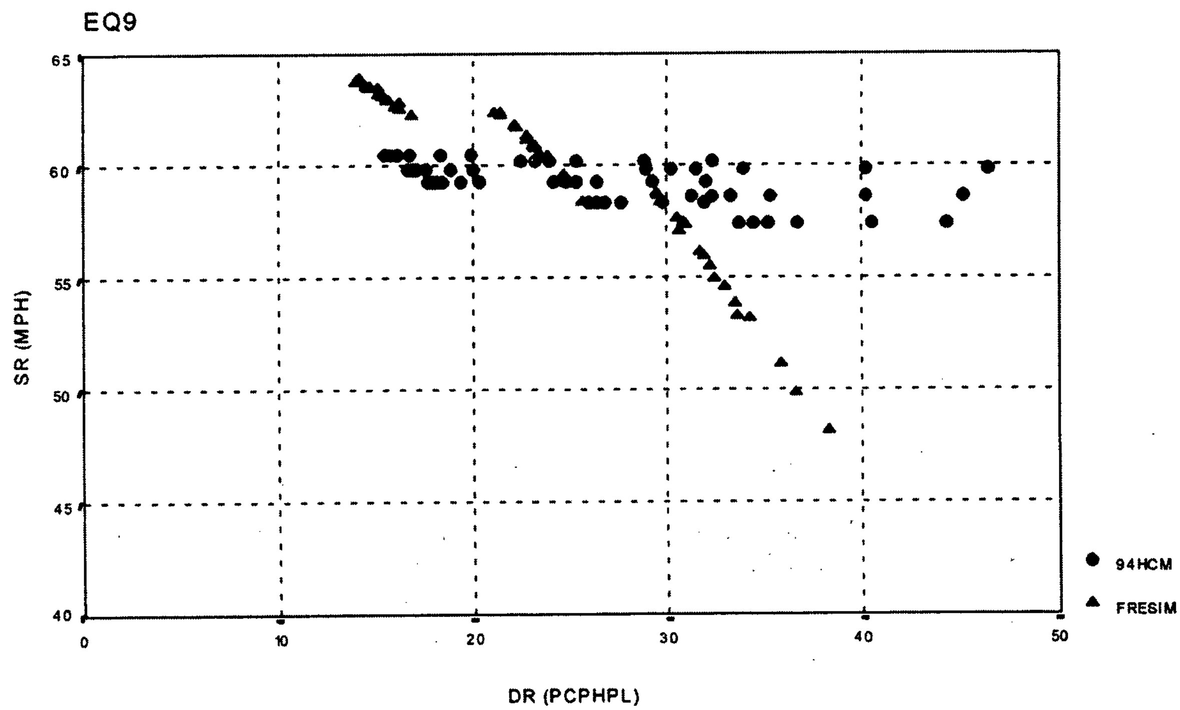


Figure 3-26. Speed versus density curves—94HCM Equation 9.

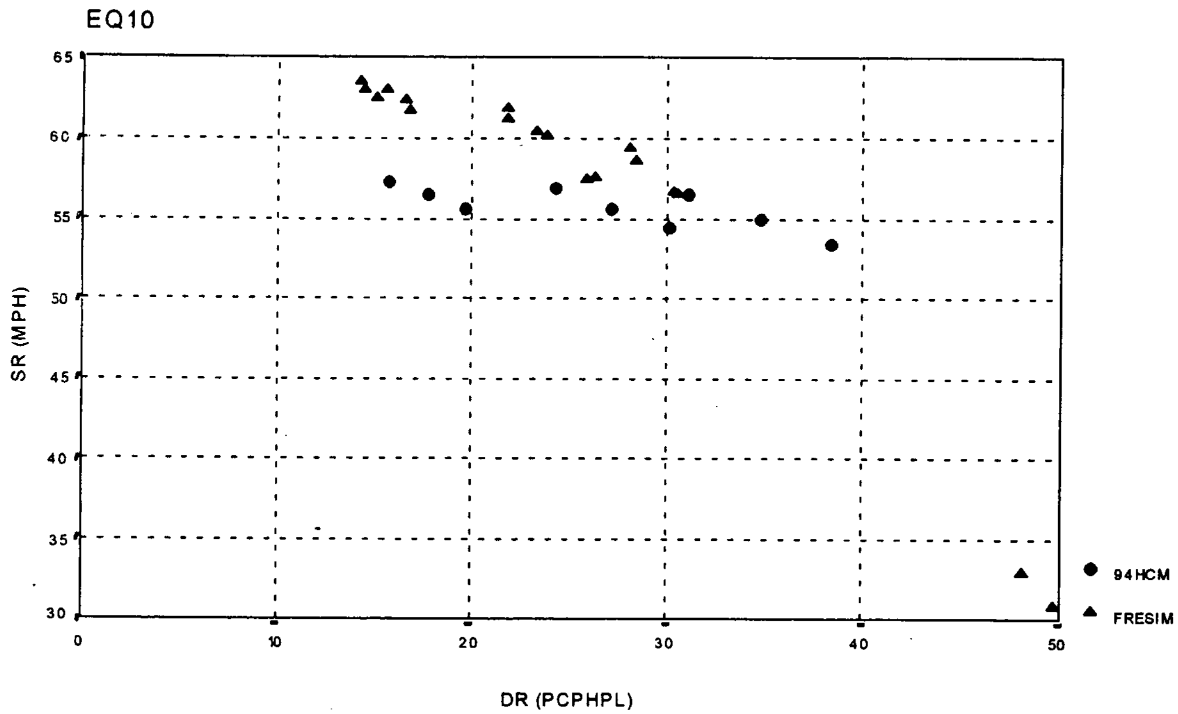


Figure 3-27. Speed versus density curves—94HCM Equation 10.

Figures 3-24 through 3-27 show the density-speed relationships that result from the sensitivity analyses of the four off-ramp equations from the 94HCM. Given the wide variances in density and speed predictions, it is not surprising that FRESIM and the 94HCM give totally different pictures of this relationship. In general, FRESIM shows a larger range of speeds and a somewhat smaller range of densities than the 94HCM. The 94HCM tends to show a relatively narrow range of speeds, and in some cases, a much larger range of densities of operation. Nevertheless, the FRESIM-generated curves generally appear to be more reasonable in comparison to expected relationships on a basic freeway section.

The 94HCM model adheres to what was a strong trend in the database, however. Diverge sections do not break down unless one of the exit legs has insufficient capacity or a downstream breakdown queuing back into the subject diverge area. This being the case, speed tends to be relatively stable through the diverge influence area. The range in densities is produced largely by a range in V_{12} values; as has been noted previously, FRESIM does not produce V_{12} values that are highly sensitive to a variety of independent variables included in the 94HCM model.

SUMMARY AND CONCLUSIONS

It is very difficult to fully interpret the results of these analyses comparing speed and density predictions. FRESIM seems to do an acceptable job of predicting density, the principal MOE for ramp influence areas, and therefore could be used, at least in analysis cases. FRESIM's method for predicting density, however, is suspect. For off-ramps, a serious flaw is its inability to adequately model a constant or fixed off-ramp volume. This casts a shadow over all of FRESIM's off-ramp area outputs and makes their exact import difficult to define.

For on-ramps, FRESIM did a better job of predicting densities for the TES sites. However, these were all isolated ramps. The fact that the 94HCM did a better job in predicting density for NCHRP sites could be due to the fact that these sites were part of the database for calibration of the 94HCM procedure or that virtually all these sites involve nearby upstream and downstream ramps. As has been shown, FRESIM is not particularly sensitive to upstream or downstream ramp situations.

Unfortunately, sensitivity analyses and comparisons raise more questions than they answer. Only a more extensive independent database would provide a better view of the situation and that is beyond the scope of this project.

CHAPTER 4

FINDINGS

The previous chapters have outlined the analyses and results therefrom on the prediction of V_{12}, D_R, and S_R. The following conclusions have been reached on the basis of these analyses:

1. In general, FRESIM produces higher estimates of V_{12} than the 94HCM. For isolated sites, FRESIM estimates appear to be reasonable. When the influence of adjacent upstream or downstream ramps is addressed, FRESIM estimates occasionally produce very large errors and are not consistently reliable predictors of V_{12}.
2. While generally resulting in higher V_{12} estimates, FRESIM also produces lower density and higher speed estimates than the 94HCM. Taken together, these two results appear to be inconsistent.
3. FRESIM is not consistently sensitive to such geometric factors as length of acceleration and deceleration lanes and the existence of, distance to, and volume on adjacent upstream and downstream ramps.

One of the objectives of this research was to make recommendations that would result in better consistency between the 94HCM and FRESIM. This was made more difficult by the fact that FRESIM was a "work in progress" while the research was being conducted. CORSIM, recently released for beta testing, was under development throughout the current work. Unfortunately, the beginning of beta testing coincided with the writing of this final report. Neither time nor funding permits rerunning many of the experiments to assess the effectiveness of incorporated changes.

In its present form, FRESIM is sufficiently at variance with the 94HCM in predicting operational conditions in the vicinity of ramp junctions to make it acceptable for use as an alternative for location-specific analyses.

Nevertheless, there is a great deal of promise if some of the insensitivities noted in the analysis of FRESIM can be ameliorated; its use could augment field data and allow a more consistent and thorough calibration of regression models for the subsequent editions of the *Highway Capacity Manual*.

RECOMMENDED ACTIONS ON FURTHER DEVELOPMENT OF FRESIM

There are three significant problems in the direct use of FRESIM for the microscopic analysis of individual merge and diverge points:

1. The insensitivity to variables found to be significant in the NCHRP Project 3-37 database;
2. The inability to absolutely control off-ramp volumes, making the analysis of diverge areas very difficult to interpret; and
3. The merging logic that forces almost all on-ramp vehicles into lane 1 within 100 ft of the gore area.

FRESIM creates lane distributions by assuming a uniform distribution across all lanes at the starting point of an entry link. From this point on, a series of logical algorithms governing the operation of individual vehicles governs lane-changing behavior. The macroscopic result of individual lane-changing maneuvers results in a lane distribution at downstream points. This downstream lane distribution does not appear to vary much from the initial assumption of uniformity. This characteristic shows up as insensitivity to many underlying variables that are believed to affect merge and diverge operations.

The following modifications to FRESIM would improve the consistency between the 94HCM and FRESIM and would allow for easier extraction of important data not easily retrieved from FRESIM in its present form:

1. The ability to preset an arbitrary lane distribution at the starting point should be incorporated into FRESIM. This was done for the report, and it helped produce more accurate output.
2. Driver-sensitivity factors must be adjusted to accomplish several objectives: (a) cause simulated vehicles to use more of the acceleration lane before merging, (b) reduce overall speeds somewhat, and (c) allow for greater variability and sensitivity in lane distribution. It is not clear that all of these objectives can be achieved by simply changing the driver-sensitivity factors. Other elements of the lane-changing logic, embedded in the software, may require alterations to accomplish this.
3. The ability to input an off-ramp volume must be added to the software. In practice, no driver fails to exit at a desired location because of an inability to change lanes, unless he/she misses a sign in an unfamiliar area. With rare exceptions, drivers wanting to exit at Point A do so at Point A.
4. The analysis of merge and diverge areas would be greatly enhanced by incorporating a module in the software that produced the appropriate value of density

and/or speed in the ramp influence area. The need to install individual lane detectors is time-consuming and inefficient.

5. The randomness of lane-changing in FRESIM is a likely cause of its insensitivity to several factors. Upstream through vehicles approaching an on-ramp have a stronger tendency to move left than they have on a basic freeway section. The decision process of drivers changes when they are in a turbulence area. FRESIM tries to adjust the results using constant decision rules and algorithms. It appears that some causative logic needs to be incorporated into the lane-changing model to reflect these aspects of driver behavior.

RECOMMENDATION ACTIONS ON FURTHER DEVELOPMENT OF THE 94HCM METHODOLOGY

The 94HCM methodology has the drawback of many regression-based models. It cannot model effects that are not evident in the database from which it is developed.

The general form of the algorithms for predicting V_{12} are logical and reasonable:

$$V_{12}\,(merge) = V_F P_{FM}$$

$$V_{12}\,(diverge) = V_R + (V_F - V_R)P_{FD}$$

The difficulty is that not all equations for P_{FM} and P_{FD} follow a consistent format. They do not necessarily include the same variables, and the general sensitivities to underlying variables vary from case to case.

For isolated on- and off-ramps, it would be desirable to establish consistent relationships between the proportions P_{FM} and P_{FD} and geometric factors such as acceleration/deceleration lane length and free-flow speed of the ramp. In fact, these factors enter some equations and not others. For ramps with adjacent ramps, these factors should remain, with additional variations accounting systematically for the type of adjacency and the distance to and volume on the adjacent ramp. Again, these variables show up inconsistently in the 10 equations of the 94HCM.

Establishing consistent relationships could be accomplished by using the simulator to produce a more uniform coverage of the data matrix required for calibration. This is only useful, however, if the simulator accurately reflects conditions observed in the field.

FRESIM needs additional work before it can be used with confidence in this manner. If additional changes can be made that rectify some of the problems noted herein, then the simulator should be used to create additional data for refinement of the 94HCM algorithms.

It would be useful to start with a data-based case to ensure that the simulator is accurately reflecting field values. Once this is established, the existing case could be varied to test sensitivity to key variables in a systematic way. With 68 field sites available, this would be a major, but fruitful and economic, way of creating a database that more uniformly covers the calibration matrix range.

A FINAL OBSERVATION

As is the case with many simulation tools, the systemwide results from FRESIM appear to be reasonable. The phrase "appear" is used advisedly, as the researchers have no system database with which to compare results. When applied to a microscopic analysis of a small point or section of a facility, results are less reasonable.

This is not surprising. The kind of site-type specific logic that is applied in modeling a particular point or section of the system is almost impossible to generate using macroscopic operational algorithms used throughout the system. As noted, drivers perhaps do not traverse a merge, diverge, or weaving area using exactly the same techniques and objectives they use on a basic freeway section.

Therefore, FRESIM's value as a system analysis tool must be weighed against the significant problems encountered when it is applied to focused merge and diverge areas.

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Appendix A
The University of Pittsburgh Car Following Model (The PITT Model)

Please note the model derivation was obtained from reference [5]. Refer to Figure A-1 and Table A-1 for a definition of all variables used in the PITT Car-Following model.

In the PITT Car-Following Model, the basic assumption is that the follower vehicle will try to maintain a space headway equal to

$$L + 10 + kv + bk(u - v)^2 \tag{1}$$

For the current calculation for the follower vehicle, we are given x_1, u_1, y, v and we must calculate *a*. The desired position at time t + T is given by equation (1) as

$$x_1 - y_1 = L + 10 + kv_1 + bk(u_1 - v_1)^2 \tag{2}$$

but $y_1 = y + vT + \frac{aT^2}{2}$ and $v_1 = v + aT$ and thus equation (2) becomes

$$x_1 - \left(y + vT + \frac{aT^2}{2}\right) = L + 10 + k(v + aT) + bk(u_1 - v)^2 \tag{3}$$

Note: Since the term $(u - v)^2$ is small, the approximation of $v_1 = v$ is used. Any difference is accounted for by the calibration of b.

Solving for the acceleration of the follower vehicle using equation (3) results in

$$a = 2\,\frac{[x_1 - y - L - 10 - v(k + T) - bk(u_1 - v)^2]}{[T^2 + 2kT]} \tag{4}$$

Equation (4) represents the basic car-following relationship. The term involving the constant b was introduced to allow for high relative closing speed behavior observed empirically. The value of b has been calibrated to

$$b = \begin{cases} 0.10 \text{ for } (u - v) \le 10 \\ 0 \text{ for } (u - v) > 0 \end{cases} \tag{5}$$

The driver reaction time c is introduced into the car-following equations, after *a* has been calculated, when the new speed and position are defined

$$v_1 = v + a(T - c)$$

and

$$y_1 = y + vT + \frac{a(T - c)^2}{2} \quad \text{where} \quad c < T$$

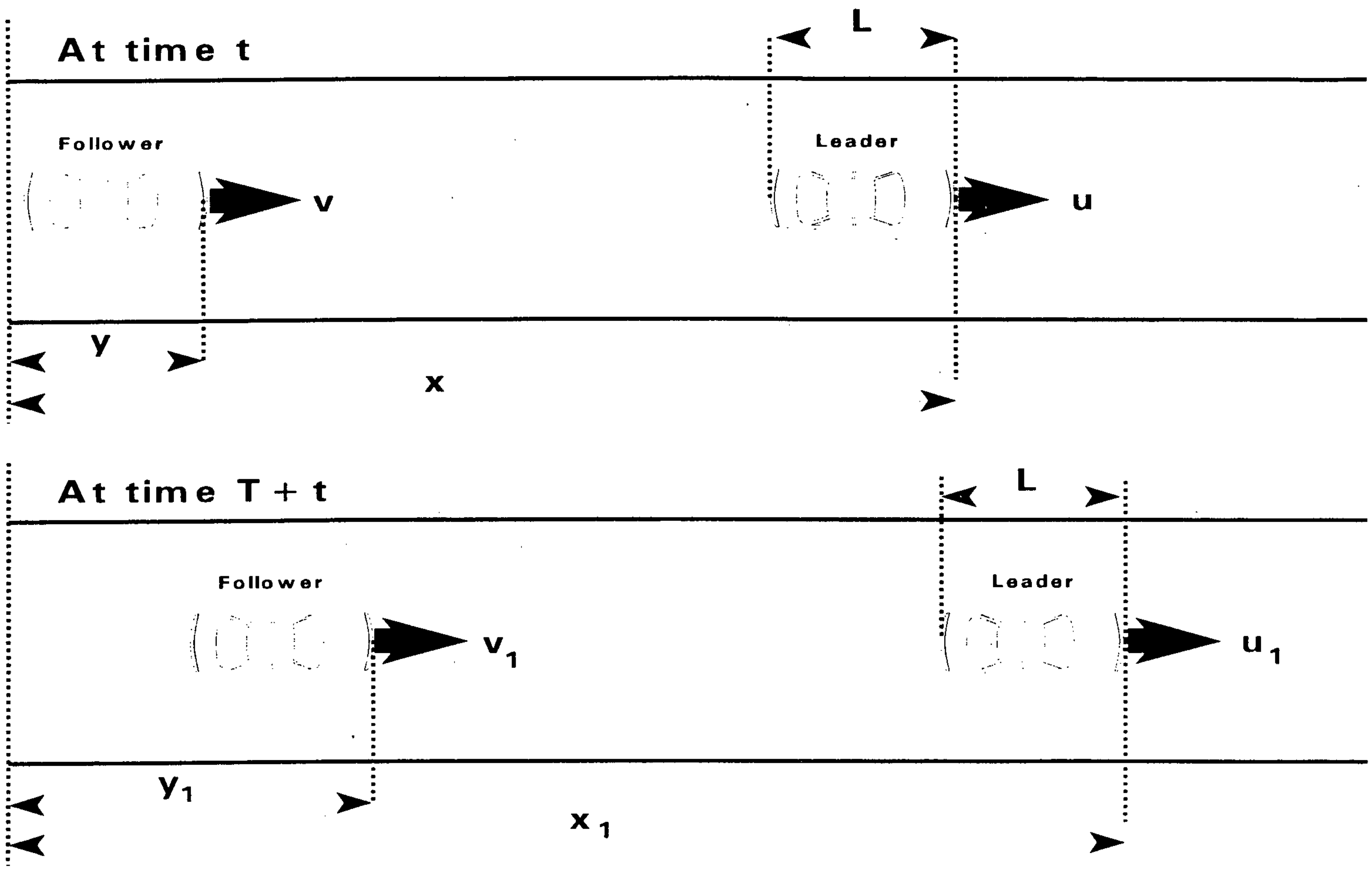

Figure A-1
Illustration of key variables for the PITT Car-Following Model

Table A-1
Variable Definition Table for the PITT Car-Following Model

Variable	Definition (all dimensions are in feet and/or seconds)
k	car following parameter (driver sensitivity factor)
L	length of the leading vehicle
T	time scanning interval
c	lag (driver reaction time, always less than T)
e	maximum emergency deceleration (15 ft/sec^2)
x	position of leader at time t
u	speed of leader at time t
y	position of follower at time t
v	speed of follower at time t
a	acceleration of follower in the interval (t, t + T)
x_1	position of leader at time t + T
u_1	speed of leader at time t + T
y_1	position of follower at time t + T
v_1	speed of follower at time t + T
b	calibration constant

An emergency constraint overrides the car-following rules established above to prevent collisions. The basic concept provides that the follower vehicle can stop safely behind the leader vehicle under the following conditions:

- The leader vehicle decelerates to a stop at the maximum emergency deceleration.

- The follower vehicle, starting at the lag time c, later decelerates to a stop behind the leader vehicle at a deceleration rate within the maximum emergency deceleration limit.

If the leader stops at the maximum deceleration then $u_1 = 0$ and

$$x_1 = x + \frac{u^2}{2e} \tag{6}$$

The follower vehicle stopping at the maximum deceleration will also give

$$y_1 = y + cv + \frac{v^2}{2e} \tag{7}$$

Since the headway between the vehicles must exceed the length of the leader vehicle, equations (6) and (7) yield

$$x_1 - y_1 = x - y + \frac{(u^2 - v^2)}{2e} - cv \geq L$$

and reformulating this equation becomes

$$x - y \geq L + cv + \frac{(v^2 - u^2)}{2e} \tag{8}$$

but for $x - y \geq L$ for all u, v and thus equation (8) is valid only if

$$cv + \frac{(v^2 - u^2)}{2e} \geq 0$$

or

$$v \geq \sqrt{(u^2 + e^2c^2)} - ec$$

The basic headway constraint then becomes

$$x - y \geq L + cv + \frac{(v^2 - u^2)}{2e} \text{ if } v \geq \sqrt{(u^2 + e^2c^2)} - ec \tag{9}$$

and

$$x - y \geq L \text{ if } v < \sqrt{(u^2 + e^2c^2)} - ec$$

If x_1, u_1, y, v, and T are given, then the acceleration *a* of the follower vehicle for the time period (t, t + T) must be determined such that the headway constraint is not violated.

Two possible cases can arise:

1. The follower vehicle has a speed $v_1 > 0$ at time t+T.

$$v_1 = v + a(T - c)$$

$$y_1 = y + vT + a\frac{(T - c)^2}{2} \quad if \quad T - c > 0 \tag{10}$$

2. The follower vehicle comes to a stop during the interval (t, t+T), assuming this occurs at time t (1+p), where 0 < p ≥ 1.

$$v_1 = v + a(pT - c) = 0$$

$$y_1 = y - \frac{v^2}{2a} \tag{11}$$

Substituting for v_1 and y_1 into equation (9) yields

$$x_1 - y_1 \geq L + cv_1 + \frac{(v_1^2 - u_1^2)}{2e} \text{ if } v_1 \geq \sqrt{(u_1^2 + e^2c^2)} - ec$$

$$x_1 - y_1 \geq L \text{ if } v_1 < \sqrt{(u_1^2 + e^2c^2)} - ec \tag{12}$$

From equations (10), (11) and (12)

$$x_1 - y - vT - a\frac{(T - c)^2}{2} \geq L + cv + ca(T - c) + \frac{\{v + a(T - c)\}^2 - u_1^2}{2e}$$

when $v_1 \geq \sqrt{(u_1^2 + e^2c^2)} - ec > 0$

and

$$x_1 - y - vT - a\frac{(T - c)^2}{2} \geq L$$

when $0 < v_1 < \sqrt{(u_1^2 + e^2c^2)} - ec$

and
$$x_1 - y + \frac{v^2}{2a} \geq L$$

when $v_1 = 0$

or

$$a^2\left[\frac{(T-c)^2}{2e}\right] - a\left[\frac{(T-c)^2}{2} + c(T-c) + 2v\frac{(T-c)}{2e}\right] + \left[x_1 - y - vT - L - cv - \frac{(v^2 - u_1^2)}{2e}\right] \geq 0$$

when $v_1 \geq \sqrt{(u_1^2 + e^2c^2)} - ec > 0$ (13)

and
$$-a\frac{(T-c)^2}{2} + x_1 - y - vT - L \geq 0$$

when $0 < v_1 < \sqrt{(u_1^2 + e^2c^2)} - ec$ (14)

and
$$a \leq \frac{-v^2}{2(x_1 - y - L)} \tag{15}$$

when $v_1 = 0$

Equation (13) reduces to

$$a^2 + a\left[e + \frac{2ec}{(T-c)} + \frac{2v}{(T-c)}\right] - \left[\frac{2e}{(T-c)^2}\right]\left[x_1 - y - vT - L - cv - \frac{(v_1^2 - u_1^2)}{2e}\right] \geq 0$$

which yields
$$a < -\frac{B}{2} + \frac{\sqrt{B^2 + 4C}}{2} \tag{16}$$

where $B = e + 2\left[\frac{ec + v}{T - c}\right]$

and
$$C = \left[\frac{2e}{(T-c)^2}\right]\left[x_1 - y - vT - L - cv - \frac{(v^2 - y_1^2)}{2e}\right]$$

The condition $v_1 \geq \sqrt{(u_1^2 + e^2c^2)} - ec > 0$ reduces to

$$v + a(T - c) \geq \sqrt{(u_1^2 + e^2c^2)} - ec > 0$$

or $$a \geq \frac{\sqrt{(u_1^2 + e^2c^2)} - ec - v}{(T - c)} > 0 \tag{17}$$

Equation (14) reduces to

$$a \leq 2\left[\frac{x_1 - y - vT - L}{(T - c)^2}\right]$$

provided $0 < v + a(T - c) < \sqrt{(u_1^2 + e^2c^2)} - ec$ (18)

or $$-\frac{v}{(T - c)} < a < \frac{\sqrt{(u_1^2 + e^2c^2)} - ec - v}{(T - c)}$$

Equation (15) can be simplified to

$$a \leq \frac{-v^2}{2(x_1 - y - L)} \tag{19}$$

provided $a \leq \dfrac{-v}{(T - c)}$

Equations (16), (17), (18), and (19) are the constraints which determine the follower vehicle's acceleration which must be maintained in order to satisfy the emergency non-collision conditions.

Provided the vehicles are in a safe position at time t, then the above constant set will be sufficient for the vehicles at time t+T. In particular B^2+4C is always positive and thus the acceleration given by equation (16) has a real value.

The emergency constraint, however, is also used in the lane changing mechanism where the vehicles (in adjacent lanes) may not be in a safe position relative to each other in a longitudinal sense. In this case the following can occur:

1) The above constraint set provides real acceleration but it is greater than e and thus the lane change is not initiated.

2) The discriminant (B^2+4C) is negative. In this case the lane change is automatically not initiated, sine the two vehicles must be in an unsafe relative position for occupying the same lane.

3) In the case $u_1 = 0$ and $x_1 - y \leq L$, then equation (19) operates and gives a false result. Thus equation (19) is modified for lane changing such that the lane change cannot be initiated if $v_1 = 0$ and $x_1 - y - L < 0$

Once again, this occurs only if the two vehicles are in an unsafe relative position for occupying the same lane.

APPENDIX B
Input and Output Formats of FRESIM

Input Format

The input data of the FRESIM program can be categorized into two major sections; (1) the run control and geometric data (remaining constant during a simulation run), and (2) the traffic data (which may vary during a simulation run). In each of the sections there are required and optional data inputs as identified in Table B-1.

a) Run Control and Geometric Data

The run control data consists of several time-related parameters. In order to simulate the changing behavior of traffic (such as volumes, vehicle type distribution, and turning movement percentages) over time, FRESIM allows for the partitioning of the simulation run time into a maximum of 19 distinct *time periods* (specified in seconds), which can be equal or unequal in length. For example, a user may wish to simulate one hour of traffic data which may have a distinct characteristic for the first 15 minutes and a totally different one over the next 45 minutes.

Due to the microscopic nature of FRESIM, each time a vehicle is processed, it is moved on the roadway system for the duration of one *time step* and its new status is determined at the end of each time step. The default and recommended value is one second. The smaller the time step value, the larger the computation time necessary for the simulation.

The geometric data consists of the physical attributes which describe the layout of the highway section being modeled, including vertical and horizontal alignment. The geometric representation of the roadway system is accomplished by constructing a network of links and nodes. Each link is uniquely identified by two different nodes. The links representing freeway sections, and the nodes representing points where physical changes occur (e.g., the introduction of a ramp junction, or a change in grade, superelevation, or horizontal alignment). The concept of geometric representation by links and nodes is illustrated in Figure B-1.

For each link the following attributes are specified:

- type of link - specified as either a mainline (freeway) link or a ramp link.
- length of link - specified in feet.
- number of lanes - up to a maximum of 5 lanes per link can be specified.

Table B-1
Required and Optional Input Cards

Record Type	Description	STD	Point Process	On-Line	Off-Line	MOE
00	Title	R	R	R	R	R
01	Identification	R	R	R	R	R
02	Run Control	R	R	R	R	R
03	Time Period Classification	R	R	R	R	R
04	Time-step Control	R	R	R	R	R
05	Output Options	R	R	R	R	R
19	Freeway Link Geometry	R,O	R,O	R,O	R,O	R,O
20	Freeway Link Operation	R,O	R,O	R,O	R,O	R,O
25	Freeway Turn Movements	R,O	R,O	R,O	R,O	R,O
28	Freeway Surveillance Specification	O	R	R	R	R
29	Freeway Incident Specification	O	O	O	O	O
32	Freeway Lane Add and/or Drop	O	O	O	O	O
37	Freeway Metering	O	O	O	O	O
38	Freeway Metering Detector Specification	O	O	O	O	O
50	Entry Link Volume Record	R,O	R,O	R,O	R,O	R,O
61	On-Line Incident Detection Specification	O	-	R	-	-
62	On-Line Incident Detection Algorithm Parameters	O	-	R	-	-

Table B-1 (Continued)

Record Type	Description	STD	Point Process	On-Line	Off-Line	MOE
63	On-Line Incident Detection Detector Station Identification	O	-	R	-	-
64	Off-Line Incident Detection, Point Processing, and MOE Estimation Specification	O	R	-	R	R
65	Off-Line Incident Detection Algorithm Parameters	O	-	-	R	-
66	MOE Algorithm Parameters	O	-	-	-	R
67	Off-Line Incident Detection, Point Processing, and MOE Estimation Detector Station	O	R	-	R	R
68	Car-Following Sensitivity Factor	O	O	O	O	O
69	Pavement Friction Coefficients and Time Lag	O	O	O	O	O
70	Miscellaneous data	O	O	O	O	O
71	Vehicle-Type Specification	O	O	O	O	O
72	Environmental Tables	O	O	O	O	O
73	Maximum Acceleration Tables	O	O	O	O	O
74	Origin Destination	O,O	O,O	O,O	O,O	O,O
170	Subnetwork Delimiter	R	R	R	R	R
210	Time Period Delimiter	R	R	R	R	R

Note: An "R" indicates that this input card is required, and "O" indicates it is optional. If given in the form "R,O" or "O,O", the first value indicates the condition for the first time period, and the second va.ue corresponds to its use in all subsequent time periods.

Legend: STD=Standard Run; Point Process=Point Processing; On-Line=On-line Incident Detection; Off-Line=Off-Line Incident Detection; MOE= Measures of Effectiveness.

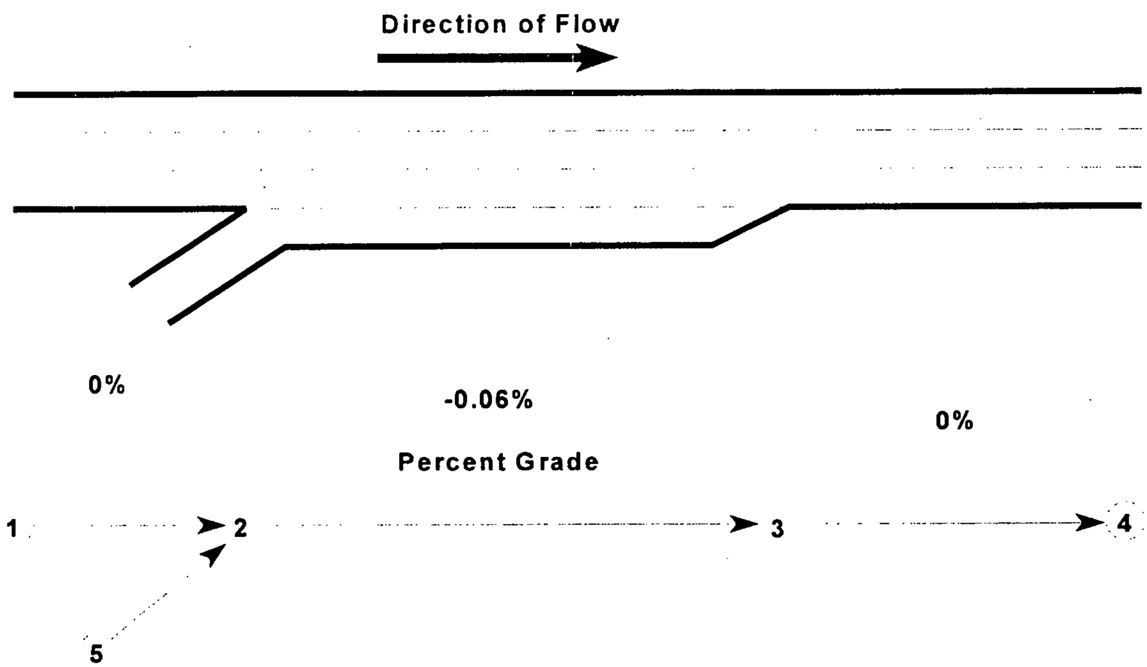

Figure B-1
Geometric Representation of A Freeway Network

- type of lane - either "through" or "auxiliary". An "auxiliary" lane is defined as a freeway lane which either receives or discharges traffic from a ramp. The auxiliary lane is further classified as being either an acceleration auxiliary lane, a deceleration auxiliary lane , or a full auxiliary lane. A "through" lane is one which is not designated as being an auxiliary lane. Up to 3 (left and/or right) auxiliary lanes can be specified. Figure B-2 illustrates the various auxiliary lane types.

- lane alignment - used by FRESIM to properly track each vehicle through the simulated highway section. Several conditions exists in which lane alignment can change. Namely, at a on-ramp gore junction where lane alignment will change, at an off-ramp gore junction, and whenever a through lane is added or dropped.

- placement of warning sign(s) - FRESIM requires that for each off-ramp the user assign a corresponding warning sign. The distance between the off-ramp gore and the sign at which drivers begin to react to the off-ramp must be specified in feet. A value of 2500 feet is recommended, but can be adjusted based on the result of model validation checks. The possibility can exist where vehicles are not changing to the appropriate lane for exiting in a timely manner, thereby missing the exit. FRESIM flags all vehicles that miss a particular exit, and prints a warning message to the user, so that changes in the location of the sign can be made accordingly.

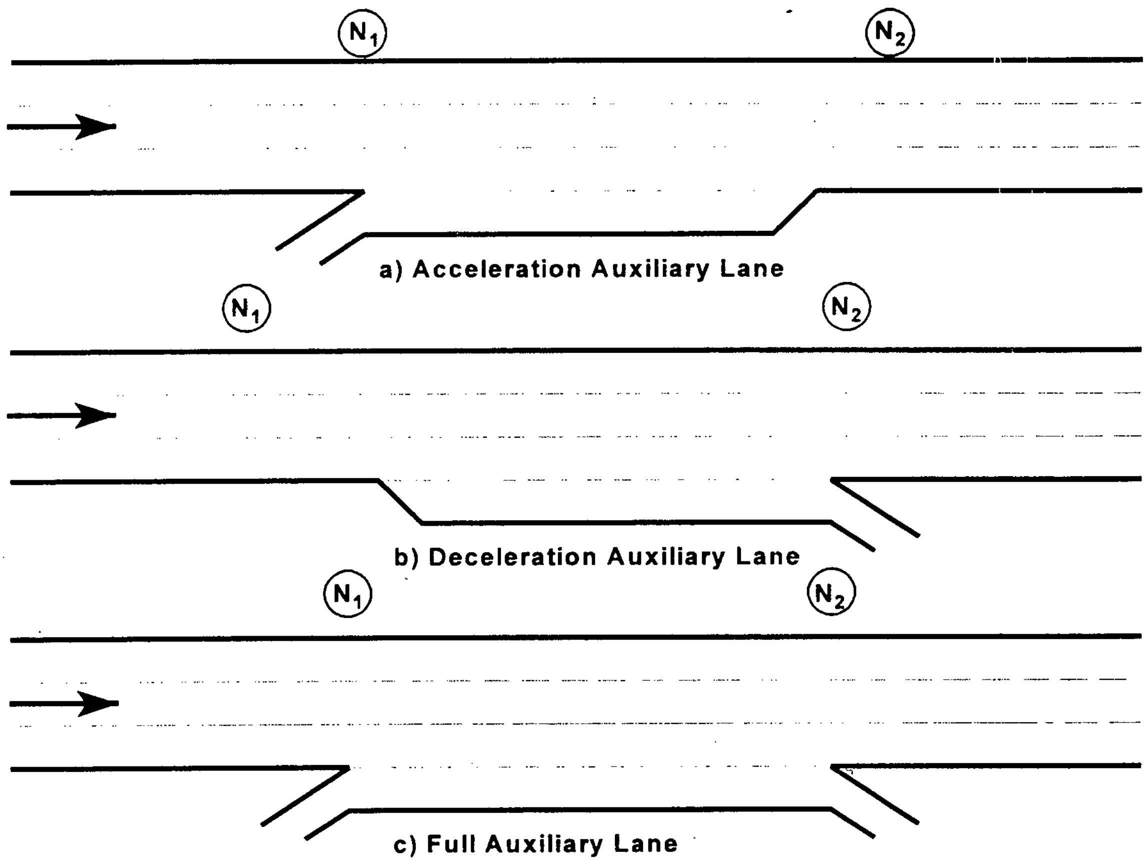

Figure B-2
Illustration of Auxiliary Lane Types

- grade - specified in percent with an upper limit of +9% and a lower limit of -9%. Grade specification is examined by the FRESIM logic to modify several vehicle operating parameters which are contained in the model's vehicle performance tables.

- superelevation - specified in percent.

- curvature or radius of curve - specified in feet.

- pavement type/condition - specified as being either (1) dry concrete, (2) wet concrete, (3) dry asphalt or (4) wet asphalt. In addition, the values of the friction coefficient for each pavement type can be modified by the user. The current default value for all pavement types is 0.16.

Changes in superelevation, horizontal curvature, and pavement condition limit vehicle performance on horizontal curves. FRESIM accounts for this by setting an upper limit for the desired free-flow speed based on these characteristics.

The variables described in the previous page are used in the following equation to mathematically describe the vehicle operation on a curve:

$$v = \sqrt{15R(e + f)}$$

where: e = rate of roadway superelevation, feet per feet
f = friction coefficient for given pavement condition
R = radius of curve, feet
v = vehicle speed, miles per hour

b) Traffic Data

The basic traffic data required as input for the execution of FRESIM consists of the following parameters:

- input flow rate - entry volumes expressed as an hourly flow rate is specified for all entry links (mainline and ramp).

- turning percentages and/or Origin-Destination percentages - upon entry, each vehicle is assigned a destination which is determined from a gravity model-type formulation, with the probability of being assigned to a given destination dependent on an accessibility factor (which is based on the entry flow rate) for each origin, an attraction factor (which is based on the exit flow rate) for each destination, and a travel function between the origin and the destination. The calculated Origin-Destination values can be manually overwritten with the percentage of vehicles exiting the mainline freeway for each exit point.

- desired free-flow speed - this speed (in mph) represents the unimpeded speed which is attained by traffic in the absence of any impedance due to other vehicles or control devices. By definition, this is equivalent to the average speed of the drivers in low volume traffic (LOS A) in which they are not impeded by other traffic. When not specified, FRESIM uses default values of 55 mph for freeway links and 35 mph for ramp links.

- mean queue discharge headway - this value (set to a default of 1.0 sec.) represents the elapsed time before a vehicle, queued behind the on-ramp metering signal, is discharged following the onset of the green signal indication. It is only applied to the fourth and subsequent vehicles on the queue.

- vehicle type distribution - FRESIM provides for the stratification of the traffic stream into three different fleet types (passenger cars, trucks, and buses). Furthermore, the passenger car fleet is subdivided into high performance and low performance cars.

The truck fleet is also subdivided into four categories (semi-trailer truck with high load, semi-trailer truck with medium load, double-bottom trailer truck, and single-unit truck). The vehicle type distribution is an embedded table of values (refer to Table 1-1) which can be overwritten by the user. For each entry link, a truck percentage for each time period is input. In addition, truck movement can be restricted or biased to certain lane(s).

- vehicle distribution across lanes - FRESIM uses an embedded table of values (refer to Table 1-2) representing the distribution across lanes. These values can be modified by the user. The project team is using a modified version of FRESIM which allows this value to be an input, rather than using the embedded values which assume an equal distribution.

c) Other Data

FRESIM provides for a complete comprehensive surveillance system. It's capable of simulating the placement of detectors on each lane of the mainline freeway links (including the auxiliary lane), and ramp links.

Three type of detectors can be specified (single loop, coupled pairs of loops, and Doppler radar), with each one capable of operating in either analog or digital mode. When set to analog mode, the program will output time and duration of actuation for loop detectors and speed and time of actuation for Doppler radar detectors. When set to digital mode, it will output occupied/not occupied status of loop detectors only.

When placing detectors, the user must specify the exact placement (distance measured in feet) of the detectors relative to the upstream node of the link which contains the detector(s). For loop detectors, the effective loop length is specified. In addition, for coupled loop detectors the separation distance must also be specified (not to exceed 20 ft). Detectors are not allowed on the entry/exit links nor on the interface links.

For the four type of ramp metering strategies available in FRESIM, specific data are required, as discussed below:

- clock time metering - the user specifies the time (in sec..) at which the metering of the traffic should start, and the metering headway (defined as the time between two successive green indications of the meter). The metering headway is held constant while the traffic is being metered. As a default, an embedded noncompliance percentage of 5% is applied to those vehicles which arrive during the red signal phase.

- demand/capacity metering - the user specifies the time at which the metering starts, as well as a desired value for the freeway capacity in vphpl. Detectors are also placed at a location upstream of the metered ramp to gather freeway flow data. This data is compared to the specified capacity, and the difference is used in computing the metering rate. The maximum metering rate is calculated such that the capacity of the freeway section is not violated. A minimum metering rate of 3 veh/min is used to ensure that waiting vehicles are not trapped between the meter and the ramp connection to the freeway (refer to Fig 1-4). The metering rate is defined as the inverse of the metering headway.

- speed control metering - the user input is similar to the demand/capacity control, with the detectors gathering speed data. The user inputs up to three speed thresholds (in mph, arranged in descending order), which are compared to the measured speeds and are used in selecting an appropriate metering headway. The metering signal is set to the input metering rate if the speed measured by the detector is below the speed threshold specified. If the speed is greater than the highest threshold, the meter is set to the maximum rate.

- gap acceptance metering - the user specifies the start time, and a minimum acceptable gap size (in tenths of a second). For this strategy, a coupled pair of detector loops are placed in the outside lane, upstream of the metered ramp and existing gaps in the traffic stream are scanned. When the detector is placed too close to the merge point the possibility exists that vehicles at the ramp signal may not be released in time to merge into an acceptable gap. When the detector is too far upstream of the merge point, the accuracy of the projected gap size is compromised.

FRESIM is capable of executing both on-line incident detection and off-line incident detection. When executing in the off-line mode, vehicle movements are not simulated. The detection is performed on detector actuations from a prior simulation run which are stored on file. When executing in the on-line mode, incident detection is performed while the simulation of vehicle movement is taking place. In terms of data inputs for performing incident detection, the user must specify the following:

- which type of incident detection is desired (on-line or off-line)

- polling frequency - specified in number per second.

- evaluation frequency - specified in number of freeway time steps between re-evaluations.

- incident detection algorithm to be used - 1, 2, or 3. Algorithm number 1 uses occupancies at sensor locations to determine the onset of the incident, the approximate location and the end of the incident. Algorithm number 2 uses compression wave suppression logic to avoid incident false alarms due to the presence of transient compression waves in the traffic flow. Algorithm number 3 uses the method of double exponential smoothing in an attempt to reduce the number of incident false alarms.

- average vehicle length - specified in feet. This parameter is used in the calculation of speed when point processing is selected.

In addition to the above data input requirements, FRESIM gives users the ability to modify embedded values used for vehicle performance measures (such as maximum acceleration, jerk, etc.), MOE measures (such as fuel consumption and pollutant emission rates), pavement friction coefficients, and driver sensitivity factors.

Output Format

The generated output of FRESIM can be categorized into two major parts: (1) input data reporting tables, and (2) simulation reporting tables.

(1) the input data reporting tables consist of a complete listing of the input data replicating the input values as specified by the user. Separate tables for each major feature of the input (geometrics, metering, lane add/drop) are also printed out. For each period specified, turning movements, link volumes, and O/D trip table are also reported. The information contained within this section is very useful for identifying coding errors. Refer to Figure B-3 for a sample output.

(2) the simulation reports consist of summary statistics for each link and each time period specified. Intermediate statistics output can also be requested. When detectors are placed on the network, detector statistics are also reported. In addition, fuel and emissions output can be requested by the user. Figure B-4 shows a sample output.

In addition to the above, the user can request intermediate link statistics and/or environmental measures of effectiveness (MOE's) as shown in Figures B-5 and B-6, respectively. Definition of each of the statistics reported in FRESIM is presented in the next section.

```
                                              START OF CASE   1

 *****************************************************************************************************
1                                    CARD FILE LIST
0SEQ.# :----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8

     1 :POLYTECHNIC UNIVERSITY - TRANSPORTATION TRAINING & RESEARCH CENTER          0
     2 :PROJECT: RAMPCAP II                                                         0
     3 :FRESIM TITLE: TES DATA SET: Site 1                                          0
     4 :LOCATION OF TEST SITE: Houston, Texas -                                     0
     5 :                       SH 225 (Laporte) Freeway Northbound                  0
     6 :DATA SET CREATION DATE: 03/28/1995, 3:00PM.                                 0
     7 :DATA SET NAME: TESSITE1                                                     0
     8 :Traffic Engineer: Jose M. Ulerio      03  28  95Polytechnic Univ. TTRC    1  1
     9 :   0   1   1      10           6          0     8 700                7581  2
    10 : 900 900 900 900 900                                                       3
    11 :                10  60                                                     4
    12 :              0   0   0                                                    5
    13 :8001   1   2    00 3 00    0 00    0 00    0 1 0 0 0                      19
    14 :   1   2   3  3000 3 00    0 00    0 00    0 1 0 0 0                      19
    15 :   2   3   4 15000 3 91  770 00    0.00    0 1 0 0 0                      19
```

```
                                              START OF CASE   1

 *****************************************************************************************************
0                        POLYTECHNIC UNIVERSITY - TRANSPORTATION TRAINING & RESEARCH CENTER
0                        PROJECT: RAMPCAP II
0                        FRESIM TITLE: TES DATA SET: Site 1
0                        LOCATION OF TEST SITE: Houston, Texas -
0                                                SH 225 (Laporte) Freeway Northbound
0                        DATA SET CREATION DATE: 03/28/1995, 3:00PM.
0                        DATA SET NAME: TESSITE1
0


                                            DATE = 03/ 28/ 95
0                                           USER = Traffic Engineer: Jose M. Ulerio
0                                         AGENCY = Polytechnic Univ. TTRC
1                                                RUN CONTROL DATA

                      VALUE                           RUN PARAMETERS AND OPTIONS

0                         1    RUN IDENTIFICATION NUMBER
0                         0    NEXT CASE CODE = (0,1) IF ANOTHER CASE (DOES NOT, DOES) FOLLOW
0                         1    RUN TYPE CODE = ( 1, 2, 3) TO RUN (SIMULATION, ASSIGNMENT, BOTH)
                                               (-1,-2,-3) TO CHECK (SIMULATION, ASSIGNMENT, BOTH) ONLY

0                         1    FRESIM OFFLINE INCIDENT DETECTION CODE = (0, 1) IF OFFLINE INCIDENT DETECTION
                               (IS NOT, IS) BEING PERFORMED
```

```
                                        TIME PERIOD   1 - FRESIM DATA

 *****************************************************************************************************
1                                            FRESIM LINK CHARACTERISTICS
                                             ---------------------------


                         --------- AUXILIARY LANE ---------

                         --- ONE --- --- TWO --- -- THREE --             G
           T             T           T           T                       R                                RIGHT  FREE
           Y       NO.   Y           Y           Y          THRU CURV    A        PAVE   TRUCK     LANE OF  FLOW  QUEUE
           P LNGTH THRU  P     LNGTH P     LNGTH P    LNGTH DEST RADIUS  D  SUPER MENT RESTRAINT SEP PAIR SPEED HDWY
   LINK    E  (FT) LANES E ID  (FT)  E ID  (FT)  E ID  (FT) NODE  (FT)   E  ELEV  CODE CODE LANE   1   2  (MPH) (SEC)  LINK NAME
---------- - ----- ----- - -- -----  - -- ----- - -- ----- ---- ------ --- ----- ---- --------- -------- ----- ----- -----------
(8001,  1) F     0   3                                        2     0    0    0   1*    0                   55*   2.2
(   1,  2) F   300   3                                        3     0    0    0   1*    0                   55*   2.2
(   2,  3) F  1500   3   A  9   770                           4     0    0    0   1*    0                   55*   2.2
```

```
                                            FRESIM TURNING MOVEMENTS
                                            ------------------------

                           --------- MAIN-LINE TRAFFIC ---------    ---------- EXITING TRAFFIC ----------

                           DOWNSTREAM NODE NO.
                           OF THE MAIN-LINE                            DOWNSTREAM NODE
           LINK            RECEIVING LINK          PERCENTAGE       NO. OF THE OFF-RAMP      PERCENTAGE
       -------------     ---------------------    -----------      --------------------    -----------
       (8001,   1)                 2                  100
       (   1,   2)                 3                  100
       (   2,   3)                 4                  100
       (   3,   4)              8004                  100
```

Figure B-3
Sample FRESIM Output - Input Data Tables

FRESIM SURVEILLANCE

LINK	LANE ID NO.	DETECTOR LOCATION	LOOP LENGTH	STATION NO.	DIST. SEPARATING COUPLED PAIR OF SHORT LOOPS	DETECTOR TYPE
(1, 2)	1	50	6	3		SHORT LOOP
	2	50	6	3		SHORT LOOP
	3	50	6	3		SHORT LOOP
	1	300	6	4		

FRESIM LINK VOLUME

LINK	FLOW RATE (VEH/HOUR)	PERCENT TRUCKS	PERCENT CARPOOL
(8001, 1)	3000	5	
(8021, 21)	200		

FRESIM OFF-LINE INCIDENT DETECTION AND/OR MOE ESTIMATION DATA

DETECTOR OPERATION DATA

DETECTOR MODE	POLLING FREQUENCY (NO./SEC)	EVALUATION FREQUENCY (SEC)	INC. DET. RE-EVALUATION TIME PERIOD (SEC)	AVERAGE VEHICLE LENGTH (FEET)
ANALOG		900	900	15

NOTE: POINT PROCESSING IS DESIRED.

DETECTOR STATIONS USED

LINK	STATION NO.
(21, 2)	1
(21, 2)	2
(1, 2)	3
(1, 2)	4
(2, 3)	5

FRESIM LANE ALIGNMENT TABLE

LINK	LINK TYPE	DISTANCE FROM UPST. NODE (FT)	UPSTREAM FEEDING LANE NUMBER 1	2	3	4	5	6	7	8	9	10	11	REASON CODE
(21, 2)	R	1000.0	9	-	-	-	-	-	-	-	-	-	-	1

FRESIM ORIGIN - DESTINATION TRIP TABLE

FOR EACH ORIGIN NODE, TABLE PROVIDES LISTING OF PAIRS OF DATA : DESTINATION/ FRACTION OF ENTRY VOLUME TRAVELING TO DESTINATION

ORIGIN NODE (8021) 4/ 1.000
ORIGIN NODE (8001) 4/ 1.000

Figure B-3 (Continued)
Sample FRESIM Output - Input Data Tables

CUMULATIVE FRESIM STATISTICS AT TIME 7 15 0

LINK STATISTICS

LINK	VEHICLES IN	VEHICLES OUT	LANE CHNG	CURR CONT	AVG CONT	VEH-MILES	VEH-MIN	SECONDS/VEHICLE TOTAL TIME	SECONDS/VEHICLE MOVE TIME	SECONDS/VEHICLE DELAY TIME	M/T	VEH-MIN/VEH-MILE TOTAL	VEH-MIN/VEH-MILE DELAY	VOLUME VEH/LN/HR	DENSITY VEH/LN-MILE	SPEED MILE/HR	LINK TYPE
(1, 2)	749	750	104	3	3.5	43.7	52.4	4.1	3.7	0.3	0.92	1.20	0.10	1026.	20.5	50.01	FRWY
(2, 3)	800	803	209	17	17.1	227.7	256.4	19.2	18.6	0.6	0.97	1.13	0.04	1070.	20.1	53.28	FRWY
(3, 4)	803	798	86	13	11.4	151.3	170.7	12.8	12.3	0.5	0.96	1.13	0.04	1066.	20.0	53.19	FRWY
(21, 2)	50	50	0	0	1.0	9.5	14.7	17.6	17.3	0.2	0.99	1.54	0.02	292.	5.2	38.84	RAMP

NETWORK STATISTICS

VEHICLE-MILES = 432.2, VEHICLE-MINUTES = 494.2, MOVING/TOTAL TRIP TIME = 0.961,

AVERAGE CONTENT = 33.0, CURRENT CONTENT = 33.0, SPEED(MPH) = 52.47,

TOTAL DELAY (VEH-MIN) = 19.22, TRAVEL TIME (MIN)/VEH-MILE = 1.14, DELAY TIME (MIN)/VEH-MILE = 0.04

POINT PROCESSING OUTPUT

EVALUATION PERIOD BEGINNING TIME = 1 (SECONDS)
EVALUATION PERIOD ENDING TIME = 900 (SECONDS)

LINK	LANE ID NO.	DISTANCE FROM UPST. NODE (FT)	LOOP LENGTH (FT)	STATION NO.	DETECTOR TYPE	VOLUME (VPH)	MEAN SPEED (MPH)	MEAN HEADWAY (SEC)	MEAN OCCUPANCY RATE
(21, 2)	1	750.00	6.0	1	SINGLE SHORT LOOP	200	33.884	17.899	1.687
(21, 2)	1	975.00	6.0	2	SINGLE SHORT LOOP	200	33.865	17.974	1.688
(1, 2)	1	50.00	6.0	3	SINGLE SHORT LOOP	928	40.654	3.860	6.913
(1, 2)	2	50.00	6.0	3	SINGLE SHORT LOOP	1088	40.050	3.306	8.151
(1, 2)	3	50.00	6.0	3	SINGLE SHORT LOOP	984	40.944	3.651	7.109
(1, 2)	1	300.00	6.0	4	SINGLE SHORT LOOP	876	44.592	4.103	5.865
(1, 2)	2	300.00	6.0	4	SINGLE SHORT LOOP	1148	45.100	3.136	7.476
(1, 2)	3	300.00	6.0	4	SINGLE SHORT LOOP	976	46.012	3.672	6.143
(2, 3)	1	250.00	6.0	5	SINGLE SHORT LOOP				

Figure B-4
Sample FRESIM Output Reports

FRESIM INTERMEDIATE LINK STATISTICS AT TIME 0 5 0

LINK	CON.	VEH DIS	TURN MOVEMENT LEFT	TURN MOVEMENT THRU	TURN MOVEMENT RT.	DELAY/ VEH.	AVG SPEED	METER CODE	LANE CHNG
(8001, 1)	3	506	0	506	0	N/A	N/A	0	5
(1, 2)	63	494	0	494	0	6.0	49.5	0	224
(2, 3)	48	531	0	531	0	8.6	39.6	0	152
(3, 4)	30	527	0	527	0	2.5	49.5	0	94
(4, 8004)	N/A	N/A	0	0	0	N/A	N/A	0	0
(21, 2)	1	50	0	50	0	0.2	46.4	0	0
(8021, 21)	0	50	0	50	0	N/A	N/A	0	0

1

FRESIM INTERMEDIATE LINK STATISTICS AT TIME 0 5 0

TABLE OF VEHICLE CONTENT BY LANE

LINK	LINK LENGTH (FT)	DISTANCE TO UPSTR. NODE (FT)	LANE 1	2	3	4	5	6	7	8	9	10	11
(1, 2)	2500	2500	23	20	20	0	0	0	0	0	0	0	0
(2, 3)	1500	770	10	10	8	0	0	0	0	0	1	0	0
(2, 3)	1500	1500	6	6	7	0	0	0	0	0	0	0	0
(3, 4)	1000	1000	9	11	9	0	0	0	0	0	0	0	0
(21, 2)	700	700	1	0	0	0	0	0	0	0	0	0	0

1

Figure B-5
Sample FRESIM Output Reports for Intermediate Link Statistics

FRESIM CUMULATIVE VALUES OF FUEL CONSUMPTION

LINK	LINK TYPE	FUEL CONSUMPTION GALLONS							M.P.G.						
VEHICLE TYPE-		1	2	3	4	5	6	7	1	2	3	4	5	6	7
(1, 2)	FRWY	13.95	23.07	3.57	2.12	2.46	0.51	0.00	12.85	21.04	3.24	5.08	4.58	4.59	0.00
(2, 3)	FRWY	13.98	22.16	4.23	1.89	3.08	0.62	0.00	8.22	14.11	2.00	3.48	2.52	2.46	0.00
(3, 4)	FRWY	8.40	13.78	2.62	1.32	2.37	0.32	0.00	9.12	15.03	2.12	3.28	2.22	3.04	0.00
(21, 2)	RAMP	0.22	0.52	0.18	0.03	0.12	0.02	0.00	22.11	27.10	3.47	4.53	3.96	7.42	0.00
SUBNETWORK-		36.56	59.53	10.60	5.35	8.02	1.47	0.00	10.28	17.12	2.47	4.07	3.08	3.39	0.00

VEHICLE TYPES 1, 2 = AUTO, VEHICLE TYPES 3, 4, 5, 6 = TRUCK, VEHICLE TYPE 7 = TRANSIT BUS

1

FRESIM CUMULATIVE VALUES OF EMISSION

LINK	LINK TYPE	VEHICLE EMISSIONS (GRAMS/ MILE) HC						
VEHICLE TYPE-		1	2	3	4	5	6	7
(1, 2)	FRWY	0.24	0.25	10.88	8.44	6.54	5.43	0.00
(2, 3)	FRWY	0.42	0.45	18.27	10.74	9.19	7.26	0.00
(3, 4)	FRWY	0.43	0.48	18.04	13.06	11.45	6.74	0.00
(21, 2)	RAMP	0.07	0.12	9.85	10.27	8.00	5.13	0.00
SUBNETWORK-		0.33	0.36	14.76	10.06	8.44	6.24	0.00

VEHICLE TYPES 1, 2 = AUTO, VEHICLE TYPES 3, 4, 5, 6 = TRUCK, VEHICLE TYPE 7 = TRANSIT BUS

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FRESIM CUMULATIVE VALUES OF EMISSION

LINK	LINK TYPE	VEHICLE EMISSIONS (GRAMS/ MILE) CO						
VEHICLE TYPE-		1	2	3	4	5	6	7
(1, 2)	FRWY	16.52	17.64	198.25	142.21	103.71	81.50	0.00
(2, 3)	FRWY	32.98	35.27	342.87	176.83	142.83	110.08	0.00
(3, 4)	FRWY	34.06	38.61	348.70	230.48	192.78	102.98	0.00
(21, 2)	RAMP	5.87	10.04	173.87	175.42	130.41	75.73	0.00
SUBNETWORK-		24.99	27.20	276.20	170.38	135.45	94.28	0.00

VEHICLE TYPES 1, 2 = AUTO, VEHICLE TYPES 3, 4, 5, 6 = TRUCK, VEHICLE TYPE 7 = TRANSIT BUS

Figure B-6
Sample FRESIM Output Reports for Environmental MOE's

Cumulative statistics are reported for each time period on a link-by-link basis, and a summary for the entire network is also given at the end of each period. Following is a description of the reported statistics:

Statistic	**Description**
LINK	Link for which data is being reported. Link is defined by a pair of O-D nodes.
VEHICLES IN	Vehicles In: Total number of vehicles which entered the link since the beginning of the simulation run. This value is cumulative from period to period.
VEHICLES OUT	Vehicles Out: Total number of vehicles discharged from the link since the beginning of the simulation run. This value is cumulative from period to period.
LANE CHNG	Lane Changes: Total number of lane changes that occurred in the link since the beginning of the simulation run. This value is cumulative from period to period.

CURR CONT	Current Content: Number of vehicles occupying the link at the time the report is produced. This value is not cumulative from period to period.
AVG CONT	Average Content: This value is the ratio of the total travel incurred by all vehicles which traversed the link since the beginning of the simulation to the elapsed simulation time.
VEH-MILES	Vehicle-Miles: Total traveled distance incurred by all vehicles which traversed the link since the beginning of the simulation run. This value can be approximated by multiplying the link length (in miles) times the VEHICLES OUT value.
VEH-MIN	Vehicle-Minutes. Total travel time incurred by all vehicles which traversed the link since the beginning of the simulation run.
TOTAL TIME	Total Time: Ratio of the link length to the average speed on the link, in Seconds/Vehicle.
MOVE TIME	Moving Time: Average travel time at a speed greater than zero which is computed as $\left[\frac{(TOTAL\ TIME\ -\ DELAY\ TIME)\ \times\ (TOTAL\ TIME\ FOR\ THE\ LINK)}{TOTAL\ TIME\ PER\ VEHICLE}\right]$
DELAY TIME	Delay Time: Difference between the Total Time and the Moving Time in Seconds/Vehicle.
M/T	MOVE TIME/TOTAL TIME: Ratio of the Moving Time to the Total Time.
TOTAL	Ratio of the Vehicle-Minutes to Vehicle-Miles, expressed in Minutes/Mile.
DELAY	The product of the TOTAL and the DELAY TIME as defined above, expressed in Minutes/Vehicle.
VOLUME	Volume: The product of DENSITY and SPEED as defined below, expressed in Vehicles/Lane/Hour.
DENSITY	Density: Ratio of the average content (AVG CONT) to the total lane-miles on each link. The calculation of density does not include acceleration nor deceleration lanes.
SPEED	Speed: Ratio of the Vehicle-Miles to Vehicle-Minutes converted to miles per hour, and reflects conditions since the beginning of the simulation run.

For each detector placed on the network key characteristics are reported for each time period specified by the user. These are described below:

Statistic	Description
LINK	Link for which data is being reported. Link is defined by a pair of O-D nodes.
LANE ID NO.	Lane identification number on which detector has been specified.
DIST. FROM UPST. NODE	Distance from upstream node where location is placed, measured in feet.
LOOP LENGTH	The effective detector loop length, in feet, as specified by the user.
STATION NO.	Station Number. This conforms to the normal practice in surveillance and control systems where a group of detectors placed across all lanes is identified with a unique identification number.
DET. TYPE	As described in previous sections on loop detectors.
VOLUME	Volume: This is the volume across the detector, expressed in Vehicles/Hour.
MEAN SPEED	Mean Speed: This is the mean speed across the detector, expressed in Miles/Hour.
MEAN HEADWAY	Mean Headway: This is the mean headway as measured by the detector, expressed in Seconds.
MEAN OCCUP. RATE	Mean Occupancy Rate: This is the mean occupancy rate, in percent.

APPENDIX C

		Volume in Lanes 1 and 2 (V12)							Speed in Influence Area (SR)							Density in Influence Area (DR)						
		Actual	Fresim	94HCM	Percent Error		Absolute Error					Percent Error		Absolute Error					Percent Error		Absolute Error	
Site	Period	AV12	FV12	HV12	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ASR	FSR	HSR	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ADR	FDR	HDR	(F - A)/A	(H - A)/A	(F - A)	(H - A)
9	1	1,396	1,396	1,396	-0.0%	0.0%	0	0	55	62	57	13.0%	3.7%	7.1	2.0	19	17	20	-14.1%	5.6%	2.7	1.1
9	2	1,432	1,425	1,432	-0.5%	0.0%	7	0	54	62	57	13.7%	4.5%	7.4	2.4	20	17	21	-14.5%	4.8%	2.9	1.0
9	3	1,624	1,610	1,624	-0.9%	0.0%	14	0	54	61	56	12.5%	3.8%	6.7	2.1	22	19	23	-13.3%	4.4%	3.0	1.0
9	4	1,592	1,589	1,592	-0.2%	0.0%	3	0	54	61	56	13.9%	5.2%	7.5	2.8	21	19	23	-13.3%	5.0%	2.8	1.1
9	5	1,664	1,655	1,664	-0.6%	0.0%	9	0	55	61	56	11.3%	2.8%	6.2	1.5	22	19	23	-11.7%	6.5%	2.6	1.4
9	6	1,532	1,537	1,532	0.3%	0.0%	5	0	55	61	56	11.9%	3.0%	6.6	1.6	20	18	21	-11.9%	7.2%	2.4	1.4
9	Average	1,540	1,535	1,540	-0.3%	0.0%	7	0	54	61	56	12.7%	3.8%	6.9	2.1	21	18	22	-13.1%	5.6%	2.7	1.2
16	1	2,346	2,346	2,346	0.0%	0.0%	0	0	57	56	53	-0.7%	-6.6%	0.4	3.7	18	15	20	-19.4%	11.7%	3.5	2.1
16	2	2,202	2,210	2,202	0.4%	0.0%	8	0	57	57	53	-0.7%	-6.8%	0.4	3.9	18	14	19	-21.5%	8.8%	3.8	1.6
16	3	1,276	1,351	1,276	5.9%	0.0%	75	0	58	58	54	0.9%	-6.8%	0.5	4.0	10	8	11	-16.7%	6.3%	1.7	0.6
16	4	1,170	1,167	1,170	-0.2%	0.0%	3	0	58	59	54	1.9%	-6.4%	1.1	3.7	9	7	10	-22.4%	3.3%	2.1	0.3
16	5	1,220	1,227	1,220	0.6%	0.0%	7	0	58	59	54	2.0%	-6.3%	1.2	3.6	9	7	10	-21.2%	4.6%	2.0	0.4
16	6	1,198	1,200	1,198	0.2%	0.0%	2	0	57	59	54	2.4%	-5.9%	1.4	3.4	10	7	10	-24.4%	1.1%	2.3	0.1
16	Average	1,569	1,584	1,569	1.0%	0.0%	16	0	57	58	54	1.0%	-6.4%	0.8	3.7	12	10	13	-20.8%	7.0%	2.6	0.9
40	1	674	677	674	0.5%	0.0%	3	0	56	55	54	-1.3%	-4.2%	0.7	2.4	13	14	14	1.2%	3.4%	0.2	0.5
40	2	756	737	756	-2.5%	0.0%	19	0	56	56	54	-0.6%	-4.0%	0.3	2.2	12	13	13	11.5%	15.9%	1.3	1.8
40	3	688	689	688	0.2%	0.0%	1	0	56	56	54	-0.4%	-4.5%	0.3	2.5	11	12	12	6.4%	8.7%	0.7	1.0
40	4	720	719	720	-0.1%	0.0%	1	0	57	56	54	-1.4%	-5.1%	0.8	2.9	10	12	12	15.2%	18.3%	1.6	1.9
40	Average	710	706	710	-0.5%	0.0%	6	0	56	56	54	-0.9%	-4.4%	0.5	2.5	12	13	13	8.1%	11.1%	0.9	1.3
8	1	2,902	3,485	3,126	20.1%	7.7%	583	224	55	54	52	-1.6%	-5.6%	0.9	3.1	25	30	29	17.4%	13.9%	4.4	3.5
8	2	3,078	3,574	3,265	16.1%	6.1%	496	187	53	54	52	1.8%	-1.6%	0.9	0.8	29	32	31	7.9%	4.7%	2.3	1.4
8	3	3,028	3,597	3,271	18.8%	8.0%	569	243	53	54	52	0.8%	-2.5%	0.4	1.3	28	32	31	13.2%	9.4%	3.7	2.6
8	4	3,072	3,631	3,301	18.2%	7.5%	559	229	52	54	52	3.6%	-0.5%	1.9	0.3	29	31	30	7.6%	4.3%	2.2	1.2
8	5	2,984	3,508	3,144	17.5%	5.4%	524	160	49	54	52	10.1%	5.6%	5.0	2.8	30	30	29	-1.0%	-4.2%	0.3	1.3
8	6	2,972	3,557	3,195	19.7%	7.5%	585	223	52	55	52	5.1%	0.1%	2.7	0.0	27	30	29	9.0%	6.3%	2.5	1.7
8	7	2,768	3,390	3,026	22.5%	9.3%	622	258	52	55	52	4.3%	-0.0%	2.3	0.0	26	29	28	10.8%	8.1%	2.8	2.1
8	8	2,688	3,295	2,953	22.6%	9.9%	607	265	53	55	53	2.9%	-1.3%	1.5	0.7	25	28	28	11.8%	9.9%	3.0	2.5
8	Average	2,937	3,505	3,160	19.3%	7.6%	568	224	53	54	52	3.3%	-0.8%	1.9	1.1	28	30	29	9.3%	6.3%	2.7	2.1

Detail Statistics for V_{12}, D_R and S_R for NCHRP Database

		Volume in Lanes 1 and 2 (V12)							Speed in Influence Area (SR)							Density in Influence Area (DR)						
		Actual	Fresim	94HCM	Percent Error		Absolute Error					Percent Error		Absolute Error					Percent Error		Absolute Error	
Site	Period	AV12	FV12	HV12	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ASR	FSR	HSR	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ADR	FDR	HDR	(F - A)/A	(H - A)/A	(F - A)	(H - A)
10	1	1,768	2,504	2,153	41.7%	21.8%	736	385	57	56	53	-1.0%	-6.3%	0.6	3.6	14	19	19	33.0%	33.6%	4.7	4.8
10	2	1,982	2,749	2,367	38.7%	19.4%	767	385	56	56	53	-0.5%	-5.7%	0.3	3.2	16	21	21	30.6%	31.4%	4.8	5.0
10	3	2,402	3,289	2,908	36.9%	21.1%	887	506	56	55	52	-2.5%	-6.3%	1.4	3.5	19	25	25	32.4%	33.4%	6.2	6.4
10	4	2,620	3,618	3,169	38.1%	21.0%	998	549	55	53	52	-4.1%	-6.1%	2.2	3.4	22	29	28	32.6%	29.3%	7.1	6.4
10	5	2,392	3,376	2,862	41.1%	19.6%	984	470	56	55	53	-1.8%	-5.5%	1.0	3.1	19	26	25	33.5%	29.4%	6.4	5.6
10	6	2,080	2,870	2,434	38.0%	17.0%	790	354	57	56	53	-2.1%	-6.8%	1.2	3.9	17	22	21	31.5%	30.0%	5.2	4.9
10	7	2,128	2,921	2,520	37.3%	18.4%	793	392	57	56	53	-1.1%	-6.1%	0.6	3.5	16	22	22	34.0%	34.1%	5.5	5.5
10	Average	2,196	3,047	2,630	38.7%	19.8%	851	434	56	55	53	-1.9%	-6.1%	1.1	3.4	18	23	23	32.5%	31.4%	5.7	5.5
18	1	2,386	2,625	2,415	10.0%	1.2%	239	29	57	59	56	3.7%	-2.0%	2.1	1.1	19	16	22	-15.9%	17.7%	3.0	3.4
18	2	1,988	2,098	1,936	5.5%	-2.6%	110	52	57	60	57	5.2%	-1.0%	3.0	0.6	17	13	19	-23.4%	8.6%	4.0	1.5
18	3	1,966	2,054	1,910	4.5%	-2.9%	88	56	55	61	57	9.4%	2.4%	5.2	1.3	17	13	18	-27.1%	4.6%	4.7	0.8
18	4	2,024	2,074	1,944	2.5%	-3.9%	50	80	55	60	57	10.2%	3.8%	5.6	2.1	18	13	19	-27.9%	3.6%	5.1	0.7
18	5	1,680	1,747	1,611	4.0%	-4.1%	67	69	55	61	57	9.4%	2.7%	5.2	1.5	15	11	16	-26.0%	5.5%	3.9	0.8
18	6	1,656	1,669	1,575	0.8%	-4.9%	13	81	56	61	57	9.1%	2.1%	5.1	1.2	15	11	16	-27.0%	5.7%	4.0	0.8
18	Average	1,950	2,045	1,899	4.9%	-2.6%	95	61	56	60	57	7.8%	1.3%	4.4	1.3	17	13	18	-24.3%	7.8%	4.1	1.3
23	1	2,334	2,369	2,245	1.5%	-3.8%	35	89	55	55	53	-0.4%	-5.2%	0.2	2.9	19	19	19	0.1%	1.6%	0.0	0.3
23	2	2,412	2,427	2,327	0.6%	-3.5%	15	85	56	55	52	-2.3%	-6.7%	1.3	3.8	19	20	21	2.3%	6.5%	0.4	1.3
23	3	2,472	2,468	2,374	-0.2%	-3.9%	4	98	56	55	52	-2.6%	-7.1%	1.4	4.0	19	19	20	1.0%	4.6%	0.2	0.9
23	4	2,512	2,446	2,365	-2.6%	-5.8%	66	147	56	54	51	-3.6%	-7.7%	2.0	4.3	21	22	23	2.2%	8.4%	0.5	1.8
23	5	2,732	2,886	2,814	5.7%	3.0%	154	82	54	50	48	-7.1%	-10.1%	3.8	5.4	24	27	28	9.2%	15.7%	2.2	3.8
23	6	2,916	2,989	2,926	2.5%	0.3%	73	10	55	51	49	-6.5%	-10.2%	3.6	5.6	23	26	27	10.7%	17.8%	2.5	4.1
23	Average	2,563	2,598	2,509	1.3%	-2.1%	58	85	55	53	51	-3.7%	-7.8%	2.1	4.3	21	22	23	4.6%	9.7%	1.0	2.0
25	1	2,668	3,132	2,956	17.4%	10.8%	464	288	53	55	53	3.0%	-1.6%	1.6	0.8	21	19	25	-11.9%	16.4%	2.5	3.5
25	2	2,996	3,448	3,305	15.1%	10.3%	452	309	54	54	52	-0.4%	-3.9%	0.2	2.1	25	22	28	-11.2%	16.1%	2.7	3.9
25	3	2,926	3,495	3,308	19.4%	13.1%	569	382	53	52	51	-1.8%	-3.9%	0.9	2.1	25	23	30	-6.9%	18.1%	1.7	4.5
25	4	3,544	3,778	3,880	6.6%	9.5%	234	336	52	49	48	-5.6%	-6.3%	2.9	3.3	31	27	35	-12.5%	11.3%	3.9	3.5
25	5	3,846	3,811	3,984	-0.9%	3.6%	35	138	46	46	47	-0.8%	1.8%	0.4	0.8	38	30	36	-21.7%	-5.0%	8.3	1.9
25	Average	3,196	3,533	3,487	10.5%	9.1%	351	291	52	51	50	-1.1%	-2.9%	1.2	1.8	28	24	31	-13.7%	9.7%	3.8	3.5

Detail Statistics for V_{12}, D_R and S_R for NCHRP Database

		Volume in Lanes 1 and 2 (V12)							Speed in Influence Area (SR)							Density in Influence Area (DR)						
		Actual	Fresim	94HCM	Percent Error		Absolute Error					Percent Error		Absolute Error					Percent Error		Absolute Error	
Site	Period	AV12	FV12	HV12	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ASR	FSR	HSR	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ADR	FDR	HDR	(F - A)/A	(H - A)/A	(F - A)	(H - A)
26	1	3,298	3,815	3,443	15.7%	4.4%	517	145	53	54	52	3.2%	-1.6%	1.7	0.8	25	23	28	-9.7%	12.0%	2.5	3.1
26	2	3,264	3,705	3,319	13.5%	1.7%	441	55	54	55	52	1.8%	-3.0%	1.0	1.6	25	22	27	-12.1%	9.0%	3.0	2.3
26	3	3,502	3,921	3,568	12.0%	1.9%	419	66	55	54	52	-0.8%	-5.6%	0.4	3.0	26	23	29	-11.4%	10.5%	3.0	2.8
26	4	3,676	3,958	3,594	7.7%	-2.2%	282	82	54	54	51	-0.3%	-4.6%	0.1	2.5	28	24	29	-15.4%	4.6%	4.3	1.3
26	Average	3,435	3,850	3,481	12.1%	1.3%	415	87	54	54	52	1.0%	-3.7%	0.8	2.0	26	23	29	-12.2%	8.9%	3.2	2.3
27	1	2,050	2,107	1,843	2.8%	-10.1%	57	207	56	57	54	2.8%	-3.7%	1.6	2.1	16	12	15	-23.2%	-5.3%	3.6	0.8
27	2	2,244	2,149	1,863	-4.2%	-17.0%	95	381	55	57	54	3.9%	-2.3%	2.1	1.2	17	13	15	-26.5%	-10.0%	4.6	1.7
27	3	2,364	2,304	1,977	-2.5%	-16.4%	60	387	55	57	54	3.5%	-2.4%	1.9	1.3	18	14	17	-25.4%	-8.8%	4.7	1.6
27	4	2,290	2,278	2,014	-0.5%	-12.1%	12	276	56	57	54	1.3%	-4.8%	0.7	2.7	17	13	16	-23.2%	-4.0%	4.0	0.7
27	5	2,570	2,572	2,203	0.1%	-14.3%	2	367	56	56	53	0.6%	-4.5%	0.3	2.5	20	16	19	-22.0%	-4.9%	4.4	1.0
27	6	2,700	2,576	2,229	-4.6%	-17.4%	124	471	57	56	53	-2.0%	-7.0%	1.2	4.0	20	15	19	-22.3%	-4.5%	4.4	0.9
27	7	2,610	2,754	2,302	5.5%	-11.8%	144	308	58	56	53	-3.9%	-8.1%	2.2	4.7	20	17	20	-15.0%	1.6%	3.0	0.3
27	Average	2,404	2,392	2,062	-0.5%	-14.2%	71	342	56	57	53	0.8%	-4.7%	1.4	2.6	18	14	17	-22.4%	-5.0%	4.1	1.0
46	1	1,572	2,524	1,543	60.6%	-1.8%	952	29	55	56	54	2.7%	-1.5%	1.5	0.8	22	21	17	-3.1%	-24.8%	0.7	5.5
46	2	1,596	2,652	1,720	66.2%	7.8%	1,056	124	54	57	54	4.3%	-1.0%	2.3	0.5	21	21	17	-1.8%	-21.3%	0.4	4.5
46	3	1,624	2,913	1,883	79.4%	16.0%	1,289	259	54	56	54	4.4%	0.2%	2.4	0.1	23	23	18	1.6%	-20.3%	0.4	4.7
46	4	1,726	3,026	1,963	75.3%	13.7%	1,300	237	56	56	54	-0.5%	-4.3%	0.3	2.4	23	24	19	5.0%	-18.2%	1.1	4.2
46	Average	1,630	2,779	1,777	70.5%	9.1%	1,149	162	55	55	54	2.7%	-1.7%	1.6	1.0	22	22	18	0.5%	-21.1%	0.6	4.7
36	1	1,926	1,928	1,926	0.1%	0.0%	2	0	54	58	54	6.2%	-0.8%	3.4	0.4	16	14	18	-16.3%	11.2%	2.7	1.8
36	2	2,072	2,049	2,072	-1.1%	0.0%	23	0	55	58	54	4.8%	-2.1%	2.6	1.1	17	15	19	-16.0%	12.0%	2.8	2.1
36	3	1,988	1,987	1,988	-0.1%	0.0%	1	0	55	58	54	4.9%	-2.2%	2.7	1.2	17	14	19	-15.4%	12.2%	2.6	2.0
36	4	2,070	2,052	2,070	-0.9%	0.0%	18	0	55	58	54	5.8%	-1.0%	3.2	0.5	17	15	19	-15.7%	11.5%	2.7	2.0
36	Average	2,014	2,004	2,014	-0.5%	0.0%	11	0	55	58	54	5.4%	-1.5%	3.0	0.8	17	14	19	-15.8%	11.7%	2.7	2.0
54	1	3,552	3,551	3,552	-0.0%	0.0%	1	0	57	56	53	-0.5%	-7.0%	0.3	3.9	28	28	31	-0.5%	11.7%	0.1	3.3
54	2	3,712	3,692	3,712	-0.5%	0.0%	20	0	56	56	53	0.5%	-5.9%	0.3	3.3	30	29	33	-2.0%	10.4%	0.6	3.1
54	3	3,638	3,636	3,638	-0.0%	0.0%	2	0	56	56	53	1.2%	-5.3%	0.7	2.9	29	29	32	-1.7%	10.1%	0.5	2.9
54	4	3,566	3,562	3,566	-0.1%	0.0%	4	0	56	56	53	1.2%	-5.2%	0.6	2.9	29	28	32	-2.7%	9.2%	0.8	2.7
54	5	3,828	3,797	3,828	-0.8%	0.0%	31	0	55	56	53	1.5%	-4.4%	0.8	2.4	31	30	34	-2.8%	9.4%	0.9	2.9
54	6	3,492	3,513	3,492	0.6%	0.0%	21	0	55	56	53	3.1%	-3.3%	1.7	1.8	29	28	31	-2.8%	8.3%	0.8	2.4
54	Average	3,631	3,625	3,631	-0.2%	0.0%	13	0	56	56	53	1.1%	-5.2%	0.7	2.9	29	29	32	-2.1%	9.8%	0.6	2.9

Detail Statistics for V_{12}, D_R and S_R for NCHRP Database

		Volume in Lanes 1 and 2 (V12)							Speed in Influence Area (SR)							Density in Influence Area (DR)						
		Actual	Fresim	94HCM	Percent Error		Absolute Error					Percent Error		Absolute Error					Percent Error		Absolute Error	
Site	Period	AV12	FV12	HV12	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ASR	FSR	HSR	(F - A)/A	(H - A)/A	(F - A)	(H - A)	ADR	FDR	HDR	(F - A)/A	(H - A)/A	(F - A)	(H - A)
56	1	3,512	3,509	3,512	-0.1%	0.0%	3	0	52	56	52	6.3%	-1.6%	3.3	0.8	32	29	33	-7.3%	2.7%	2.3	0.9
56	2	3,988	3,912	3,988	-1.9%	0.0%	76	0	53	55	52	4.0%	-1.8%	2.1	0.9	36	33	37	-8.6%	1.1%	3.1	0.4
56	3	4,030	4,014	4,030	-0.4%	0.0%	16	0	52	55	52	4.3%	-1.0%	2.3	0.5	38	34	37	-8.6%	-1.2%	3.2	0.4
56	4	4,286	4,228	4,286	-1.3%	0.0%	58	0	50	54	52	9.2%	4.3%	4.6	2.1	41	36	39	-10.4%	-3.3%	4.2	1.3
56	5	4,868	4,470	4,868	-8.2%	0.0%	398	0	52	53	51	1.1%	-0.9%	0.6	0.5	44	40	44	-9.8%	0.4%	4.3	0.2
56	6	4,214	4,533	4,214	7.6%	0.0%	319	0	49	52	52	5.5%	5.0%	2.7	2.5	40	41	39	0.8%	-4.3%	0.3	1.7
56	7	4,706	4,526	4,706	-3.8%	0.0%	180	0	49	52	52	6.6%	6.1%	3.2	3.0	46	41	43	-11.1%	-6.2%	5.1	2.8
56	Average	4,229	4,170	4,229	-1.4%	0.0%	150	0	51	54	52	5.2%	1.3%	2.7	1.5	39	36	39	-8.0%	-1.8%	3.2	1.1
15	1	3,058	3,273	3,170	7.0%	3.6%	214	111	54	57	52	5.0%	-4.0%	2.7	2.2	25	27	29	6.2%	17.0%	1.6	4.3
15	2	3,240	3,462	3,352	6.9%	3.5%	222	112	53	56	52	5.8%	-2.7%	3.1	1.4	27	29	31	5.5%	14.8%	1.5	4.0
15	3	3,396	3,633	3,588	7.0%	5.7%	237	192	53	56	51	4.7%	-3.7%	2.5	2.0	28	30	33	6.9%	17.5%	1.9	4.9
15	4	3,492	3,767	3,689	7.9%	5.7%	276	197	52	56	51	7.5%	-0.8%	3.9	0.4	30	31	34	4.7%	13.4%	1.4	4.0
15	5	3,565	3,872	3,793	8.6%	6.4%	307	228	52	56	51	7.6%	-0.5%	3.9	0.2	31	32	35	6.0%	14.1%	1.8	4.3
15	6	3,696	3,991	3,900	8.0%	5.5%	295	204	51	55	51	9.0%	1.2%	4.6	0.6	33	34	36	1.6%	8.2%	0.5	2.7
15	7	3,769	4,031	3,881	6.9%	3.0%	262	112	47	55	51	16.7%	8.8%	7.9	4.2	36	34	36	-4.1%	0.1%	1.5	0.0
15	8	3,779	4,070	3,834	7.7%	1.5%	291	55	48	55	52	14.3%	7.8%	6.9	3.7	35	35	35	-0.4%	1.5%	0.2	0.5
15	9	3,952	4,136	3,917	4.7%	-0.9%	184	35	45	55	52	20.6%	14.1%	9.4	6.4	37	35	36	-4.5%	-2.7%	1.7	1.0
15	Average	3,550	3,804	3,680	7.2%	3.7%	254	139	51	56	52	9.8%	1.9%	5.0	2.3	31	32	34	2.0%	8.5%	1.3	2.9
35	1	3,282	3,236	3,129	-1.4%	-4.7%	46	153	55	57	53	2.9%	-4.4%	1.6	2.4	29	27	30	-5.6%	4.3%	1.6	1.2
35	2	3,254	3,200	3,119	-1.7%	-4.1%	54	135	55	57	53	2.8%	-4.6%	1.6	2.5	29	27	30	-6.4%	3.9%	1.8	1.1
35	3	3,474	3,523	3,478	1.4%	0.1%	49	4	54	56	52	4.6%	-2.8%	2.5	1.5	31	30	33	-4.6%	5.5%	1.4	1.7
35	4	3,616	3,588	3,502	-0.8%	-3.2%	28	114	54	56	52	2.6%	-4.6%	1.4	2.5	32	30	33	-4.7%	3.4%	1.5	1.1
35	5	3,682	3,699	3,649	0.5%	-0.9%	17	33	55	56	52	1.1%	-5.8%	0.6	3.2	32	31	34	-2.0%	6.7%	0.6	2.1
35	6	3,546	3,589	3,499	1.2%	-1.3%	43	47	56	56	52	0.1%	-6.7%	0.0	3.7	31	30	33	-0.7%	7.7%	0.2	2.3
35	Average	3,476	3,473	3,396	-0.1%	-2.3%	39	81	55	56	52	2.3%	-4.8%	1.3	2.6	31	29	32	-3.9%	5.3%	1.2	1.6
37	1	3,882	3,929	3,763	1.2%	-3.1%	47	119	52	56	53	7.2%	2.9%	3.7	1.5	36	34	35	-6.9%	-2.2%	2.5	0.8
37	2	4,034	3,957	3,870	-1.9%	-4.1%	77	164	51	55	53	9.4%	4.7%	4.8	2.4	38	34	36	-11.3%	-5.4%	4.3	2.1
37	3	4,092	4,089	3,899	-0.1%	-4.7%	3	193	51	55	53	7.9%	4.1%	4.0	2.1	39	35	36	-8.7%	-5.8%	3.4	2.3
37	4	4,068	4,125	3,946	1.4%	-3.0%	57	122	50	55	53	8.9%	5.2%	4.5	2.6	39	36	37	-7.7%	-5.1%	3.0	2.0
37	5	3,788	3,889	3,658	2.7%	-3.4%	101	130	52	55	53	6.8%	2.8%	3.5	1.5	35	33	34	-4.4%	-1.5%	1.6	0.5
37	6	3,864	3,912	3,687	1.2%	-4.6%	48	177	51	55	54	7.6%	4.2%	3.9	2.2	36	34	35	-5.8%	-2.7%	2.1	1.0
37	Average	3,955	3,983	3,804			56	151	51	55	53			4.1	2.0	37	34	36			2.8	1.4

Detail Statistics for V_{12}, D_R and S_R for NCHRP Database

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
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