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SPEED-CHANGE LANES

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

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Richard M. Michaels, Abishai Polus, James M. Schoen

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ABSTRACT

This report documents and presents the findings of a study of the operational and design aspects of freeway speed-change lanes. Current design parameters for speed-change lanes as contained in the AASHTO geometric design manual were examined in order to identify deficient areas. Based on field data collected at 35 freeway sites, speed-change models were developed for both the entrance and exit cases. The entrance model is based on gap acceptance and acceleration characteristics of drivers as determined by the controlling geometry. The exit model is based on the driver's behavioral response to design geometrics. Field observations of the entry and exit processes were used to calibrate and validate each model. The general framework for the entry and exit models includes a series of zones in which the driver completes certain tasks in the entry or exit process. The findings of the study suggest that for certain traffic conditions, the current speed-change lane design criteria do not provide sufficient length for proper execution of the merge or diverge process. In addition, they do not offer adequate flexibility in design. Based on the study findings, new design procedures for freeway speed-change lanes, which will alleviate these deficiencies, have been developed and are recommended for acceptance by the AASHTO Task Force on Geometric Design.

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SUMMARY OF FINDINGS

The primary purpose of this research was to evaluate the design guidelines for freeway speed-change lanes and develop new criteria, which offer greater flexibility than the current AASHTO (1984)[a] design guidelines. The current design standards do not provide the designer with the ability to reflect important geometric and traffic conditions. In order to define new guidelines, however, a thorough understanding of the entry and exit processes was essential. Current speed-change lane design criteria, including those of AASHTO, are based essentially on the acceleration and deceleration characteristics of early model vehicles, and to a lesser degree, on traffic flow characteristics or driver behavior.

The major tasks of the research included the collection of data on the entry and exit processes, development of models to describe these processes, and the formulation of design guidelines based on the entry and exit models. Data were collected at 35 sites in three states using videotape. The data of interest were extracted from the videotape in a laboratory environment. The videotape allowed the researchers to closely observe the entry and exit processes, control the sampling process, and review site characteristics.

The entry and exit models which were developed were based on driver behavior and traffic flow characteristics observed in the field and on known human factors. Both models were divided into several components in which certain driver tasks were performed. Figure 1 diagrams the entry process and defines the various components of the entry model. The entry model components are defined as:

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[a] Throughout this report, reference to AASHTO standards and guidelines is frequently made. Normally, this reference denotes the 1984 AASHTO Green Book entitled, A Policy on Geometric Design of Highways and Streets. Reference to other versions of AASHTO or AASHO guidelines will be given as AASHTO (1973) or AASHO (1965).

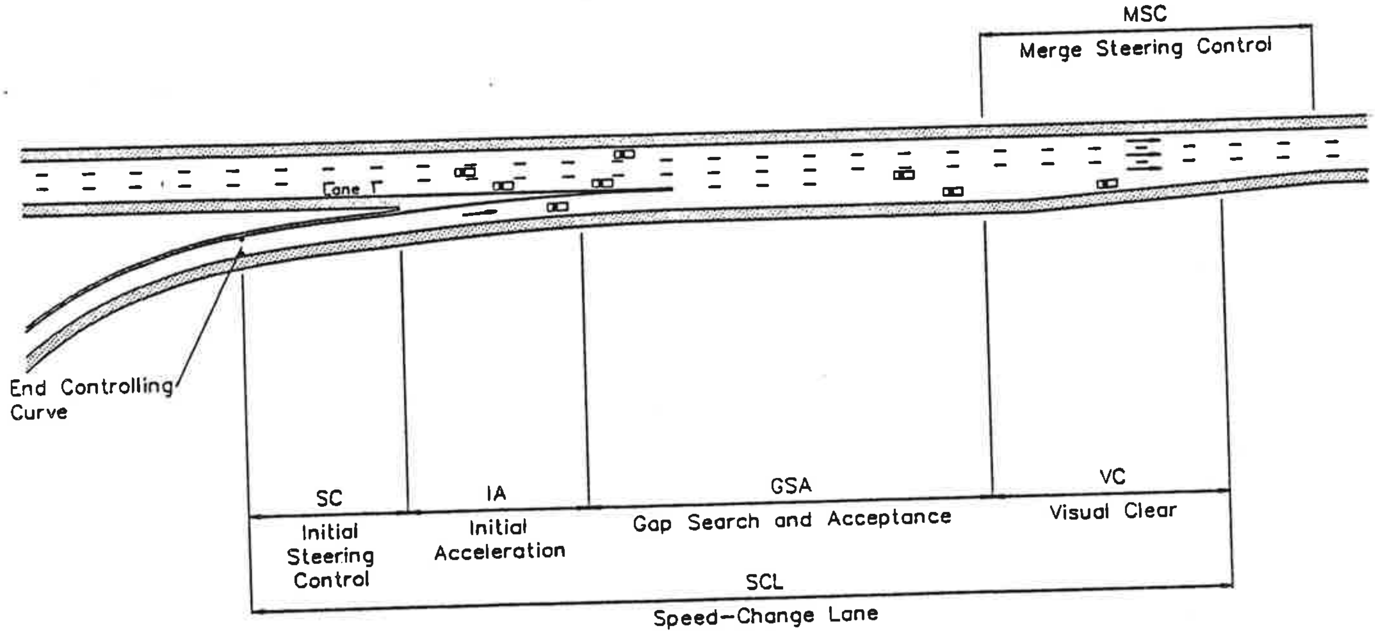

FIGURE 1

THE ENTRY PROCESS

1. Steering Control Zone (SC) which involves the steering and positioning of the vehicle along a path by steering from the controlling ramp curvature onto the speed-change lane.
2. Initial Acceleration Zone (IA) in which the driver accelerates to reduce the speed differential between the ramp vehicle and the freeway vehicles to an acceptable level for completing the merge process.
3. Gap Search and Acceptance Zone (GSA) during which the driver searches, evaluates, and accepts or rejects the available lags or gaps in the traffic stream. This zone is the key component of the entry model.
4. Merge Steering Control Zone (MSC) during which the driver enters the freeway and positions the vehicle in Lane 1. This zone, however, is not considered a determinant of the speed-change lane length.
5. Visual Clear Zone (VC) which provides a buffer between the driver and the end of the acceleration lane. Once a driver reaches this zone, he must take one of two actions, either merge onto the freeway in a forced maneuver, or abort the merge process and begin to decelerate at a reasonable rate.

The components of the exit model are defined as:

1. Steering Control Zone (SC) in which the driver steers and positions a vehicle from the freeway lane onto the deceleration lane.
2. Diverge Steering Zone (DS) which is the distance upstream from the exit gore[b], at which a driver begins to diverge from the freeway.
3. Deceleration in Gear Zone (DG) in which the vehicle decelerates prior to braking.
4. Deceleration While Braking Zone (DB) in which braking occurs in order to reach a reduced speed dictated by the geometrics, terminus, or traffic conditions on the off-ramp.

A diagram of the exit process is given in Figure 2.

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[b] The Research Team recognizes that the term "gore" is a commonly used term, however, it is felt that this term has negative connotations and does not accurately depict the geometric feature as well as the term "wedge" might. The Research Team suggests that the AASHTO Task Force on Geometric Design, consider replacing the existing terminology "gore" with "wedge." The term "wedge" is used throughout this report.

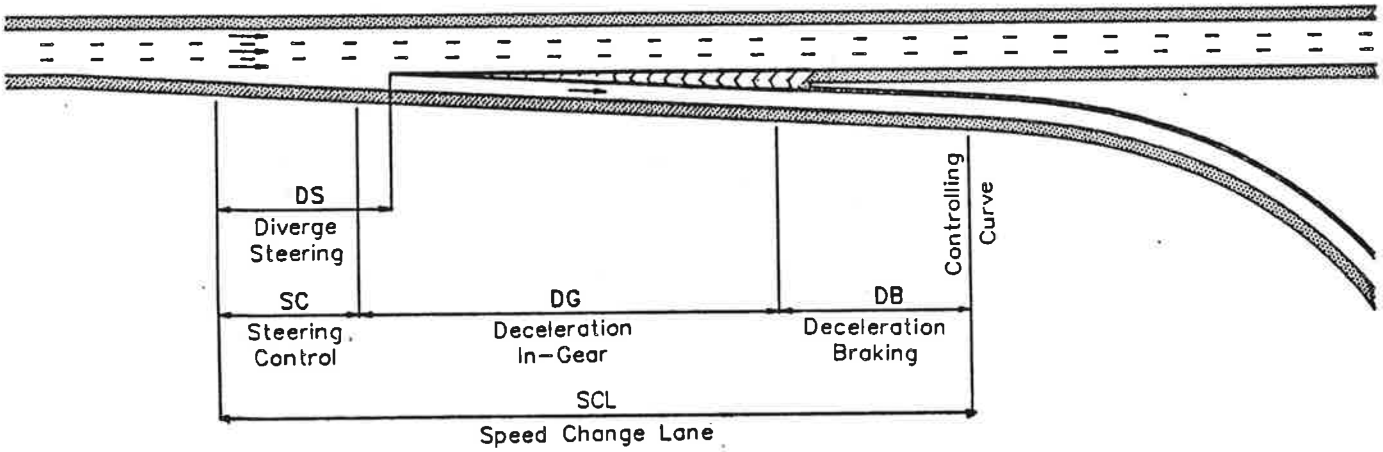


FIGURE 2

THE EXIT PROCESS

For each model, a series of equations was developed to determine the length of each zone. Certain design factors, such as grade, vehicle type, horizontal curvature, and traffic volume were built into each model. Each model was tested for sensitivity to variation in certain key components. Based on these results, the elements in each model were defined as either constant or variable in order to reflect the desired design factors. Field data were used to calibrate and validate certain components of each model.

Preliminary design values were generated for both the acceleration and deceleration lanes using the models. A limited example of the design values produced by the entry and exit models is provided in Table 1. These values represent several speed combinations for a single design condition. This condition comprises a passenger car on level grade, within an urban/suburban traffic environment. The models are capable of covering a wide range of design variables, including freeway and ramp speeds, grade, vehicle type (passenger car or truck), and traffic volume. The design values produced by the entry model for speed-change lane length, when compared to the current AASHTO values were slightly lower at low freeway speeds and significantly higher at moderate to high freeway speeds. The exit model values for length were significantly higher than AASHTO for all freeway and ramp speeds.

TABLE 1

EXAMPLE RECOMMENDED DESIGN VALUES

Acceleration Lane Length (ft.)

V'_f	v'_o = 15 mph v'_{r_1} (mph)			v'_o = 30 mph v'_{r_1} (mph)		
(mph)	40	50	60	40	50	60
70	2,550	2,025	2,400	2,475	1,975	2,425
60	1,750	2,025	*	1,675	1,975	*
50	1,700	*	*	1,625	*	*

* For this design condition, use next lowest value of v_r

V'_f = Freeway speed

v'_o = Initial ramp speed

v'_{r_1} = Ramp speed at beginning of GSA zone

Deceleration Lane Length (ft.)

V'_d	V'_c (mph)		
(mph)	15	30	50
70	1,035	825	825
60	730	730	535
50	630	630	435

V'_d = Freeway diverge speed

V'_c = Ramp controlling speed

1. INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Currently, in the design of freeway speed-change lanes, most state highway agency standards and certainly the standards of the American Association of State Highway and Transportation Officials (AASHTO) are based on vehicle characteristics taken from 30 to 40 years ago. Clearly, the characteristics of todays vehicles on the freeway are different from those of decades past. Such factors as truck size, acceleration, and deceleration characteristics of heavier vehicles, the increase of recreational vehicles, and the power characteristics of smaller automobiles, need to be updated and applied to speed-change lane design guidelines.

The degree of explicit knowledge required by the practicing professional designing the speed-change lane is unclear. The designer of todays speed-change lanes needs to make certain specific design decisions, including some for which design standards have not been developed. It is necessary then to determine which design standards are important to the designer and which need not be explicitly defined. In addition, little information is available on how the designer should analyze the performance of a speed-change lane. Definition of performance standards and criteria is essential for the designer.

The interaction of roadway, driver, and vehicle is the key element in establishing a performance model for speed-change lanes on freeways. Those characteristics of drivers which affect speed-change lane operations need to be identified.

Finally, although design guidelines are available for speed-change lanes, a set procedure for adapting these guidelines to local conditions has not been available.

Too often in the past, we have pretended that a set of values in a look-up table were set in concrete and that local conditions creating changes in driver and vehicle behavior should be ignored. A procedure is required which will allow the designer the capability of calibrating the design standards using local conditions. This research was intended to address these problems and produce design guidelines which lead to more appropriate speed-change lanes on freeways.

RESEARCH OBJECTIVES AND SCOPE

The objective of this research was to examine the current design parameters which establish speed-change lane length. The major research elements undertaken to achieve this primary objective were: 1) review current design practices, vehicle performance characteristics, and driver behavior data, 2) recommend design procedures and values for specific applications on freeway speed-change lanes, and 3) prepare a standard design guide tailored to highway designers.

Items which were incorporated into this research included traffic volumes, gradient, vehicle type, sight distance, terminal types, and driver-roadway-vehicle interaction. Considerable emphasis was placed on actual field data in order to reflect the conditions of the 1980's.

Key issues which were addressed by this project included determination of the level of detail of design factors required by the designer, actual problems observed and reported on freeway speed-change lanes, determination of measures of effectiveness with which to analyze performance, and definition of current vehicle characteristics on the freeway. The importance of new field data was of significant concern and data collection and analysis was given a high level of effort.

RESEARCH APPROACH

The general approach to this research included four elements: 1) examination of current speed-change lane design criteria and identification of any deficiencies which exist; 2) examination and update, if necessary, of current vehicle performance characteristics which might influence speed-change lane design; 3) development of a thorough understanding of the freeway entry and exit process, particularly with respect to driver behavior and traffic flow characteristics; and 4) development and testing of models which will adequately describe the entry and exit processes. To accomplish these general goals, a set of detailed tasks were defined and followed. Figure 3 presents a flowchart of the tasks completed as part of this research. A more detailed description of each of the major tasks is provided below.

To gain an indication of operational and design problems associated with current speed-change lane guidelines, pertinent literature and on-going research were reviewed, and the design experience of state, federal and consulting engineers was surveyed. Detailed surveys of selected design engineers were performed as part of this task. An additional objective of this task was to gather the most up-to-date data on vehicle characteristics, including acceleration and deceleration rates, vehicle dimensions, and vehicle population. These data were used to develop recommendations for design vehicles which would be used in the model development. In order to better understand the entry and exit processes, field observations at 35 sites with varying traffic and geometric conditions were made. The data collected in the field were used to identify and quantify the key variables in the entry and exit processes for use in the development of appropriate models. It was important to collect not only operational data such as speed differences between merging and freeway vehicles, acceleration and deceleration rates, and headways accepted for

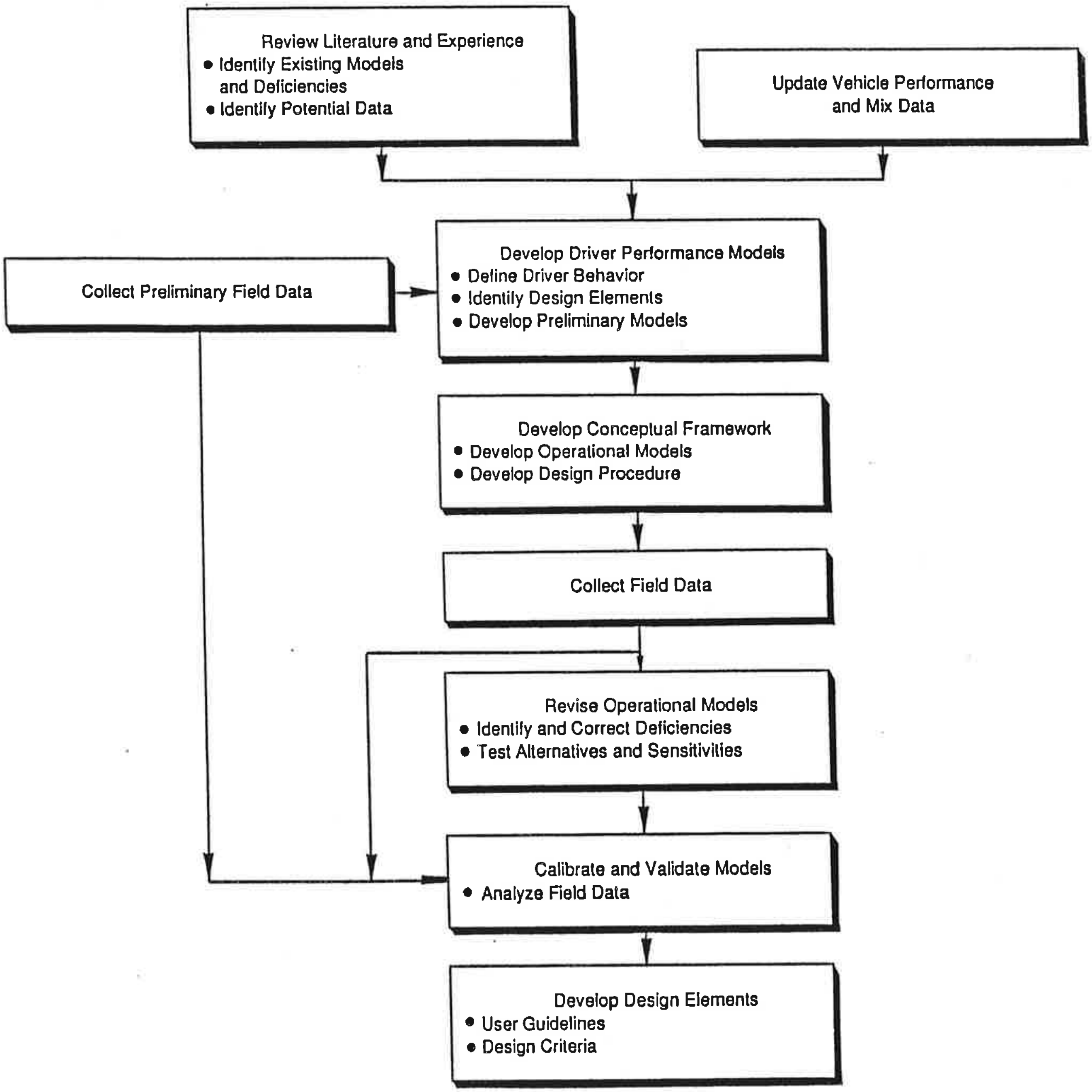


FIGURE 3

RESEARCH APPROACH - NCHRP 3-35

merge, but also to observe driver behavior and provide insight into the actual steps occuring during the entry or exit process. These data were used to define the entry and exit design cases.

Finally, the field data and established driver behavioral concepts were used to develop entry and exit models. These models were tested and calibrated using field data. Additional discussion on the research approach is given in Appendix C.

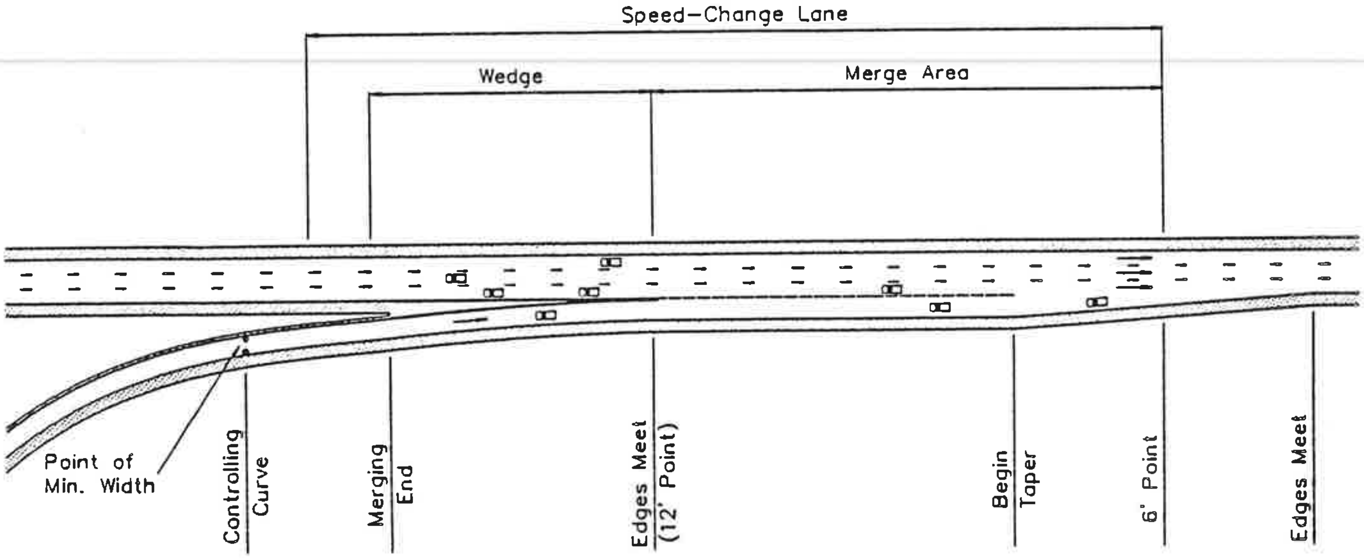
2. FINDINGS

DYNAMICS OF THE ENTRY PROCESS

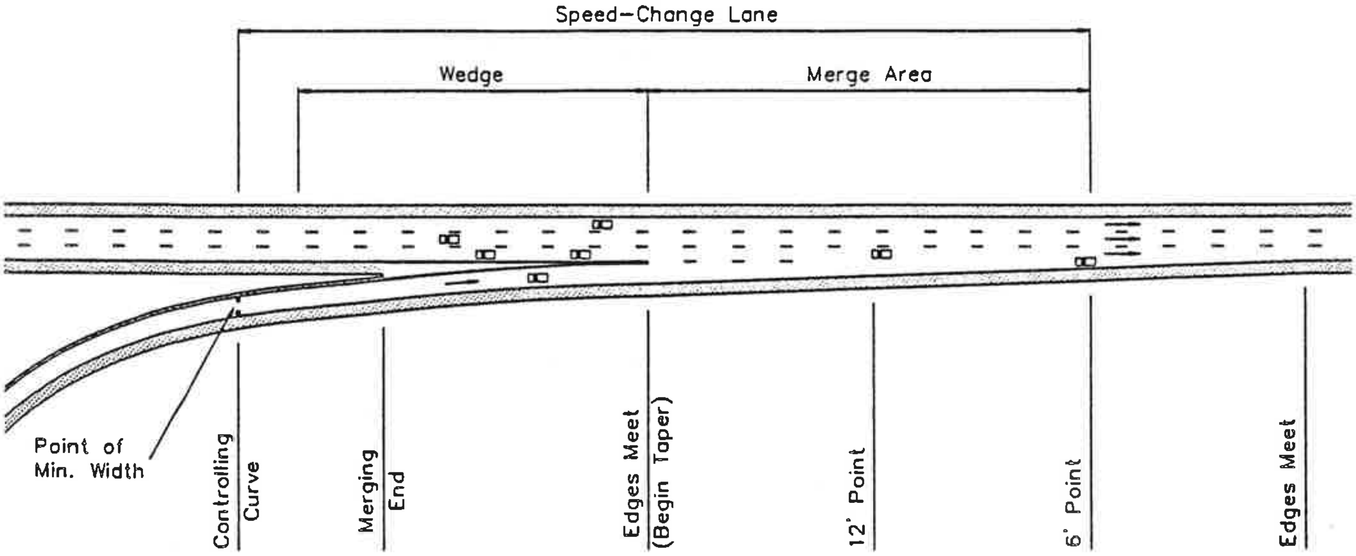
The process of changing from one facility to another, via a ramp, requires drivers to make a series of decisions and carry out control tasks, all within the capability of the driver to process the information and respond appropriately. It is the job of the designer to understand the dynamics of these phenomena and design the transition geometry that will facilitate, rather than complicate the driver's control task. Figure 4 illustrates typical acceleration lane designs and identifies certain key elements of each design.

The movement between facilities, along a ramp, involves successive navigational decisions, pursuit tracking, positional control relative to other vehicles and roadway elements, and gap search and acceptance operations. In some instances, the driver may be doing more than one of these tasks in a time-sharing mode. Each step involves the driver's capacity to both process information from roadway and traffic and translate that information into speed and position control responses on the vehicle. A fundamental issue is to specify the essential information the driver needs to safely and efficiently accomplish the required lateral and longitudinal positioning, both in space and time along the speed-change lane. The remainder of this section seeks to resolve this issue, developing an analytical framework for the design of a specific portion of a ramp -- the acceleration lane. Throughout the discussion of the entry model, the term acceleration lane is used in lieu of speed-change lane in order to minimize confusion between the entry and exit cases.

Traversing a ramp involves navigational decisions from the initial approach to the acceleration for entry to the freeway. Upon entering onto the lane, the driver



PARALLEL DESIGN



TAPERED DESIGN

FIGURE 4

TYPICAL ACCELERATION LANE DESIGNS

must adjust speed to meet the controlling conditions of the ramp. As the vehicle reaches a speed appropriate for the ramp curvature and superelevation, the driver enters a pursuit tracking mode, in which the speed and steering are adjusted to curvature on the basis of both visual and kinesthetic cues. As the acceleration lane is approached, there usually is a transition to a flat curvature, or tangent section, to allow the vehicle to accelerate to near freeway speed. It is in this section that the driver also initiates a search for an acceptable lag, or headway, in Lane 1 of the freeway, into which the vehicle must finally be steered. Finally, the driver must also determine the ramp terminus location so as to decide on any possible maneuvers required as it is approached.

The Entry Process

The entry process is considered to begin when the ramp driver is able to initiate the steering control actions to transition from the curvature of the ramp to the flatter geometry of the acceleration lane. The driver must respond to changing curvature and direct the vehicle to a straighter path. The driver may then initiate acceleration in order to approach anticipated freeway speed. As the driver approaches the merging end, the traffic in Lane 1 of the freeway becomes visible and at an angle and speed differential that allows the driver to begin to evaluate the headway situation.

Figure 5 contains a simple diagram of the situation that occurs as a ramp vehicle approaches the merging end and considers the headway that is present. The ramp vehicle must ultimately fit between Vehicles 1 and 2, or allow Vehicle 2 to pass and then consider the following vehicle headways. Since Vehicle 1 is assumed to have passed the merging end prior to the arrival of the ramp vehicle, the ramp

	CASE 1	CASE 2
	Lag Acceptance	Lag Rejection
Condition	A $\geq$ Min. Car Following B $\geq$ Min. Acceptable	A $<$ Min. Car Following B $<$ Min. Acceptable
Potential Driver Actions	a) Move Immediately into Lag b) If Speed Differential is significant, May Accelerate Before Entry	a) Adjust Position to Trailing Headway(s) b) Acceleration into Lag (If Above Min. Car Following)
Comments		Case 2a is Most Probable, Especially if Speed Differential is Large
Length Requirements	Only lane change distances required	Distance to Adjust Position Relative to Trailing Vehicle For Case 2a, Distance to Search for Acceptable Trailing Headways

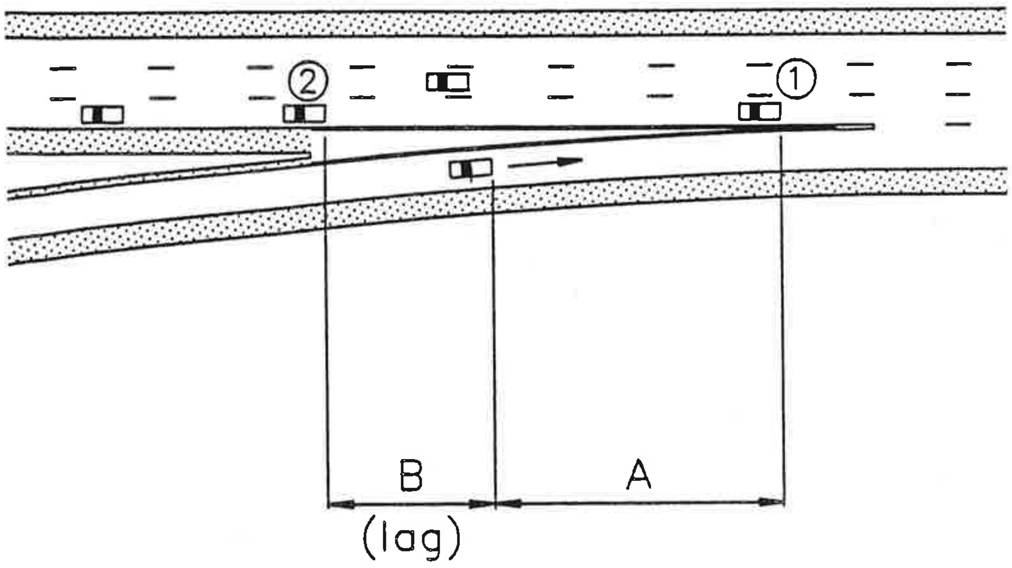


FIGURE 5

GAP SEARCH AND ACCEPTANCE CASES

vehicle initially is considering the remaining portion of the headway formed by Vehicles 1 and 2. This is referred to as the initial lag.

The driver of the ramp vehicle may determine that the initial lag is sufficiently long such that the vehicle may be moved into it. The acceptance of the initial lag will allow completion of the entry maneuver. This condition is shown as Case 1 in the figure. It is possible that, if the initial lag is very large, the driver could enter Lane 1 of the freeway while traveling significantly below the freeway operating speed. In such a case, the ramp vehicle would continue to accelerate to near freeway speed while in Lane 1 and while the spacing to the trailing vehicle is reduced (Case 1a). However, it is also possible that even though the ramp vehicle driver has accepted the initial lag, the driver may prefer to remain in the acceleration lane until the vehicle has attained a speed near freeway conditions (Case 1b).

For Case 1, the ramp needs be extended beyond the merging end only a distance required to allow the vehicle to move from the ramp to Lane 1 of the freeway. Additional distance may be provided if the hypothesized desire to enter at a low speed differential is considered necessary for driver comfort and convenience.

If the initial lag is insufficient for entry (Case 2), the driver must either allow the trailing vehicle in Lane 1 of the freeway to approach and pass the ramp vehicle so that the driver of the ramp vehicle may consider trailing headway (Case 2a), or accelerate sufficiently to increase the length of the lag (thus creating a new lag) to a point where it becomes acceptable (Case 2b). Either of these possibilities is considered a rejection of the initial lag.

For Case 2, the distances required include both that necessary to adjust the relative position of the ramp and trailing freeway vehicle, and that necessary (in

Case 2a) to search among, and accept trailing headways. These distances are in addition to the distance required to move from the ramp to Lane 1 of the freeway.

Design Condition

The critical issue is to decide for which traffic and roadway conditions an acceleration lane should be designed. This depends, of course, on the design objectives for a speed-change lane. AASHTO provides some useful guidance in this regard.

> "A speed-change lane should, as a minimum requirement, have sufficient length to enable the driver to make the necessary change between the speed of operation on the highway and the speed on the turning roadway in a safe and comfortable manner. Moreover, in the case of an acceleration lane, there should be additional length sufficient to permit adjustments in speeds of both through vehicles and entering vehicles so that the driver of the entering vehicle can position himself opposite a gap in the through traffic stream and maneuver into it before reaching the end of the acceleration lane. The latter requirement has much to do with both the configuration and length of an acceleration lane" (1).

While AASHTO has adequately defined the minimum operational requirements for an acceleration lane, there are other elements which should be considered:

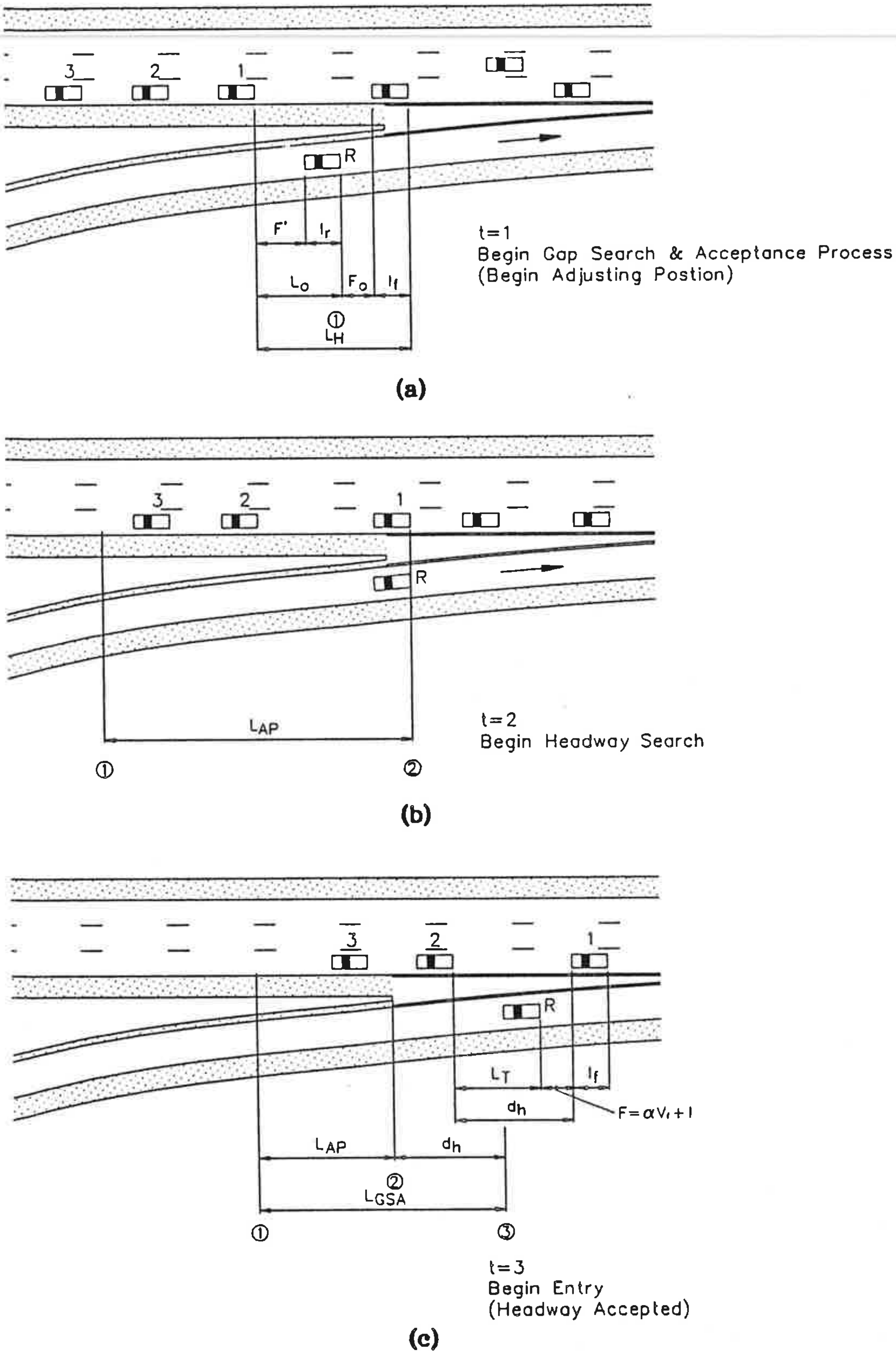
1. Minimize disruption to the freeway flow,
2. Meet driver expectations, and
3. Avoid overlapping control requirements for the driver

The design objectives noted above must be met for most drivers. This means that a majority of drivers will be able to complete the entry maneuver in a shorter length and/or easier manner than is designed for. For the purposes of this effort, a driver representative of the 85th percentile is generally used. Therefore, the design case should be one which has a greater length than required by most drivers.

Considering Case 1 (see Figure 5), the length required in order to immediately enter the freeway, is not as great as for Case 2, because the latter involves additional distances to search for and accept a headway. Case 2a is considered most appropriate for design because Case 2b would only be likely to control when speed differentials are great. However, when speed differentials are large, it is not likely that the driver will choose to accelerate. This is confirmed from observations of driver behavior at the sites which were filmed.

Figure 6 characterizes three points in time (begin gap search and acceptance, begin headway search, and begin entry), which occur during the entry process for the design condition. Figure 6a depicts the ramp vehicle as it approaches the merging end (time t=1). The vehicles in Lane 1 of the freeway are in view so that the ramp driver can assess the situation. The headway (L_H) is divided into the initial lag (L_o), the gap to the lead freeway vehicle (F), and the length of the lead freeway vehicle (l_f). The initial lag is divided into the car following gap (F') and the length of the ramp vehicle (l_r).

The driver of the ramp vehicle assesses the initial lag and determines, for the design case, that it is insufficient. The driver further decides that the vehicle must be positioned adjacent to the trailing Lane 1 freeway vehicle to begin considering trailing headways. This may involve deceleration, reduction of acceleration, maintaining current acceleration, or increasing acceleration, as the conditions (primarily speed differential) may dictate. It is assumed that the freeway vehicle maintains a constant speed across the entry area. This facilitates the objectives regarding impact on the freeway of the operation of the speed-change lane. It



t=1
Begin Gap Search & Acceptance Process
(Begin Adjusting Postion)

t=2
Begin Headway Search

t=3
Begin Entry
(Headway Accepted)

FIGURE 6

ENTRY MODEL DESIGN CASE

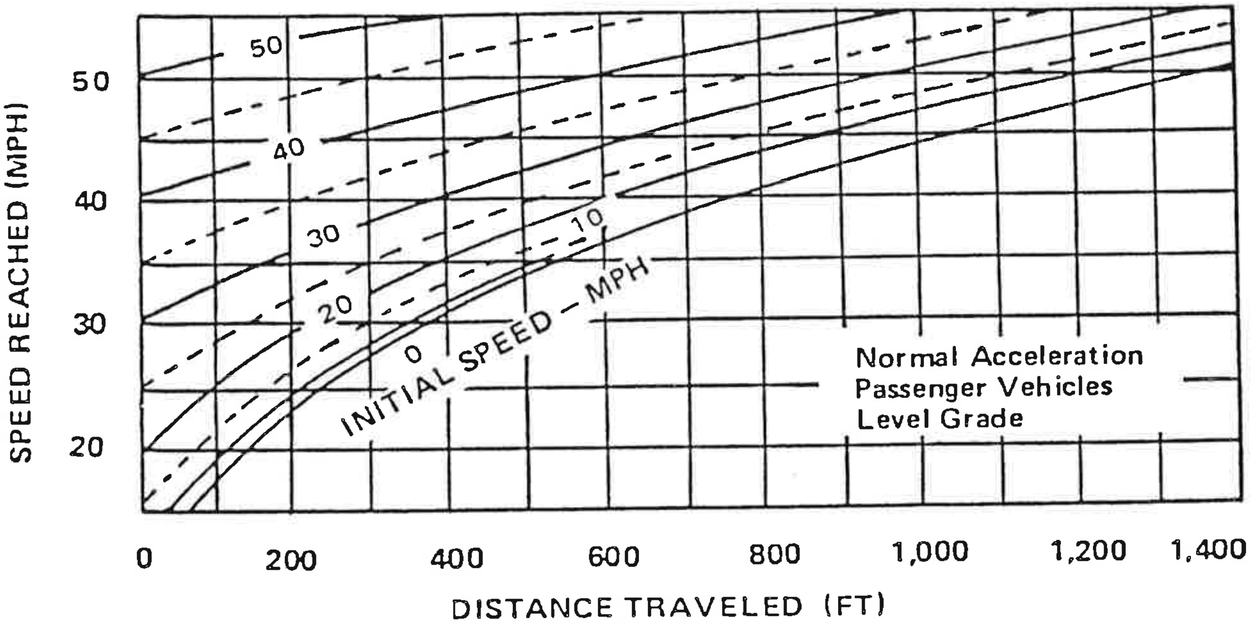
should be noted, however, that observation in the field showed significant accommodation of the ramp vehicles by Lane 1 freeway vehicles.

Figure 6b depicts the condition at the point where the ramp vehicle has been positioned adjacent to the trailing freeway vehicle in Lane 1. The vehicle has traveled a certain distance (L_{AP}), while moving to this relative position. The ramp driver is now in position to begin considering trailing headways. The distance traveled while searching for, and accepting, a headway is d_h. The moment at which the headway is accepted is depicted in Figure 6c. It is at this point that the driver of the ramp vehicle may initiate steering control to enter Lane 1 of the freeway.

It is concluded that this process best describes the dynamics of vehicle entry to a freeway from a ramp for design purposes. The objective is to model this process in a validated and calibrated form, which allows it to be applied for design purposes. The modeling is the subject of the remainder of this section. A brief discussion of previous attempts to model and study the entry process is given, so that the reader has a basis for comparing and assessing models developed in this research.

Review of Previous Models of the Entry Process

Acceleration Models. The current AASHTO approach to design of acceleration lanes uses an acceleration model. The policy provides a table of acceleration lane lengths for various combinations of highway and entrance curve design speeds. The lengths are based upon the distance required to accelerate from the initial speed associated with the design speed of the entrance curve to the "speed reached" (defined as the approximate running speed on the freeway less 5 miles per hour). The distances are determined using "normal" acceleration rates (Figure 7). These vary from 1.5 to 3 feet per second per second. They are said, by



Source: 1984 AASHTO Green Book (1), Figure II-12, Page 36

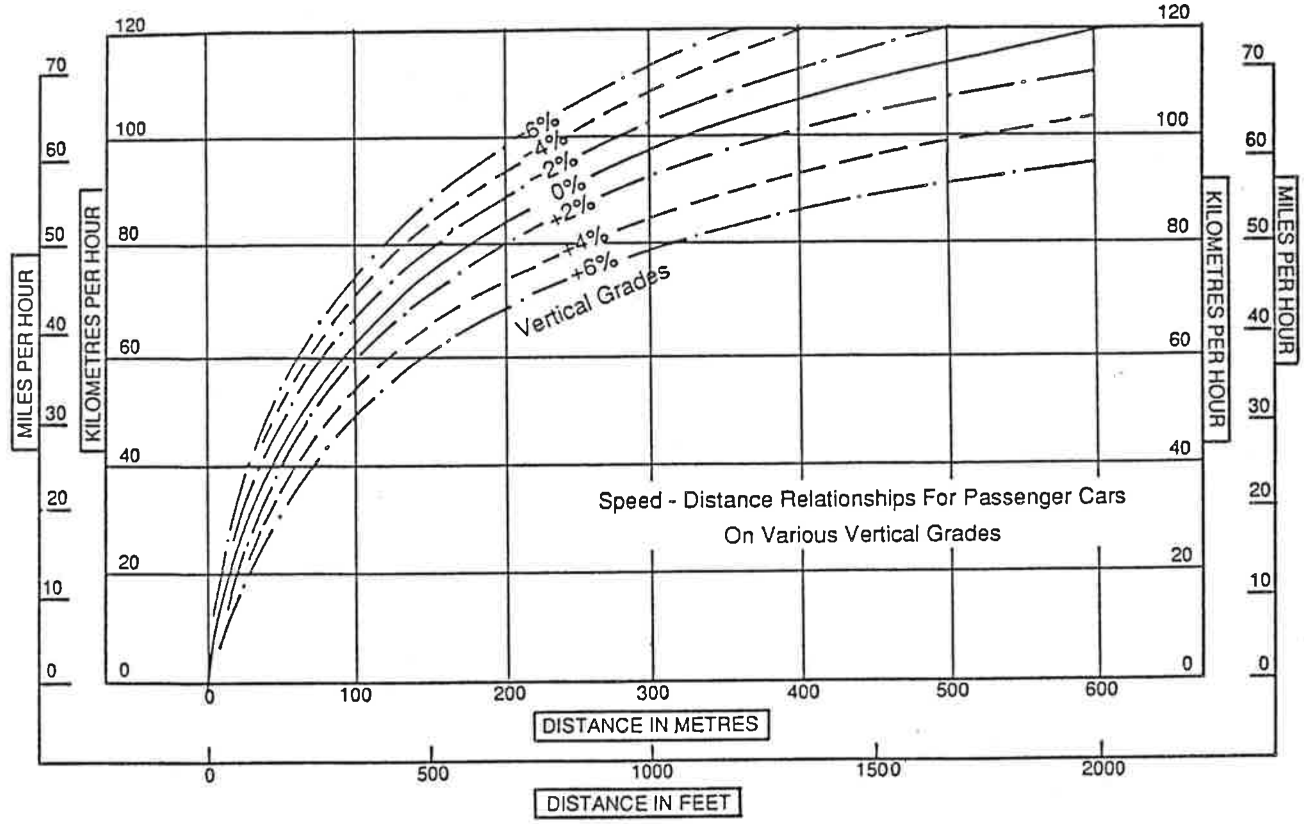
FIGURE 7

ACCELERATION DISTANCES FOR PASSENGER CARS ON LEVEL GRADE

AASHTO, "to depict... the low-horsepower (compact) car or the loaded truck or bus" (2). While the acceleration lane length is based solely on the acceleration calculation, there is a seemingly arbitrary requirement that at least 600 feet of the acceleration lane be placed downstream of the merging end. The current AASHTO policy states that for high volume conditions, the acceleration lane length would desirably be at least 1,200 feet, plus taper.

The current AASHTO policy notes that a portion of the acceleration lane may be placed upstream of the merging end where the radius of the curve is at least 1,000 feet. The concept of acceleration and speed patterns of the entering vehicle being tied directly to the geometry approaching the entry and through the acceleration lane, is carried further in a 1981 FHWA unpublished research document (3). In this manual, a graphical technique is presented which allows the designer to develop a running speed profile which is constrained by the curvatures and superelevations, as well as the assumed accelerations and decelerations of the design vehicle. The manual provides a tool for not only determining the length of acceleration lane required for a given ramp geometry, but also assists in identifying where geometry may be improved for a smoother speed profile. There are no special guidelines given for the portion of the ramp which must be contiguous with the freeway (i.e., downstream of the merging end). The acceleration rates are taken from the Transportation and Traffic Engineering Handbook (4). An example of the curves for acceleration from a stopped condition are reproduced here as Figure 8.

Lag/Gap Acceptance Models. A number of traffic flow theorists have developed both stochastic and deterministic approaches to gap acceptance at intersections and ramp entries. For the most part, the application of these theories



Source: BAKER (3), Figure 43, Page 87

FIGURE 8

NORMAL ACCELERATION - INITIAL SPEED 0 km/hr (0 mph) to entrance ramps has involved the extension of the relatively simple case of a single vehicle, having assumed gap acceptance characteristics, considering a stream of headways past a single point. A few examples are discussed below to indicate the nature of these approaches and their potential application to design.

Drew (5), in his text on traffic flow theory, uses data from Texas freeways to derive a relationship for predicting the critical gap based upon the length of the acceleration lane (merging end to end of taper) and the angle of merge (not precisely defined). This critical gap is then used to determine a maximum service volume or possible capacity for the ramp. Examples of the resulting curves are shown here as Figures 9 and 10. The capacity is determined from a relationship which assumes a stationary vehicle considering a crossing stream of headways distributed according to an Erlang function.

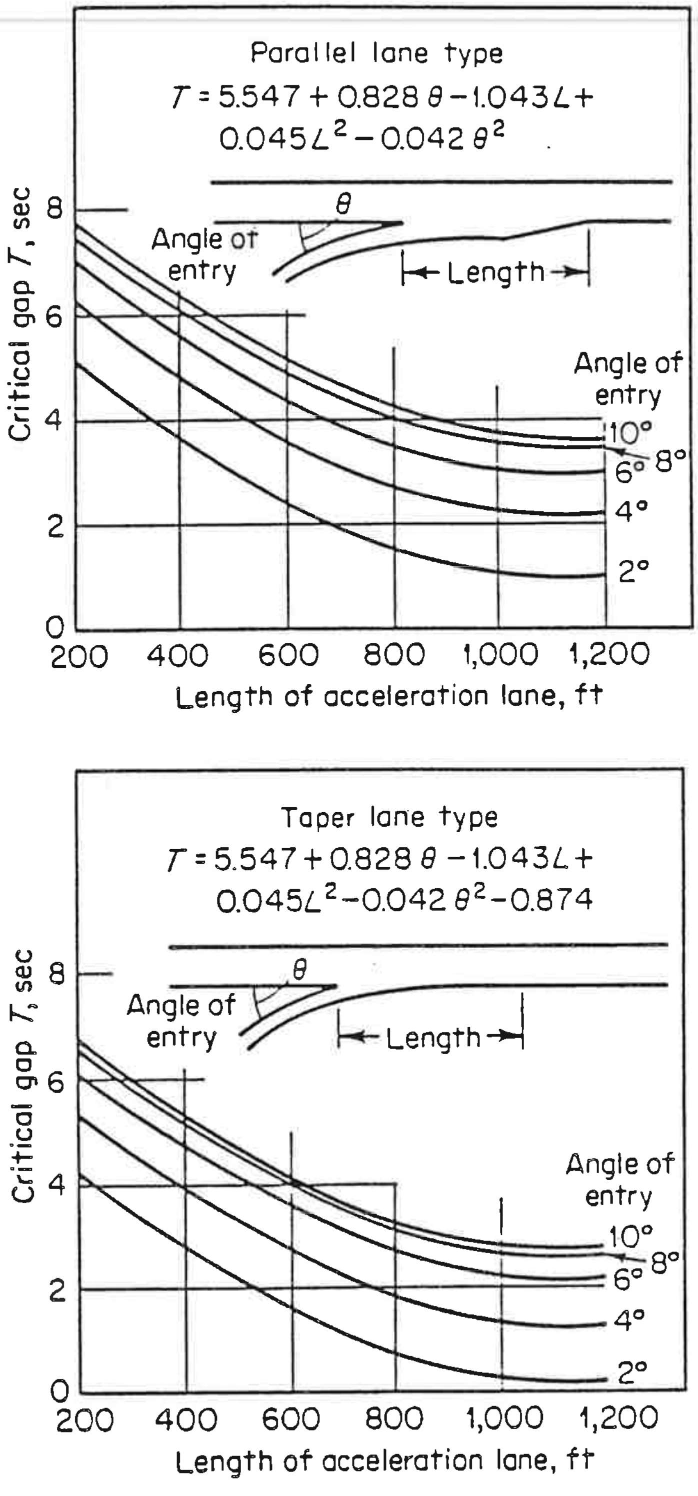
Major and Buckley (6) developed a delay criterion for entry into a traffic stream. This is applied to a stream of vehicles, each of which must stop before entry into the traffic stream. The delay estimate is accomplished by development of a function using a basic gap acceptance model for stationary vehicles at a crossing roadway. The resulting estimate of mean delay to vehicles is shown in Figure 11. The analysis allows for an estimation of the effect of entry stream volume on the delay to entering vehicles. Blumenfeld and Weiss (7) extend this to moving vehicles on a ramp seeking entry to a traffic stream. The conversion to a moving stream analysis is accomplished by introducing the speed differential term:

$$\beta = 1 - \frac{v}{V}$$

Where,

v = speed of ramp vehicle

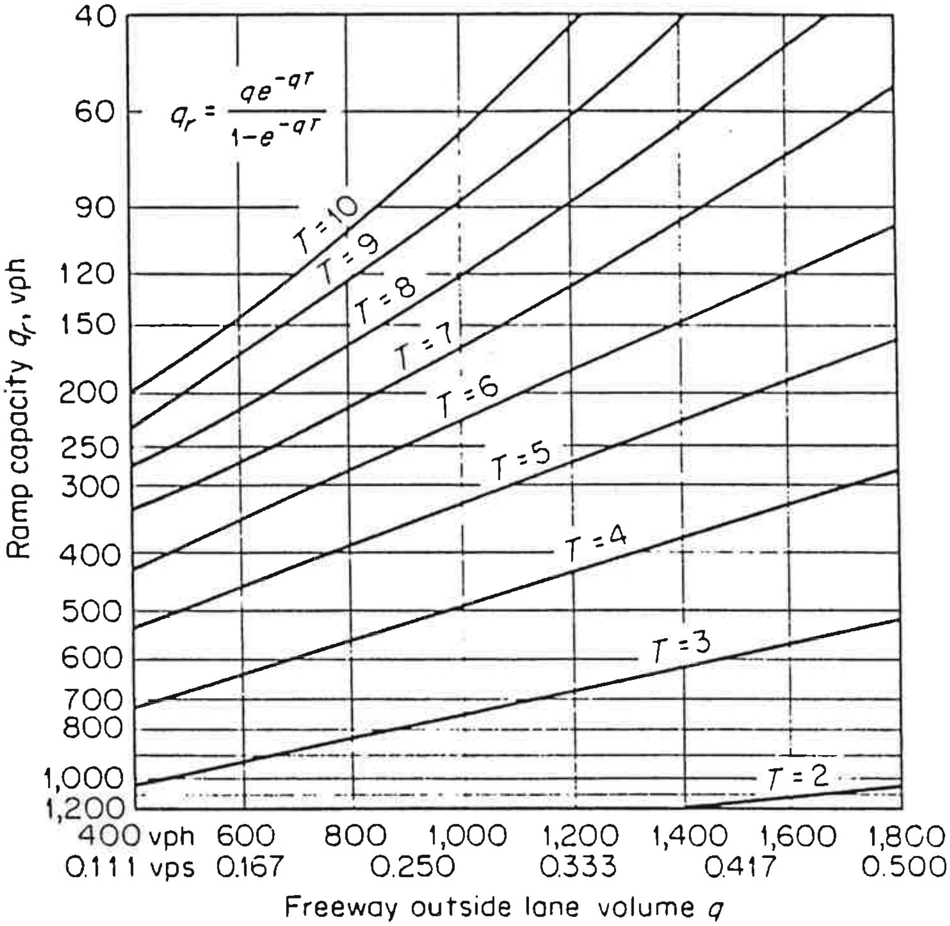
V = speed of freeway vehicles in Lane 1.



Source: Drew (5), Figure 9.25, Page 219

FIGURE 9

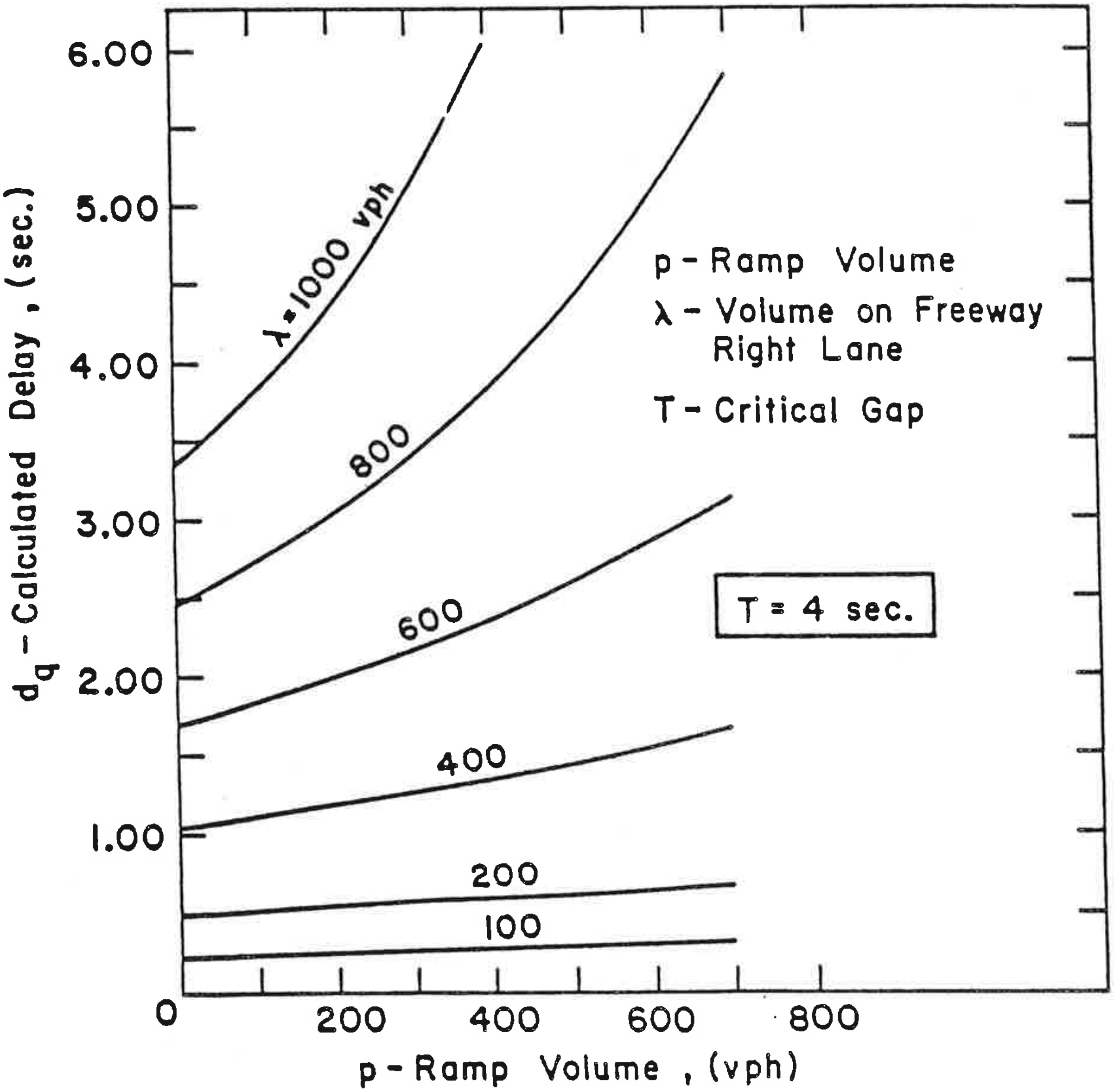
CRITICAL GAP T BASED ON ENTRANCE RAMP GEOMETRICS



Source: **Drew (5), Figure 9.22, Page 217**

FIGURE 10

POSSIBLE CAPACITY OF MERGING AREAS



Source: Major and Buckley (6), Figure 1, Page 208

FIGURE 11

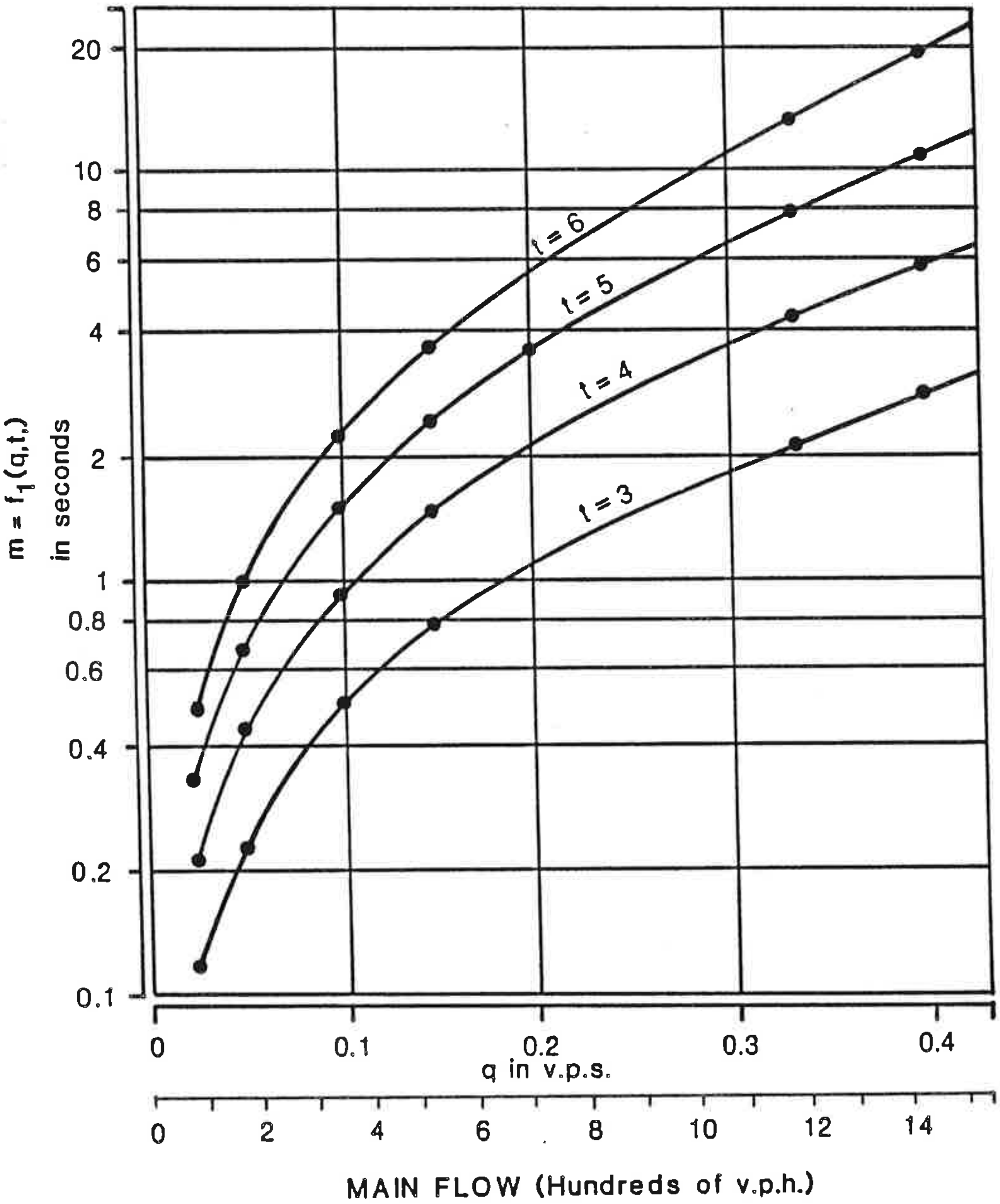
MEAN DELAY TO VEHICLES ENTERING A TRAFFIC STREAM

Polus and Livneh (8) utilize the models suggested by Major and Buckley and apply the beta term suggested by Blumenfeld and Weiss to calculate the delay experienced by a ramp vehicle which is associated with a high probability of accomplishing a merge (i.e., finding an acceptable headway). An example of the results is shown here as Figure 12. Appendix B contains further details on the use of this term and its application in this project.

Design, Operational, and Human Factor Considerations

The entry process, as defined in this report, is a complex patterning of driver behavior. Obviously, any random or unpredictable event that deviates from a driver's learned expectations will disrupt the processing of information and timing of response. Such disruptions can result from unique events on the acceleration lane, unexpected behavior of other drivers either on the acceleration lane or on the freeway, or geometric conditions on the ramp or acceleration lane that significantly deviate from driver expectations. Therefore, it becomes clear that the objective of design is to provide a static and dynamic environment that has maximum predictability for the driver. Any undesired information, variability in the environment or disruption of the patterning of driver behavior tend to overload the driver. Ideal design is one which minimizes the likelihood of overload and is adapted to the behavioral requirements of the entry process. Several design elements which would affect the merge process are described below.

Ideally, the curve or tangent section connecting the ramp to the acceleration lane should be continuous, of constant radius or taper, and with a natural terminus in the acceleration lane. Any lesser design creates an unexpected condition for the driver and will increase steering control complexity. The driver must carry out a corrective steering maneuver in order to align the vehicle properly on the



Source: Polus and Livneh (8), Figure 4, Page 14

FIGURE 12

CALCULATED DELAY FOR VARIOUS RAMP VOLUMES AND FREEWAY RIGHT-LANE VOLUMES acceleration lane. A lesser design would increase the distance required for steering onto the acceleration lane, or at least, shift the whole entry process further down the acceleration lane. A proper design would allow the driver to smoothly transition from the ramp curvature onto the acceleration lane with a minimal amount of steering. It is important that the angle of divergence of the wedge area is properly defined for the driver, either physically or with lane markings. Lane markings in general are of high visibility and are continuous indicators of geometry for drivers.

The wedge area of the ramp can be variable in design. Clearly, if the wedge is extended physically or by paint, it inhibits drivers from immediate entry onto the freeway lane. Proper design of the wedge area can reinforce the initial acceleration phase of the entry process and provide better overall operation of the acceleration lane.

Optimally, the tangent section of the acceleration lane, or at least that section in which the driver begins to observe Lane 1 of the freeway, should be of level or slight grade, (between +2% and -2%). This design would minimize the presence of higher order motion vectors which the driver must sort through and analyze. Another means of improving the driver's capability of handling the entry process is to provide an unobstructed view of approaching freeway traffic. Physical obstructions such as guard rails, signs, or vegetation should be placed so as not to inhibit the driver's field of vision. This allows the driver to direct more time to the task of merging and to avoid time sharing with other objects in the visual field.

The entry process, as described in the previous section, is based on driver response to various geometric and traffic conditions present on the entry ramp and the freeway. Therefore, in defining a model which describes the entry process, it is reasonable to consider known elements of driver behavior. Summarized below are several human factors which are useful in describing driver response during the entry process.

Angular Velocity Threshold

In attempting to enter a freeway from an acceleration lane, a driver observes nearby freeway vehicles which make up the gap into which the driver will eventually merge. Depending on the grade of the ramp, the position and velocity of the adjacent freeway vehicles are made up of first, second, and third degree motion vectors. Most evidence in the psychological literature, however, suggests that humans do not use higher order derivatives of motion (9). Therefore, the ramp driver is only capable of processing a first order motion vector when analyzing an adjacent freeway vehicle. Essentially, the driver of a ramp vehicle can evaluate the angular velocity of a freeway vehicle relative to the ramp vehicle. Simply stated, angular velocity is the rate of change of the angle of an object, either fixed or moving, relative to a driver. An example of angular velocity would be as a driver approaches a stationary vehicle at a traffic signal. As the driver approaches, the angle produced by the rear of the stationary vehicle, relative to the driver is constantly changing. The rate of change is defined as angular velocity. A more detailed description of angular velocity, for both the entry and exit cases is provided on Appendix B.

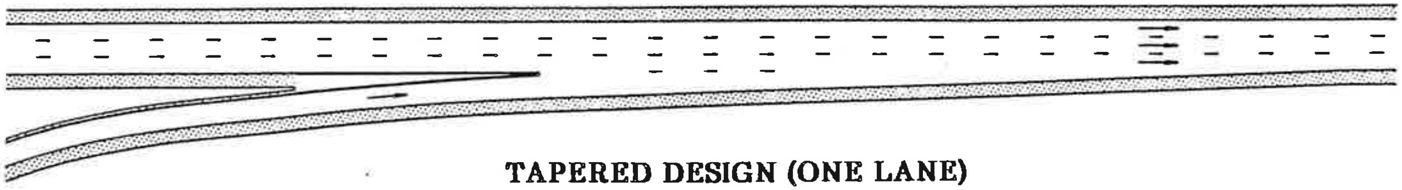
Based on this element of driver behavior, it is hypothesized that most drivers operate at some threshold level of angular velocity. The driver will only take action, such as merging into a freeway gap, when the angular velocity of the freeway vehicle is at or below the threshold of the driver. From previous research (10,11) there is empirical evidence that the angular velocity threshold of most drivers is in the range of 0.01 to 0.001 radians per second with a nominal value of 0.004 radians per second.

Time-Sharing of Driver Tasks

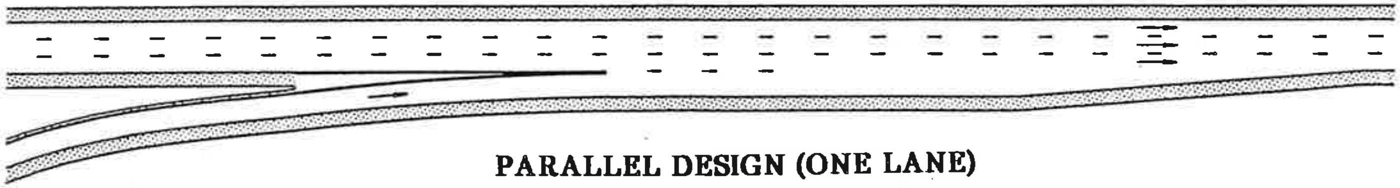
As described previously, a driver performs several different tasks during the entry process. These tasks include tracking of the ramp curvature, steering from the ramp curvature onto a tangent acceleration lane, accelerating from the ramp controlling speed up to a speed closer to the freeway speed, searching for an acceptable gap, and steering from the acceleration lane onto the freeway lane. Drivers, however, cannot perform two separate tasks simultaneously, rather, drivers will time-share between tasks. Therefore, a driver on the acceleration lane will alternate between accelerating and gap searching. This results not only in an increased distance necessary to complete the entry process, but also in a degradation in control and performance. In order to minimize this degradation, it is desirable to design an acceleration lane which would reduce the amount of time-sharing required by the driver.

Parallel and Taper Lane Designs

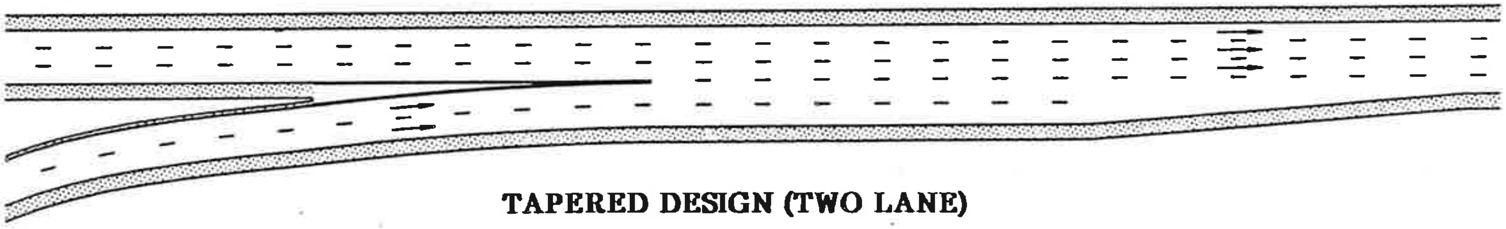
Considerable discussion has been given to the operational superiority of either parallel or taper lane designs. AASHTO (1984) notes a trend toward the preferential use of a taper design for acceleration lanes. Figure 13 illustrates typical parallel and taper design of single lane acceleration lanes. In theory, the taper design reduces the complexity of steering control tasks which a driver must perform during the entry process. The taper design provides a more direct entry onto the freeway lane, thus reducing the amount of steering control which must be carried out. However, the taper design also requires that the driver time-share between the task of searching for an acceptable gap and steering along the lane. Drivers might be



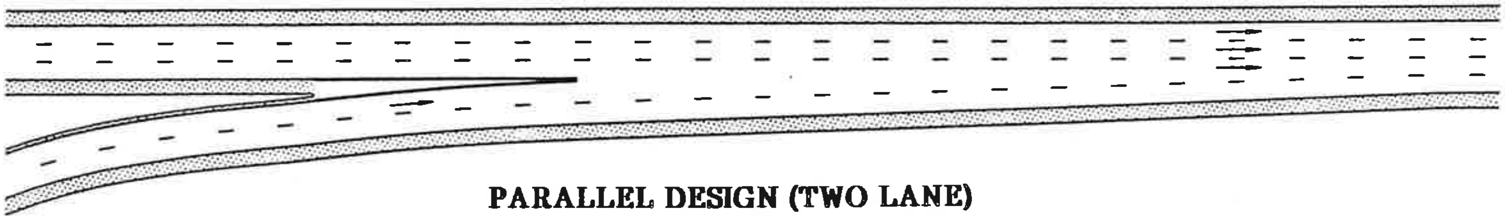
TAPERED DESIGN (ONE LANE)



PARALLEL DESIGN (ONE LANE)



TAPERED DESIGN (TWO LANE)



PARALLEL DESIGN (TWO LANE)

FIGURE 13

TYPICAL PARALLEL AND TAPERED DESIGNS
OF ONE AND TWO-LANE ENTRANCE RAMPS

forced onto the freeway before an acceptable gap has been located. This would be especially true on shorter taper design acceleration lanes.

Two-Lane Entrance Ramps

The entry process, as described above, is based on a single-lane ramp. However, the principles are also applicable to two-lane entrance ramps. Figure 13 also illustrates typical tapered and parallel designs for two-lane entrance ramps. These designs involve the addition of a lane to the freeway. In the case of the tapered design, the driver on the inside lane is required to merge, but onto the freeway, while the driver on the outside lane does not need to merge and enters the freeway on the lane being added. On the parallel design, the reverse is true, the driver on the outside lane is required to merge into the inside lane before entering the freeway on the added lane.

Operationally, the two-lane entrance ramp provides more potential problems for the merging driver. Improper use of the lanes by unfamiliar or overly aggressive drivers can reduce the efficiency and safety of the acceleration lane. It is important to delineate the lane assignments to the merging drivers so as to reduce the appearance to the driver of the need to merge twice, once into the inside acceleration lane and again onto the freeway.

Ramp Metering

Ramp metering usually increases the amount of acceleration required of the ramp vehicle in order to complete the entry process. In one respect, ramp metering can simplify the entry process, since the driver is usually aligned properly on the acceleration lane at the ramp meter. Thus, the driver has already completed the steering control necessary to transition from the ramp curvature to the tangent section. The ramp meter becomes the control point or the beginning of the acceleration lane. The ramp meter, however, must be positioned far enough upstream from the merging end to allow the driver to accelerate to an acceptable speed to begin the gap/lag search process. If the ramp meter is improperly designed or retrofitted, operational and safety problems will occur. Many drivers will enter the freeway at slower speeds than desired, causing disruptions to the freeway traffic flow, while others will remain on the acceleration lane until they have reached an adequate speed, increasing their likelihood of aborting the merge process.

A Model of Acceleration Lanes

Framework. The discussion of the operation of an entrance ramp is based upon the results of the literature review, field studies and conceptual developments conducted by the research team. In order to translate the findings into a working model, a basic framework is needed. This is accomplished by dividing the length, along which the entry process occurs, into zones, as depicted in Figure 14 and described below.

- L_{SC} - The steering control zone includes the distance required to steer and position the vehicle as it transitions from the ramp controlling curvature to the flatter geometry of the entrance ramp terminal area.
- L_{IA} - The initial acceleration zone is that length along which the driver accelerates to reduce the speed differential between the ramp vehicle and the vehicles expected to be in Lane 1 of the freeway, to a speed expected to be acceptable for beginning the gap search and acceptance process. The speed attained is constrained by the ramp geometry across this zone and the acceleration rate used by the ramp vehicle.
- L_{AP} - The adjust position zone is the length needed for the ramp vehicle to reject the initial lag and adjust position relative to the Lane 1 freeway

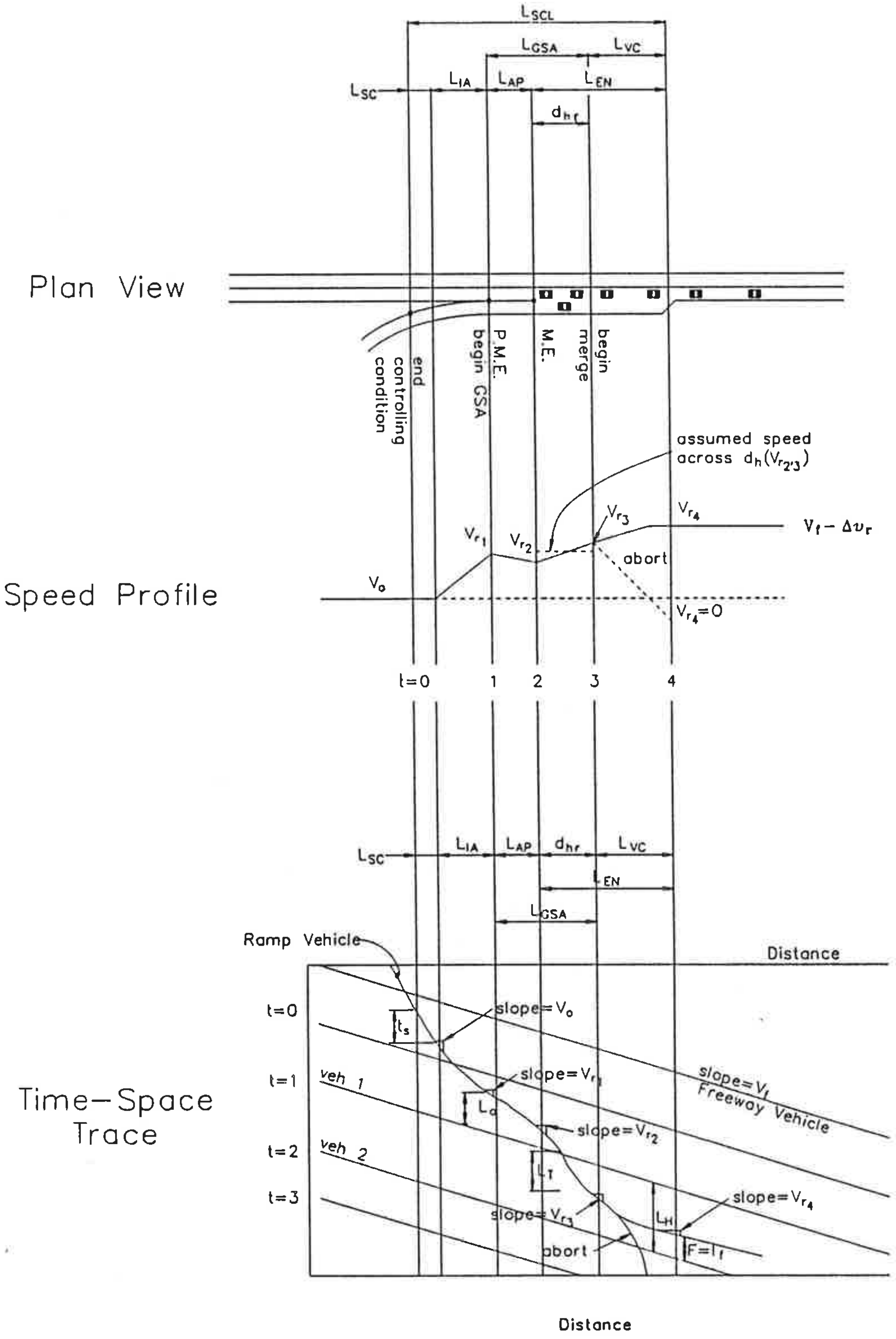


FIGURE 14

ENTRY MODEL FRAMEWORK

vehicle which forms the initial rejected lag. The zone begins when the ramp vehicle arrives at the point where the gap search and acceptance may begin.

- d_{hr} - The distance along the ramp required to search for, and accept, a headway is determined by considering the distribution of headways in Lane 1 of the freeway, the gap acceptance characteristics of the driver of the ramp vehicle, and the volume on the ramp. L_{AP} and d_{hr}, together, comprise the gap search and acceptance zone - L_{GSA}.
- L_{VC} - The final element of the SCL is the visual clear zone. As the driver of the ramp vehicle approaches the freeway terminus of the entrance ramp, it will become detectable (i.e., the elements of the terminus will have an angular velocity in the driver's field of vision equal to, or greater than, the driver's threshold) and cause the driver to timeshare between the task of gap acceptance and the task of tracking the terminus for possible avoidance maneuvers that may be required. This timesharing will make the gap acceptance process less efficient and less safe. Therefore, this length is added to the end of the d_{hr} to avoid timesharing. The d_{hr} and L_{VC} zones, together, comprise the minimum entry length, L_{EN}, which must be provided downstream of the physical merging end.

It is possible for a ramp vehicle to enter into an acceptable headway at a speed well below the operating speed in Lane 1. In such a case, the headway will be quite long and the vehicle completes the acceleration on the freeway. It is also possible that a driver on the ramp, having selected an acceptable headway in Lane 1, will remain on the acceleration lane, waiting to enter Lane 1 at its terminus. This would allow additional length for the ramp vehicle to accelerate closer to the speed of vehicles in Lane 1. The framework of possibilities outlined above, has not been included directly in the determination of the acceleration lane length, L_{SCL}.

An alternative scenario for the end of the entry process, involves the case where the ramp vehicle arrives near enough to the end of the ramp that the driver finds it necessary to either force the ramp vehicle into an insufficient headway, or abort the maneuver by decelerating to a stop. The trigger for such an action is the same as for the visual clear zone (i.e., the angular velocity of the terminus exceeds the driver's threshold). Therefore, the onset of braking for the abort maneuver, should no acceptable headway be found, would be at the beginning of the visual clear zone. Although the abort zone is not considered a part of the acceleration lane length, the required deceleration rate must be checked to assure that unreasonable levels do not result from the design.

Mathematical Model

The process outlined above, has been translated into a mathematical form. The length of each of the zones may be derived using equations for vehicle dynamics and driver behavior, and assumptions regarding the values of the set of parameters found in those equations. The models are presented in Table 2. They are discussed, briefly, below. The entry model nomenclature is provided in Table 3.

The acceleration lane length is comprised of lengths of four zones.

$$L_{SCL} = L_{SC} + L_{IA} + L_{AP} + L_{EN} \tag{1}$$

o The steering control zone length is defined by

$$L_{SC} = t_S v_0 \tag{2}$$

TABLE 2

ENTRY MODEL EQUATIONS

Acceleration Lane Length, L_{SCL}

1. $L_{SCL} = L_{SC} + L_{IA} + L_{AP} + L_{EN}$

Steering Control Zone, L_{SC}

2. $L_{SC} = t_s v_0$

Initial Acceleration Zone, L_{IA}

3. $L_{IA} = \dfrac{v_{r_1}{}^2 - v_o{}^2}{2a_o}$

Adjust Position Zone, L_{AP}

4. $L_{AP} = v_{r_1} t + \dfrac{a_l t^2}{2}$

5. $t = \dfrac{2\Delta d}{\Delta V + \sqrt{\Delta V^2 + 2\Delta a \Delta d}}$

6. $\Delta V = V_f - v_{r_1}$

7. $\Delta a = a_f - a_l$

8. $\Delta d = L_o = \alpha V_f + l_r$

9. $v_{r_1} = \sqrt{v_o{}^2 + 2a_o L_{IA}}$

Minimum Entry Length, L_{EN}

10. $L_{EN} = d_{hr} + L_{VC}$

11. $d_{hr} = f_{hr} d_h$

12. $d_h = \dfrac{v_{hr}}{\lambda\beta^2}(e^{\lambda\beta T} - \lambda\beta T - 1)$

13. $T = \dfrac{L_H}{V_f}$

14. $L_H = L_T + F + l_f$

15. $L_T = \sqrt{\dfrac{(D+O)(V_f - v_{hr})}{\omega_t}}$

16. $\beta = 1 - \left(\dfrac{v_{hr}}{V_f}\right)$

17. $F = \alpha V_f$

18. $\lambda = \dfrac{k\lambda'}{3600N}$

19. $v_{hr} = f_h (V_f - v_{r_2} + \Delta V_f) + v_{r_2}$

20. $v_{r_2} = v_{r_1} + a_l t$

21. $\sigma^2 = \dfrac{1}{\lambda\beta^2}(e^{2\lambda\beta T} - 2\lambda\beta T e^{\lambda\beta T} - 1)$

22. $\lambda_r = \dfrac{\lambda'_r}{3600}$

Visual Clear Zone, L_{VC}

23. $L_{VC} = \sqrt{\dfrac{D' v_{r_3}}{\omega_t}}$

24. $v_{r_3} = \sqrt{v_{r_2}{}^2 + 2a_h d_{hr}}$

25. $L_{AZ} = \dfrac{v_{r_3}{}^2}{2a_A}$

26. $v_{r_4} = \sqrt{v_{r_3}{}^2 + 2a_A L_{VC}}$

TABLE 3

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
a_A	Average acceleration (deceleration) rate across the abort zone	f/s/s
a_f	Average acceleration rate of Lane 1 freeway vehicle across AP zone	f/s/s
a_h	Average acceleration across d_{hr}	f/s/s
a_l	Average acceleration rate of ramp vehicle across AP zone	f/s/s
a_o	Average acceleration rate of ramp vehicles in IA zone	f/s/s
D	Width of trailing vehicle in Lane 1 of freeway	ft
D'	Width of pavement at ramp terminus upon which driver will focus as terminus is approached	ft
d	Distance traveled after lag rejection to position vehicle to consider next headway	ft
d_h	Distance required to search for and accept a gap without affect of ramp volume	ft
d_{hr}	Distance required to search for and accept a headway, including delay due to ramp volume	ft
d_s	Added distance required for search and acceptance of a headway, due to affect of ramp volume	ft
F	Minimum car following distance	ft
f_h	Factor to estimate average speed across d_{hr}	ft
f_{hr}	Factor relating d_h and d_{hr}	ft
k	Volume distribution factor	ft
L_{AP}	Length of adjust position zone	ft
L_{AZ}	Length of abort zone	ft

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

TABLE 3 (CONTINUED)

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
L_{EN}	Length of entry zone	ft
l_f	Length of freeway design vehicle	ft
L_{GSA}	Length of gap search and acceptance zone	ft
L_H	Acceptable distance headway at threshold angular velocity	ft
L_{IA}	Length of initial acceleration zone	ft
L_{MSC}	Length of merge steering control zone	ft
L_o	Initial lag	ft
l_r	Length of ramp design vehicle	ft
L_{SC}	Length of initial steering control zone	ft
L_{SCL}	Length of speed-change lane	ft
L_T	Acceptable distance lag at threshold angular velocity	ft
L_{VC}	Length of visual clear zone	ft
N	Number of lanes in one direction on the freeway	--
O	Offset between ramp and trailing freeway vehicle	ft
T	Acceptable time headway	sec
t	Time to juxtapose ramp vehicle opposite lag vehicle in Lane 1 of the freeway	sec
t_s	Time to complete steering control	sec
V_f	Speed of vehicle in Lane 1 of the freeway	f/s
v_{hr}	Average speed of ramp vehicle across d_{hr}	f/s
v_o	Speed of ramp vehicle at end of controlling condition	f/s

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

TABLE 3 (CONTINUED)

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
v_{r_1}	Speed of ramp vehicle at beginning GSA zone (also v_r)	f/s
v_{r_2}	Speed of ramp vehicle at end of AP zone	f/s
v_{r_3}	Speed of ramp vehicle at end of EN zone	f/s
v_{r_4}	Speed of ramp vehicle at end of VC zone	f/s
ω_t	Threshold angular velocity	rads/s
β	Relative speed factor	--
λ	Freeway Lane 1 volume	pcps
λ'	Total freeway volume	pcph
α	Car following constant	sec
Δa	Difference in acceleration rates of ramp and lag vehicle in Lane 1 of the freeway at end of IA	ft
Δd	Difference between absolute distances traveled by the freeway and ramp vehicles during the vehicle adjustment process	ft
ΔV	Speed differential between freeway Lane 1 vehicle and ramp vehicle at begin GSA	f/s
ΔV_f	Allowable speed differential between ramp vehicle and trailing freeway vehicle after merge	f/s
σ^2	Variance associated with d_h	sec^2
λ_r	Ramp volume	pcps
λ'_r	Ramp volume	pcph

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

oThe initial acceleration zone length is defined by

$$L_{IA} = \frac{v_{r_1}^2 - v_o^2}{2a_o} \tag{3}$$

o The adjust position zone length is defined by

$$L_{AP} = v_{r_1}t + \frac{a_1 t^2}{2} \tag{4}$$

o The entry zone length is defined by

$$L_{EN} = d_{hr} + L_{VC} \tag{10}$$

L_{SC}. The steering control zone (Equation 2) is determined by the time required for the steering control maneuver and the speed at which the ramp vehicle is traveling at the time. The speed across the zone is assumed to be constant and equal to the operating speed associated with the controlling condition from which the driver is transitioning. The time for the steering maneuver is considered to be a constant.

L_{IA}. The initial acceleration length (Equation 3) is determined by the operating speed associated with the controlling ramp condition and the acceleration rate across the zone. The acceleration rate is expected to vary directly with the speed differential between the controlling condition on the ramp and Lane 1 of the freeway. The equations do not guarantee that the resulting speed at any point is within the design speed of the geometry at that point. This must be checked separately.

L_{AP}. The length of the zone for the ramp vehicle to reject the initial lag and adjust its position relative to the lag vehicle (Equation 4) is determined by the speed at the beginning of the zone, the acceleration rate across the zone and the time required to complete the adjustment of position. The time required to complete the adjustment of position (Equation 5) is determined by the speed differential between the ramp vehicle and the Lane 1 vehicle (Equation 6), the difference between their acceleration rates (Equation 7) and the size assumed for the initial lag (Equation 8). The length of the initial lag could be determined in several ways. It was decided that the lag rejected would be best represented by the minimum car-following distance. That is, if the ramp vehicle were to arrive at a distance in front of the Lane 1 vehicle greater than the minimum car-following distance, then there might be a tendency to accelerate into the lag. The derivation of Equation 5 is summarized in Appendix B.

The speed at the beginning of the zone (Equation 9) is a function of the controlling speed condition, the acceleration rate across the IA zone, and the length of the IA zone. The acceleration rate across this zone is likely to vary with the speed differential present.

At high speed differentials, the length of the AP zone will be quite short and acceleration will be more directly related to reaching freeway speed. At low speed differentials, the length of the zone becomes large and the choice of acceleration rate becomes significant as the driver may have to either reduce the rate of acceleration or decelerate to appropriately juxtapose the vehicle within a reasonable distance.

L_{EN}. The entry zone consists of two elements, or subzones, d_{hr} and L_{VC} (Equation 10). The d_{hr} element is the most complex of the SCL model. It is summarized below and its derivation is found in Appendix B. The length, d_{hr}, (Equation 11) is that associated with a high probability that an acceptable headway will arrive opposite the vehicle. It assumes that vehicles in Lane 1 of the freeway are distributed according to an Erlang distribution.

The d_{hr} length is determined by deriving a basic length (Equation 12) which is necessary for the gap search and acceptance process under low volume conditions. This length is then factored to account for higher ramp volumes. The basic length is determined by:

1. A critical gap (Equations 13, 14, 15, 17, 19 and 20) of which a critical determinant is the threshold angular velocity for the driver of the ramp vehicle.
2. The volume in Lane 1 of the freeway (Equation 18).
3. The speeds of both the ramp and freeway vehicles (Equation 16).

The factor (Equations 19 to 24) that is applied to account for ramp volume is primarily a function of the ramp volume and the estimated variance of the distance. The highly theoretical nature of these relationships, while useful, have some limitations on ranges of variables for which a reasonable solution is derived. This is the reason that a representative set of factors was modeled rather than directly inserting the equations into the model. The derivation of the factors is found in Appendix B.

L_{VC}. The visual clear zone length (Equation 25) is determined by the angular velocity of the target pavement area at the end of the ramp taper. This includes the effect of the speed of the ramp vehicle at the beginning of the zone (Equation 26).

Also shown in Table 2 is the model for the determination of the abort zone length (Equations 24 and 25). While this is not part of the acceleration lane, it should be checked to determine if the acceptable deceleration limits are being exceeded.

While the series of equations represent a very complex model, containing some highly theoretical elements, it represents the first comprehensive attempt to model the dynamics along a freeway acceleration lane. Furthermore, it attempts to fully integrate the human factors dimension with the operational characteristics of vehicles and geometry. The challenge is to utilize this basic model to arrive at a relatively simple set of values, graphs or equations which the designer and/or policy maker may use to determine acceleration lane lengths. The first step in this process is to better understand the attributes of the model. The section below describes attributes of the model, and subsequent sections include results of a series of sensitivity analyses.

The next step is to arrive at values for those parameters which are not design variables so that they may be placed into the models directly, leaving only true design variables for input by the designer. The selection of parameter values is described in another section, below.

After completion of these two steps, it is possible to begin the task of translating the model into a design tool.

Model Attributes

In this section, the model for acceleration lane length is analyzed in terms of its sensitivity to variation of the key input parameters. A complete listing of the input parameters for the model appears as Table 4. The values shown are those selected as most reasonable for the purposes of testing the model. Some of the

TABLE 4

ENTRY MODEL INPUT PARAMETERS

Item	Symbol	Units	Value
Independent Variables			
Roadway			
Freeway speed - Lane 1	V_f	f/s	103
Ramp speed - at controlling curve	v_o	f/s	44
Ramp speed - at begin GSA	v_{r_1}	f/s	0
Freeway speed - Lane 1	V'_f	mph	70
Ramp speed - at controlling curve	v'_o	mph	30
Ramp speed - at begin GSA	v'_{r_1}	mph	0
Freeway volume	λ'	pcph	4,000
Number of freeway lanes	N	none	3
Lane 1 volume distribution factor	k	none	1
Ramp volume	λ'_r	pcph	500
Driver			
Initial acceleration rate on ramp	a_o	f/s/s	5
Acceleration rate of ramp vehicle across AP zone	a_1	f/s/s	2
Acceleration rate of Lane 1 vehicle across AP zone	a_f	f/s/s	0
Acceleration rate of ramp vehicle across d_{hr} zone	a_h	f/s/s	3
Time for steering control	t_s	sec	1.5
Angular velocity threshold	ω_t	rads/s	.002
Car following factor	α	none	1
Pavement width for visual clearance	D'	ft	6

TABLE 4 (CONTINUED)

ENTRY MODEL INPUT PARAMETERS

Item	Symbol	Units	Value
Driver (Continued)			
Maximum deceleration rate for abort zone	a_A	f/s/s	9
Allowable speed difference at begin merge	ΔV	f/s	7.3
Allowable speed difference at begin merge	$\Delta V'$	mph	5
Vehicle			
Vehicle width	D	ft	7
Offset between ramp and freeway vehicles	O	ft	6
Length of lead freeway vehicle	l_f	ft	15
Length of ramp vehicle	l_r	ft	15

variables in the list are derived, rather than input directly. The obvious derivations are those which are transformations of units (e.g., miles per hour to feet per second), while the less obvious ones are acceleration rates which are selected via table look-up, based on a speed differential criterion, as will be discussed below. The values shown in Table 4, are the ones used in the analyses presented below, except where the variables are varied in the sensitivity analysis, or the table look-up results in the selection of a value other than that shown in Table 4.

Note that the speeds used for Lane 1 of the freeway and the controlling condition on the ramp are given without tying them to a particular type of geometry. Relation to geometry will be achieved in the user document which is a companion document to this report. However, the speeds that have been selected for illustrative purposes, are intended to reflect design speed, rather than some lower operating speed, that might be associated with design speed. This reflects the following philosophy:

> "However, more recent observations show that many operators drive just as fast on wet pavements as they do on dry. To account for this factor, design speed in place of running speed is used to formulate stopping distance values. . . . ." (12).

It seems appropriate to apply the same reasoning to drivers on dry pavement moving along acceleration lanes. It is important to note, however, that an important characteristic of the models developed in this research is that they may be used to generate design values for a range of variables, including speed. Thus, as vehicle or driver characteristics change and affect freeway operating speeds, the design values can be upgraded.

Acceleration Lane Length Components. Figure 15 shows the acceleration lane length which results from the model for a relatively high ramp volume. The Lane 1 freeway volume was chosen to complement the ramp volume in such a manner that it results in the maximum allowable merge point volume for Level of Service (LOS) E, as defined in the Highway Capacity Manual, 1985 (HCM) (13). Each bar represents a different value for the speed at the beginning of the GSA zone, as noted on Figure 15.

Figure 16 presents similar information in a different format. Whereas Figure 15 tends to emphasize the whole, Figure 16 emphasizes the parts. Note that scale for volume in these figures is different.

The d_{hr} component dominates the total length when speed differentials between ramp and Lane 1 are large. However, as the speed differential decreases, the overall length decreases and, equally significantly, the d_{hr} component decreases until it becomes a more balanced part of the components. The steering control zone is relatively short because the initial speed is assumed to be only 15 mph in Figure 16. The initial acceleration length grows significantly, as expected, as the speed at the begin GSA is increased. The adjust position zone also increases as the speed differential decreases. This is because it takes a longer distance to adjust the ramp vehicle, relative to a freeway vehicle, when the two vehicles are traveling at about the same speed. The increase of both the initial acceleration zone and the adjust position zone more than offsets the decrease in d_{hr} (distance to search for, and accept, a headway) over the range of speeds shown. Therefore, there is an increase in required total acceleration lane length at the higher approach speed condition. While this is counter to current thinking, it is quite logical to expect, given the way the design condition has been defined. The visual clear zone remains relatively constant.

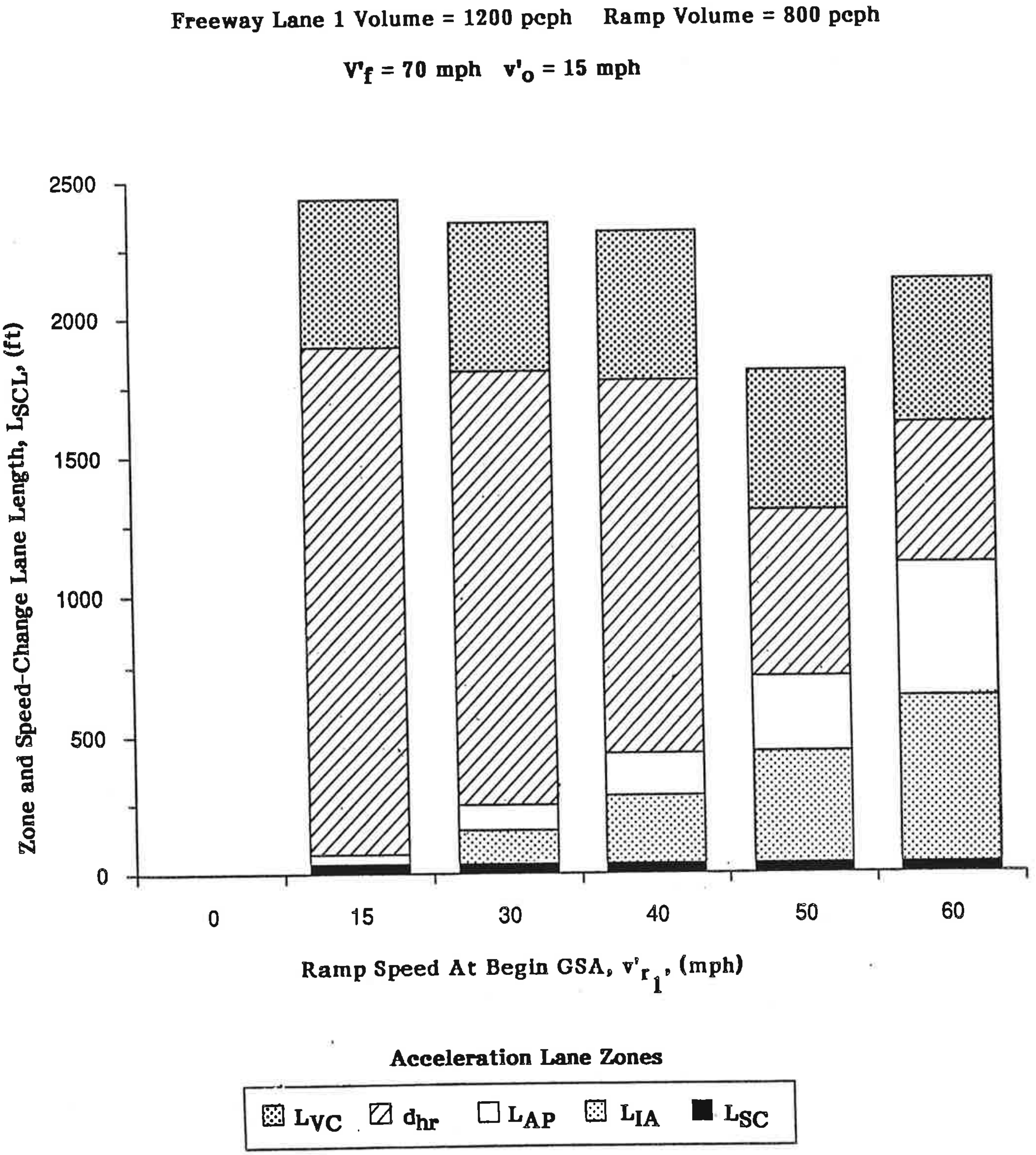


FIGURE 15

ACCELERATION LANE COMPONENTS
HIGH VOLUME CONDITIONS

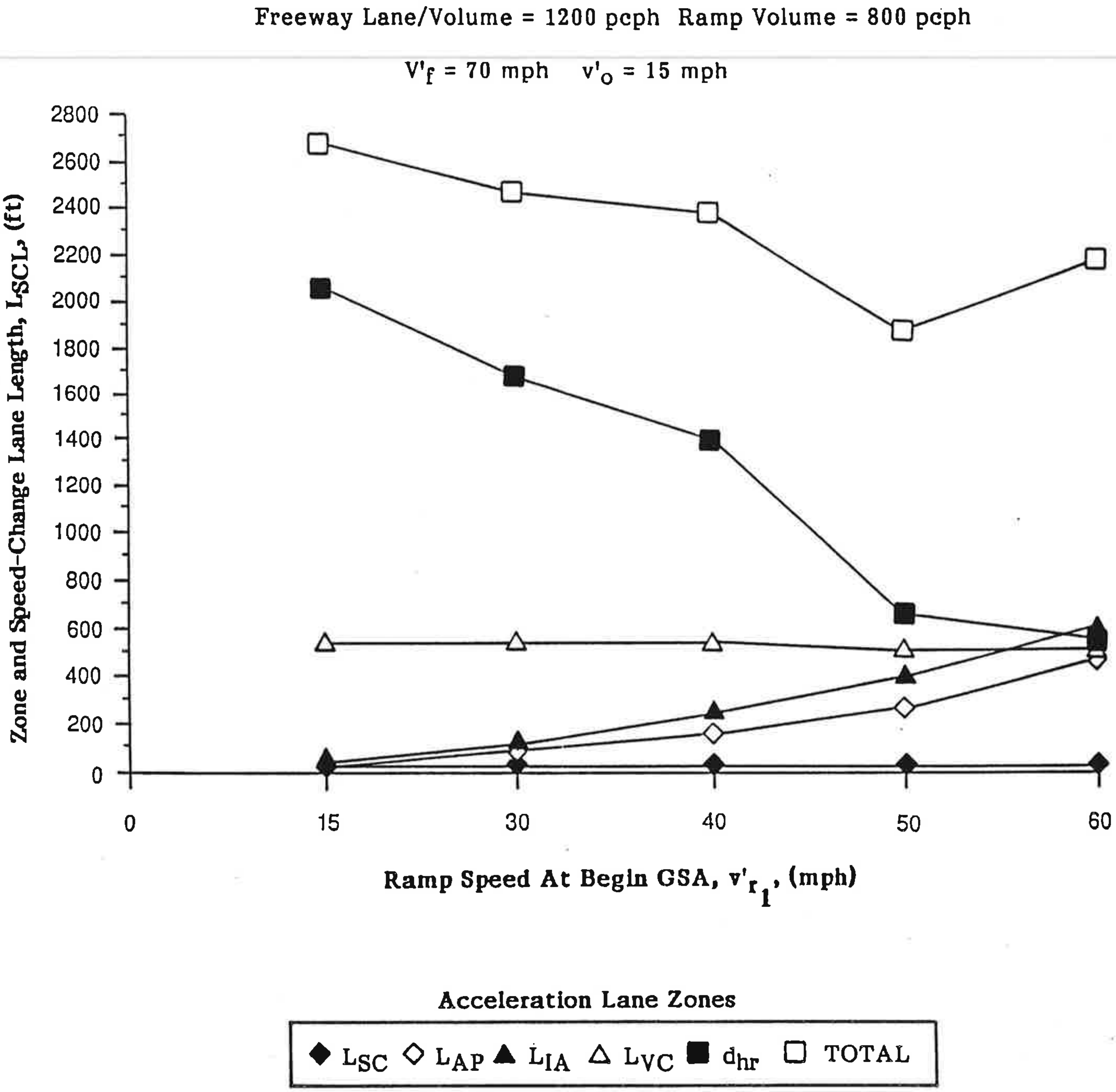


FIGURE 16

EFFECT OF SPEED ON LENGTH OF ACCELERATION LANE COMPONENTS

It is important to identify the different components, and how they vary, since this both adds understanding and has an application in design. The L_{EN} component (i.e., d_{hr} plus L_{VC}) cannot be placed any further upstream than the merging end of the ramp, whereas it is possible for the other elements to be either upstream, or downstream (but preferably upstream), of the merging end. Thus, for the case shown in Figure 16, if the speed at the begin GSA were only 15 mph, most of the acceleration lane (about 2,400 feet) would have to be downstream of the merging end. However, if that speed were 60 mph, then only about 1,000 feet of the acceleration lane need be placed downstream of the merging end.

Figures 17 through 19 show component variation for various volume and speed conditions. Although total lengths do change, the pattern of relationships between components, as described above, remains essentially the same.

Freeway Lane 1 Volume. Figures 20 and 21 show the effect of freeway Lane 1 volume on the acceleration lane length. As Lane 1 volume decreases, the d_{hr} component decreases, becoming so small as not to be a factor of significance for design. In addition, as speed differential is reduced at the begin GSA, the effect of Lane 1 volume on the d_{hr} requirement is also reduced.

Ramp Volume. As documented in the description of the model, a factor has been developed to help estimate the average speed across the d_{hr}, including the effect of acceleration across the zone. The factor is selected through a table look-up. The table of factors appears here as Table 5. The effect of this factor on the length of the speed-change lane is examined in a section below.

The effect of ramp volume on d_{hr} is reflected for in the model by means of a factor applied to a base, low-volume, length. The formulation for the factor is described above in the section on the model. For the purposes of the calculations, a

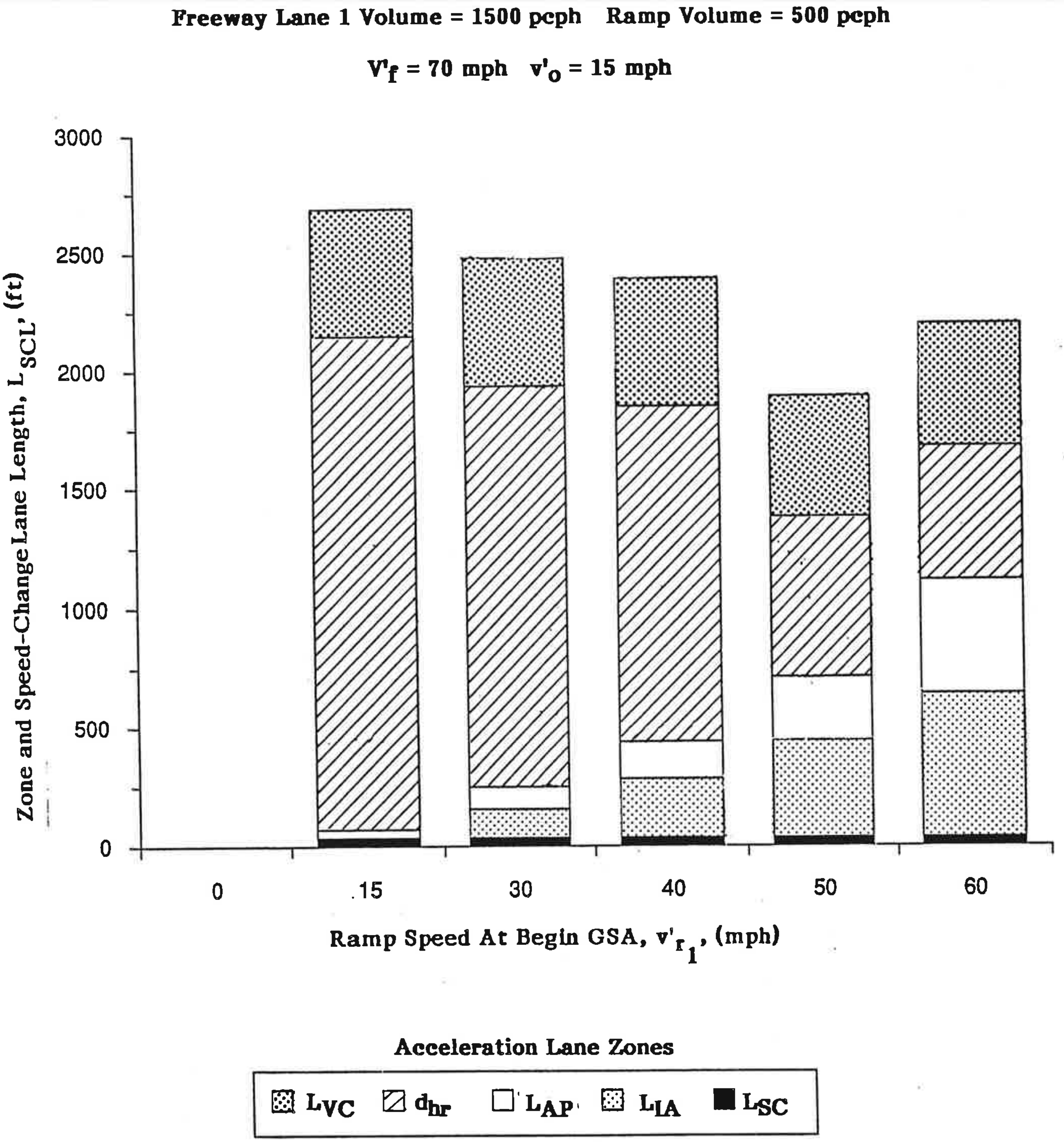


FIGURE 17

ACCELERATION LANE COMPONENTS

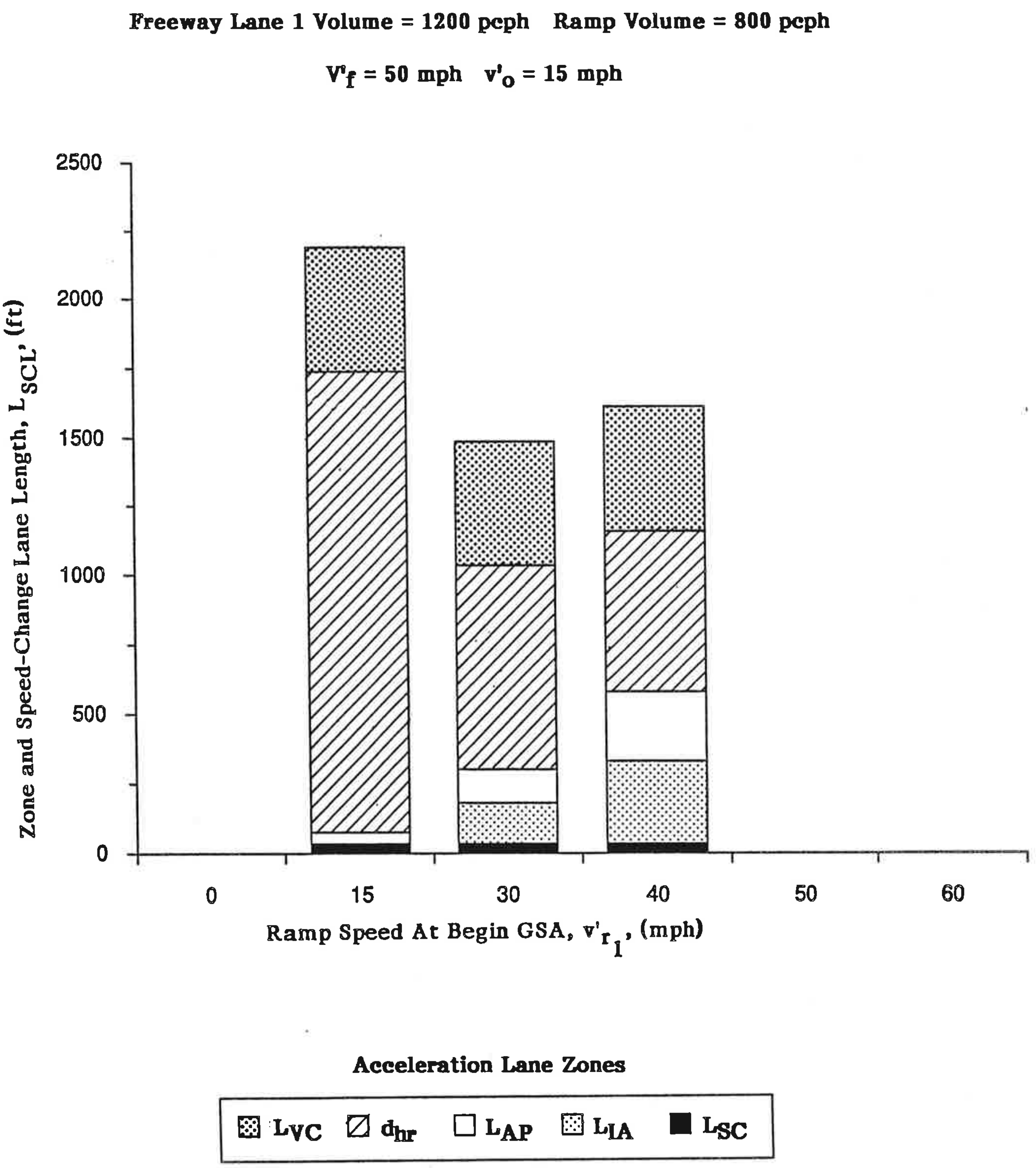


FIGURE 18

ACCELERATION LANE COMPONENTS

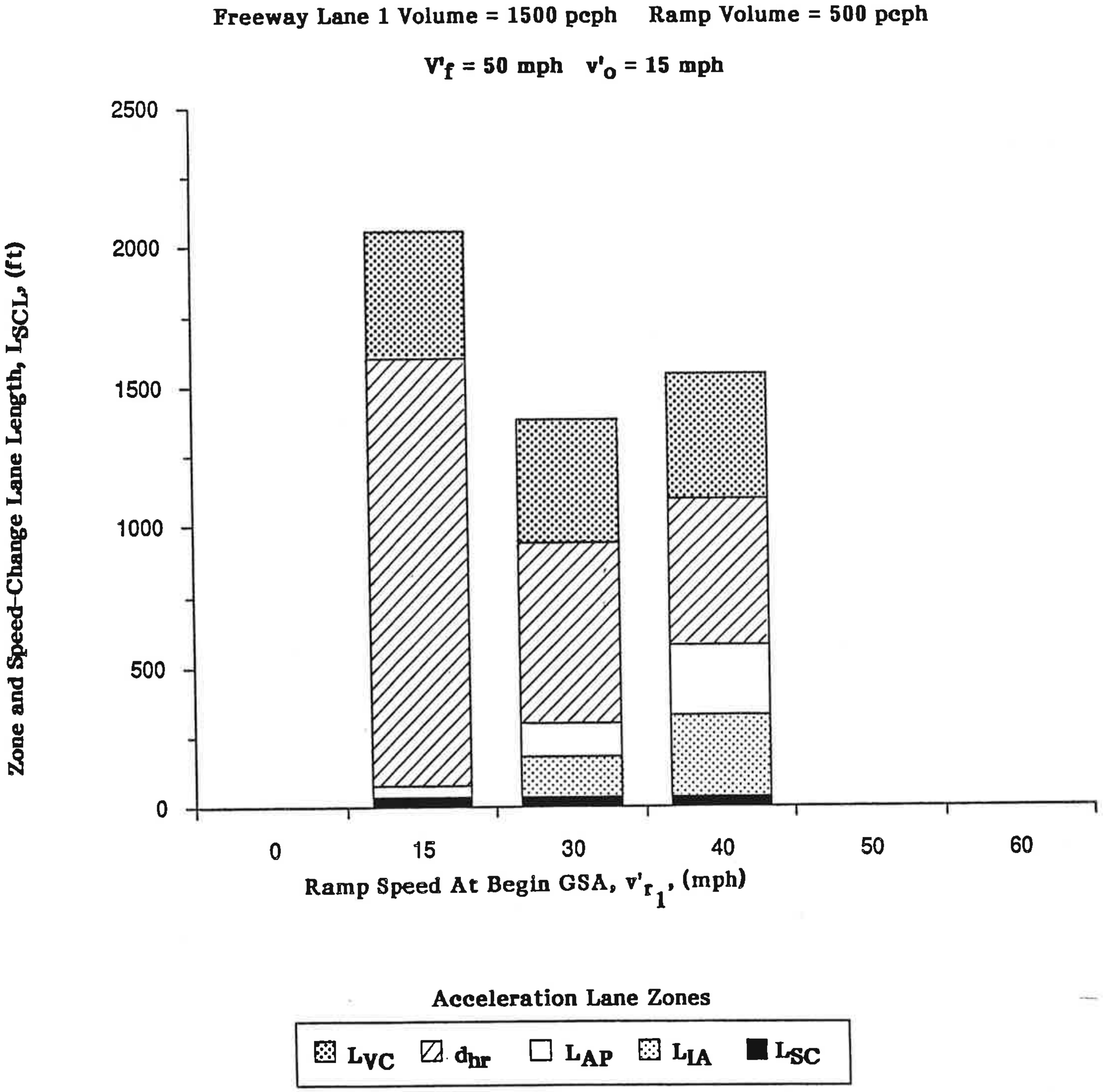


FIGURE 19

ACCELERATION LANE COMPONENTS

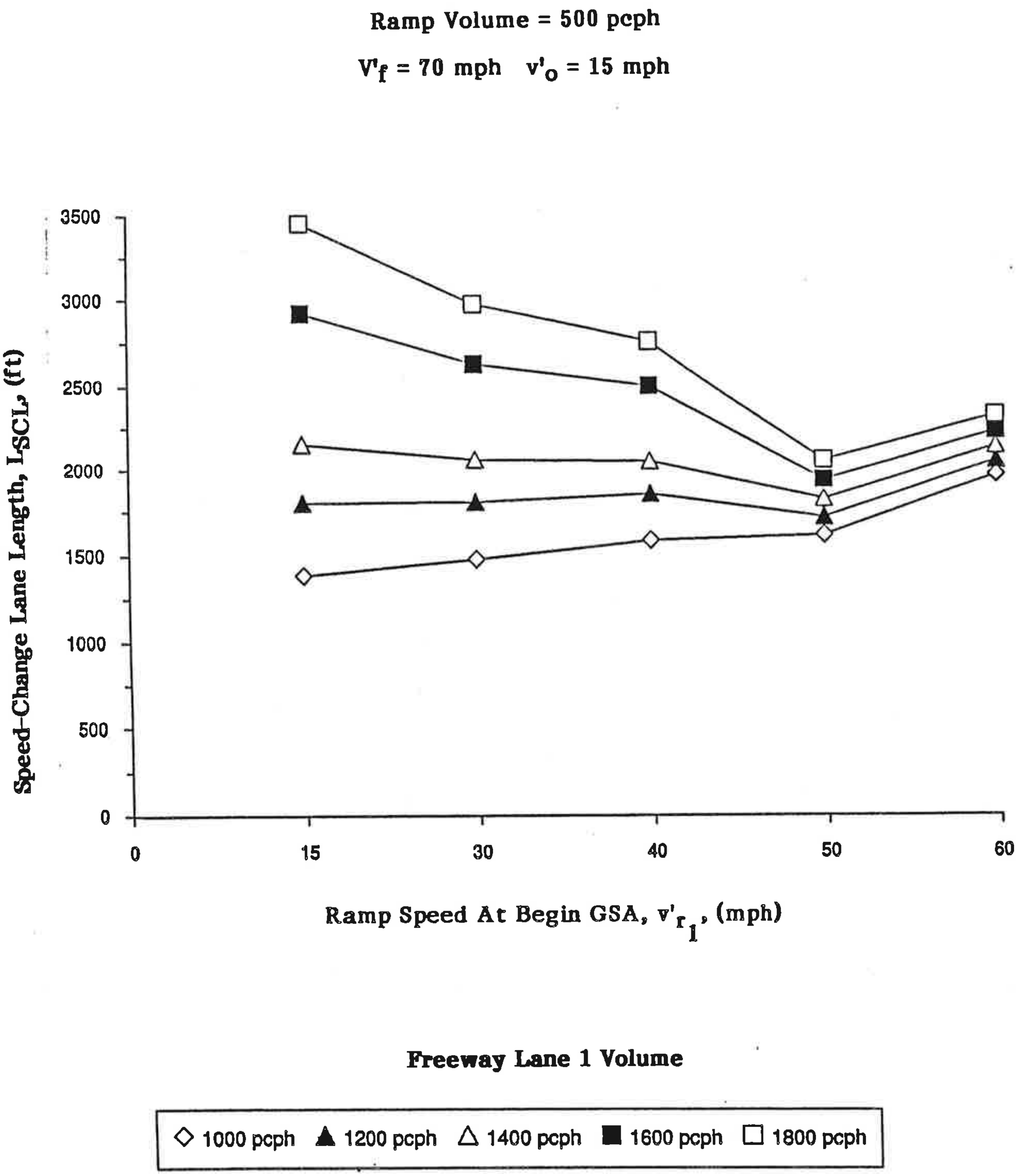


FIGURE 20

EFFECT OF FREEWAY LANE 1 VOLUME
ON ACCELERATION LANE LENGTH
(v'_o = 15 mph)

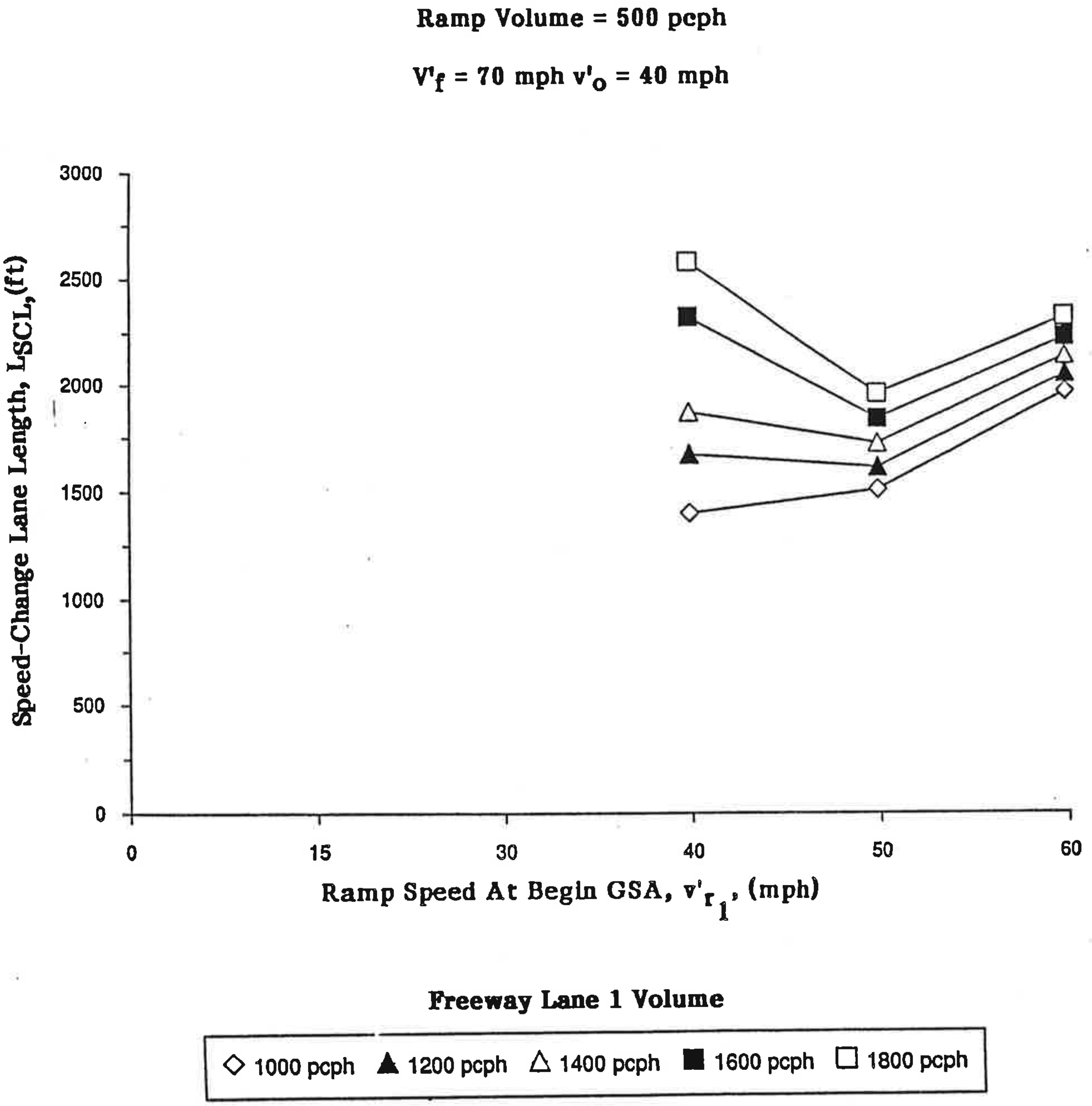


FIGURE 21

EFFECT OF FREEWAY LANE 1 VOLUME ON ACCELERATION LANE LENGTH

(v'_o = 40 mph)

TABLE 5

VALUES FOR d_{hr}

V'_f (mph)	v'_{r_2} (mph) 0	15	30	40	50	60
50	0.52	0.52	0.43	0.48	--	--
60	0.43	0.41	0.41	0.34	0.37	--
70	0.36	0.33	0.33	0.34	0.27	0.30

table of values is included for look-up, depending on the speed differential at the begin GSA and the freeway volume. The classification of the ramp speed differential and the factors, related to Lane 1 and ramp volumes, are shown in Table 6. Their ultimate effect on speed-change lane length is shown in Figure 22. It shows that ramp volumes above 200 pcph have been determined to have an effect. These effects are particularly significant across a range of ramp volumes from 300 to 800 pcph, when associated with speed differentials at the begin GSA, of 20 mph, or greater.

Freeway and Ramp Volume. The combined effect of freeway Lane 1 volume and ramp volume is depicted in Figures 23 and 24 for two different assumptions of speed at the begin GSA. While distances are different for the two cases, the relationships are essentially the same. Some of the values on the graph exceed LOS E and LOS F, as defined in the HCM, although the limit of LOS E is indicated. Since the model does not have a LOS constraint, it would have to be provided externally through the choice of values for the input variables. The effect of freeway volume is quite proportional across all values for the ramp volume. The diminishing effect determined for ramp volumes above 800 pcph is also apparent.

Acceleration Rates. As noted above, the acceleration rates that are used in the model are selected from a table, based upon the speed differential associated with them. The value for the initial acceleration rate, a_0, is chosen based upon the difference between the freeway speed (reduced by the allowable speed difference at entry - 5 mph in these examples) and the speed associated with the controlling condition on the ramp. The effect of variations in the rate on the initial acceleration zone is shown in Figure 25. It demonstrates that there is relatively

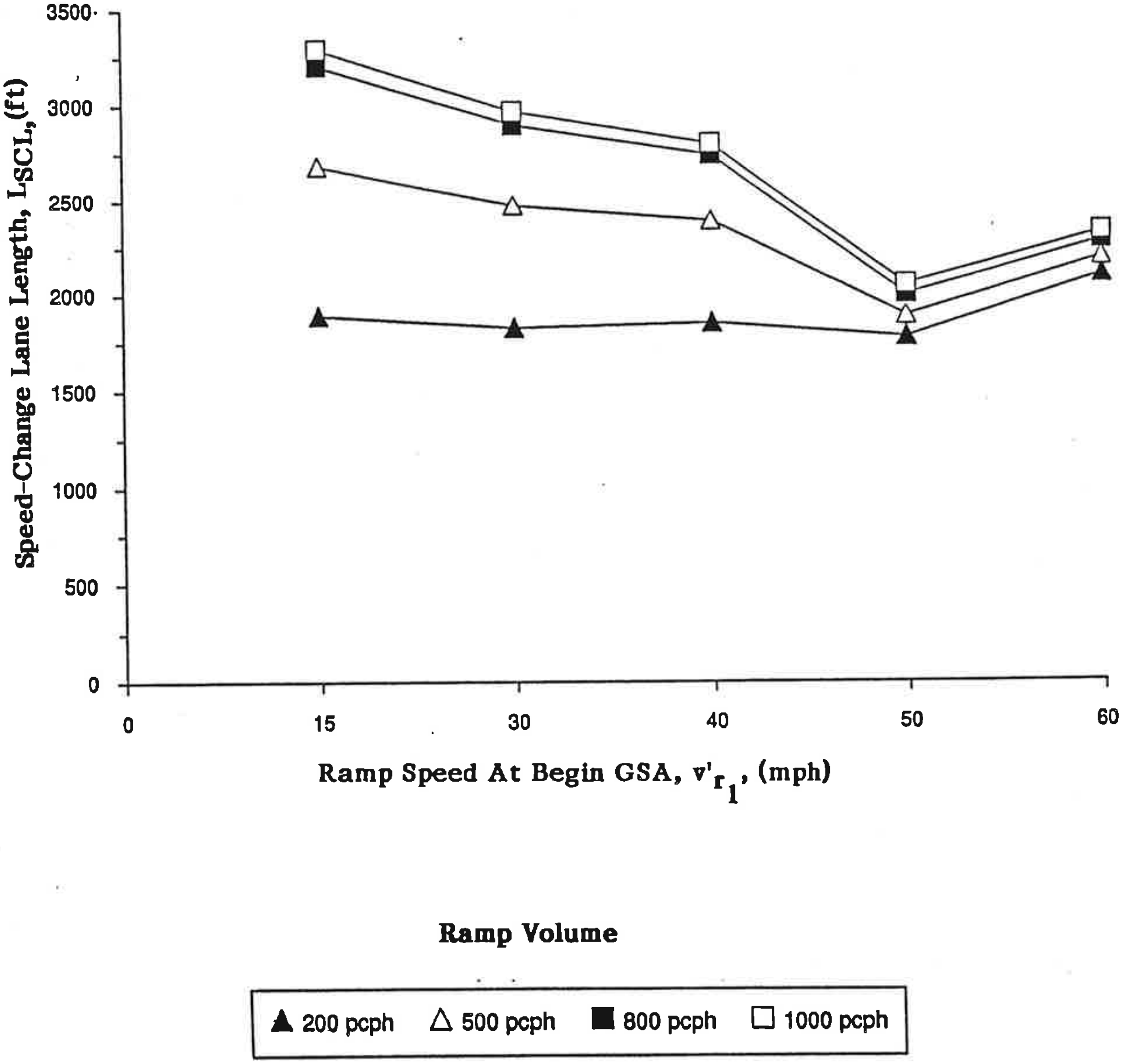
TABLE 6

FACTORS FOR REFLECTING RAMP VOLUME

$V'_{(f)}$ (mph)	Ramp Speed Differential Classification v'_{r_1} (mph) 0	15	30	40	50	60
50	1	1	2	2		
60	1	1	1	2	2	
70	1	1	1	1	2	2

Note: 1 = High Speed Differential
2 = Low Speed Differential

Freeway Volume (Lane 1) (pcph)	Factor for Reflecting Ramp Volume (f_{hr})							
	Low Speed Differential Ramp Volume (pcph)				High Speed Differential Ramp Volume (pcph)			
	200	500	800	1,000	200	500	800	1,000
1,000	1.1	1.3	1.4	1.6	1.3	1.8	2.6	3.1
1,200	1.1	1.3	1.5	--	1.4	2.0	3.0	--
1,500	1.1	1.3	--	--	1.5	2.4	--	--
1,800	1.1	--	--	--	1.6	--	--	--

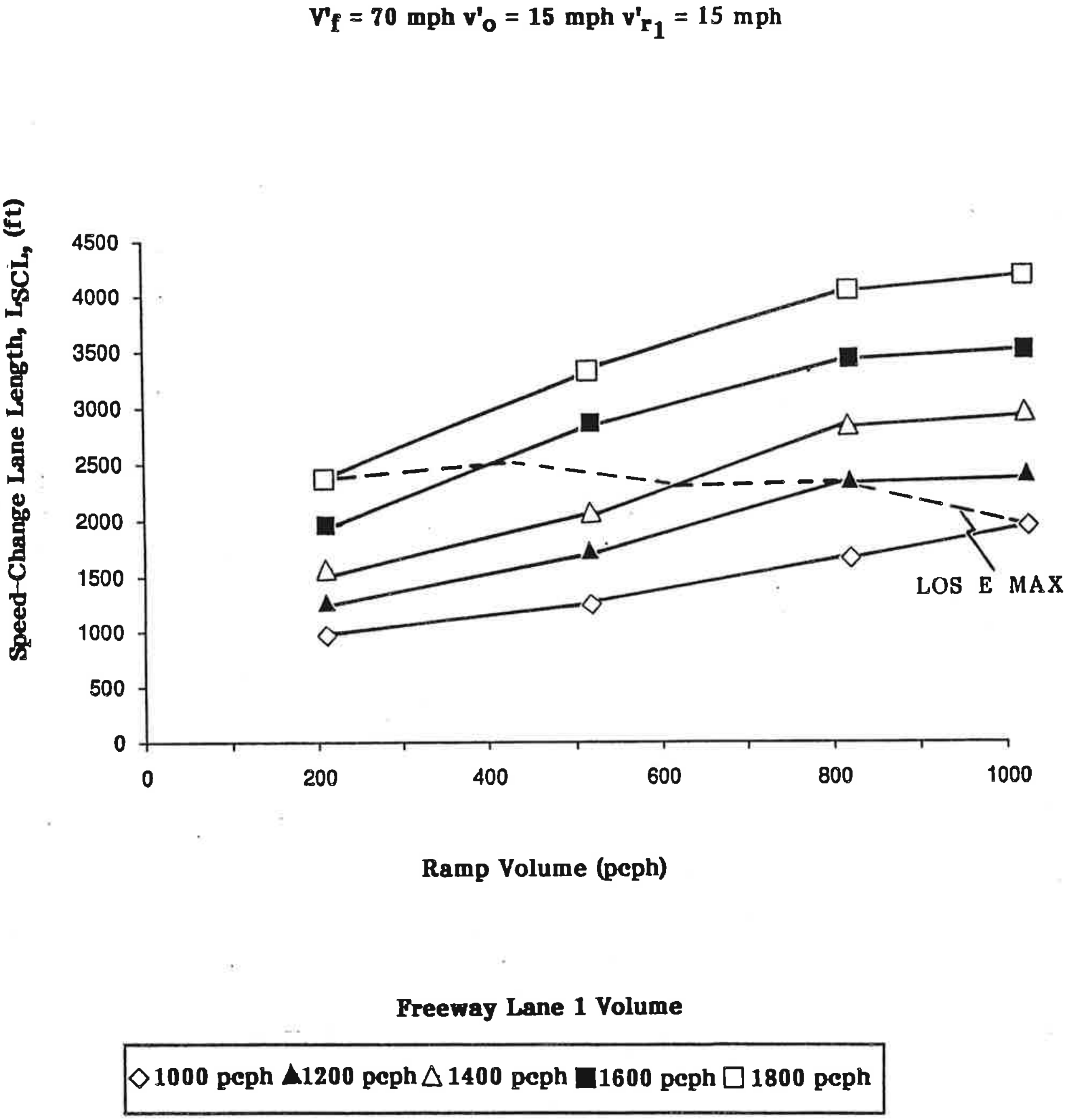


Freeway Lane 1 Volume = 1500 pcph

V'_f = 70 mph v'_o = 15 mph

FIGURE 22

EFFECT OF RAMP VOLUME ON ACCELERATION LANE LENGTH



V'_f = 70 mph v'_o = 15 mph v'_{r_1} = 15 mph

FIGURE 23

COMBINED EFFECT OF FREEWAY LANE 1
AND RAMP VOLUME ON ACCELERATION LANE LENGTH
(v'_{r_1} = 15 mph)

$V'_f = 70$ mph, $v'_o = 15$ mph, $v'_{r_1} = 50$ mph

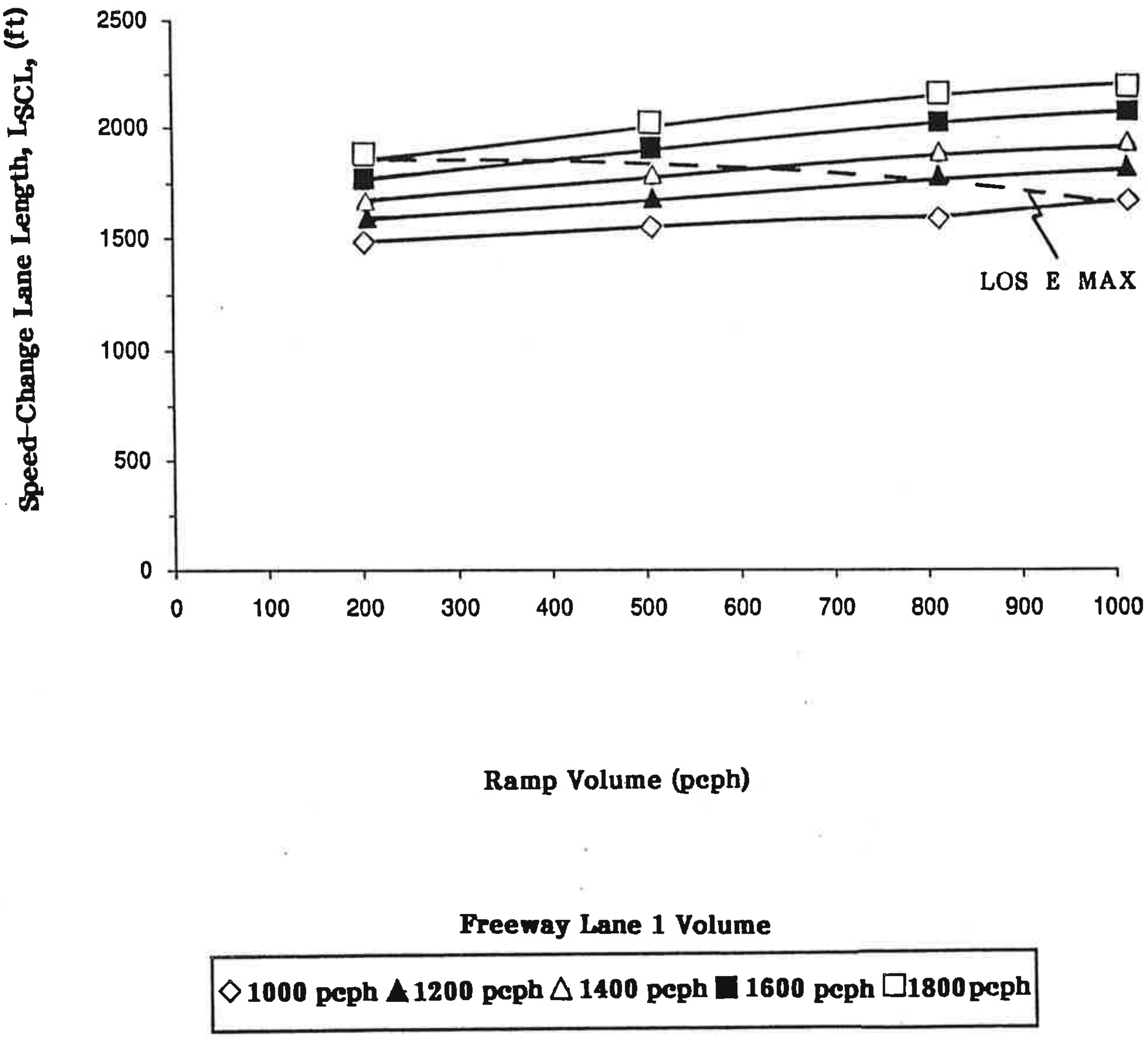


FIGURE 24

COMBINED EFFECT OF FREEWAY LANE 1 AND RAMP VOLUME ON ACCELERATION LANE LENGTH

(v'_{r_1} = 50 mph)

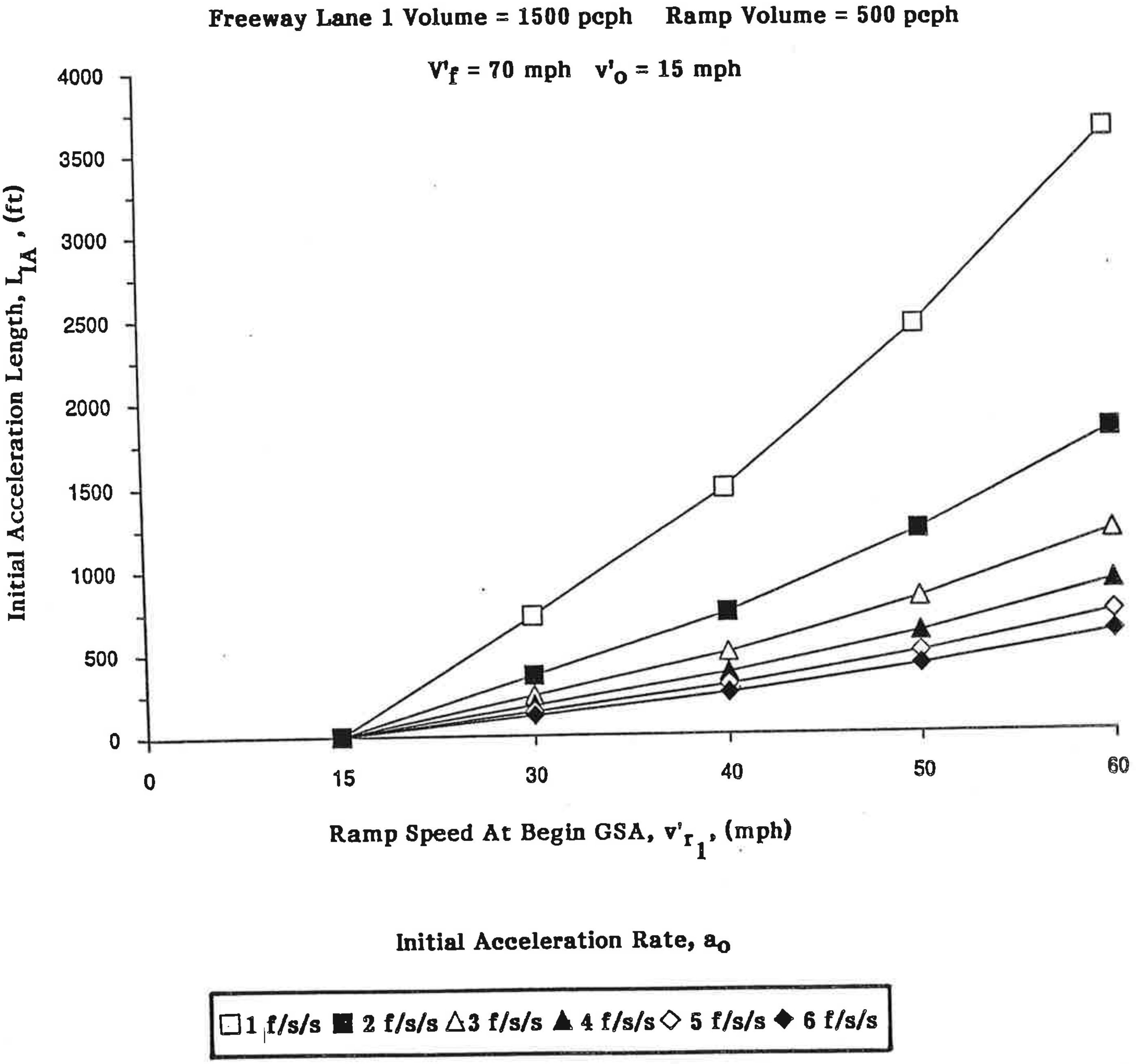


FIGURE 25

EFFECT OF INITIAL ACCELERATION RATE
a_o, ON IA ZONE LENGTH

small variation of length for initial acceleration, across the selected rates, for small speed differentials and for rates above 4 f/s/s.

Figure 26 depicts the effect of the acceleration rate chosen across the d_{hr} on the acceleration lane length. It can be seen that there is little change in length with changing rate.

Figure 27 demonstrates the effect of variation of the acceleration rate, across the adjust position zone, on the acceleration lane length. It shows an overall maximum effect of about 250 feet, across the range plotted. It also shows a reversal of role as the speed differential with Lane 1 of the freeway becomes less than 20 mph. It is logical to expect the driver to choose to decelerate across the L_{AP} zone, when the speed differential is relatively small, so as to minimize the distance taken to adjust position, but avoiding a level of slowing which significantly increases the headway required to enter the traffic stream.

The preliminary choice of acceleration rates, representative of a passenger vehicle on a near-level roadway, for use in the model are given in Table 7. These rates reflect the knowledge gained during the research on vehicle characteristics. The rates also reflect the field experience of the research team and the analyses summarized above. It has been assumed that the acceleration rate of vehicles in Lane 1 is zero across the area of the ramp merge. The set of acceleration rates finally chosen for design must be developed for each design vehicle to be represented in the SCL determination. The effect of grades on the acceleration rates for each of these design vehicles must also be included.

Threshold Angular Velocity. The choice of the threshold value of angular velocity is a difficult one because of the difficulty in accurately measuring it. It can be seen from Figure 28 that the acceleration lane length is quite sensitive to the

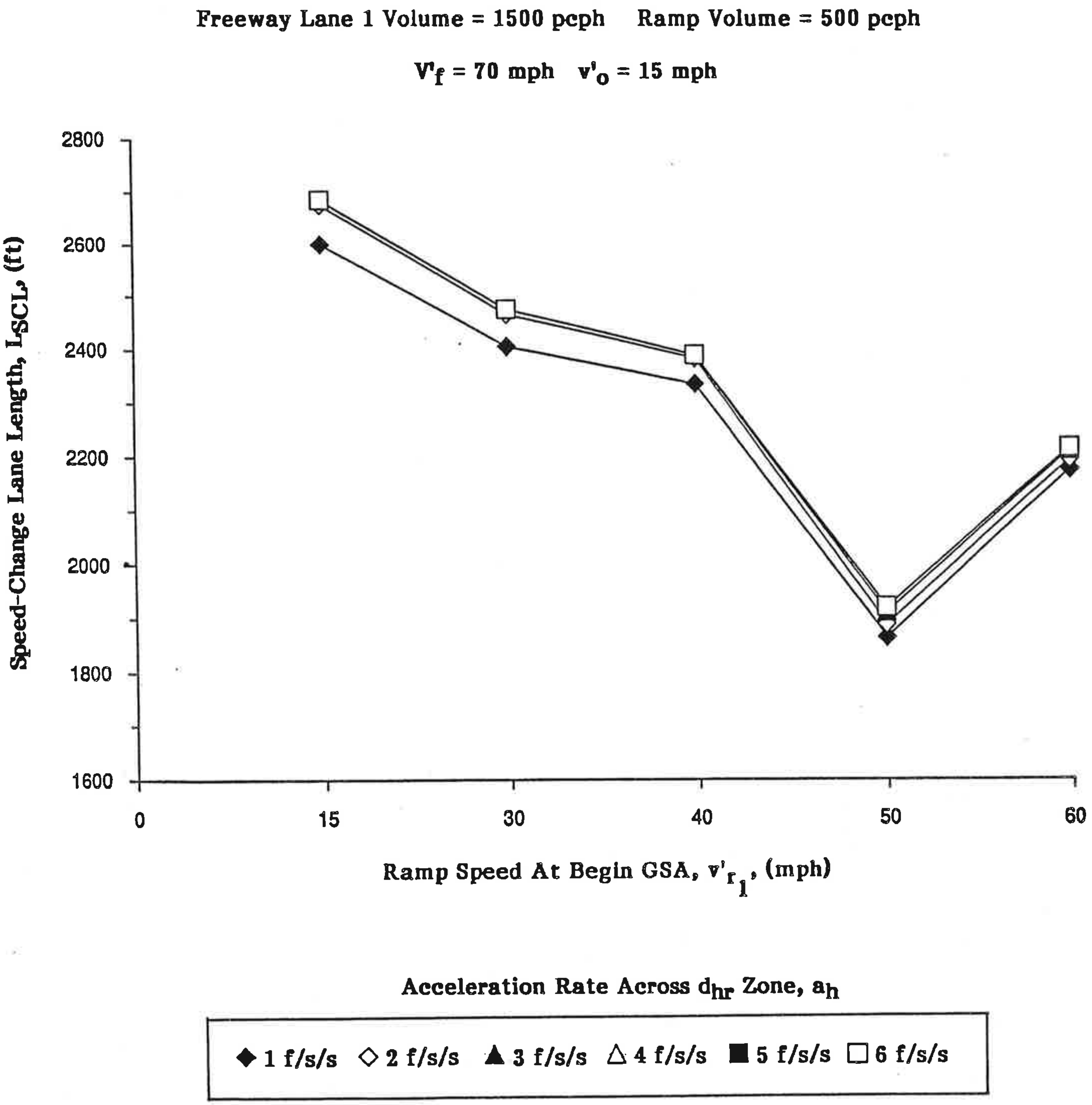


FIGURE 26

EFFECT OF ACCELERATION RATE ACROSS
d_{hr} ZONE ON ACCELERATION LANE LENGTH

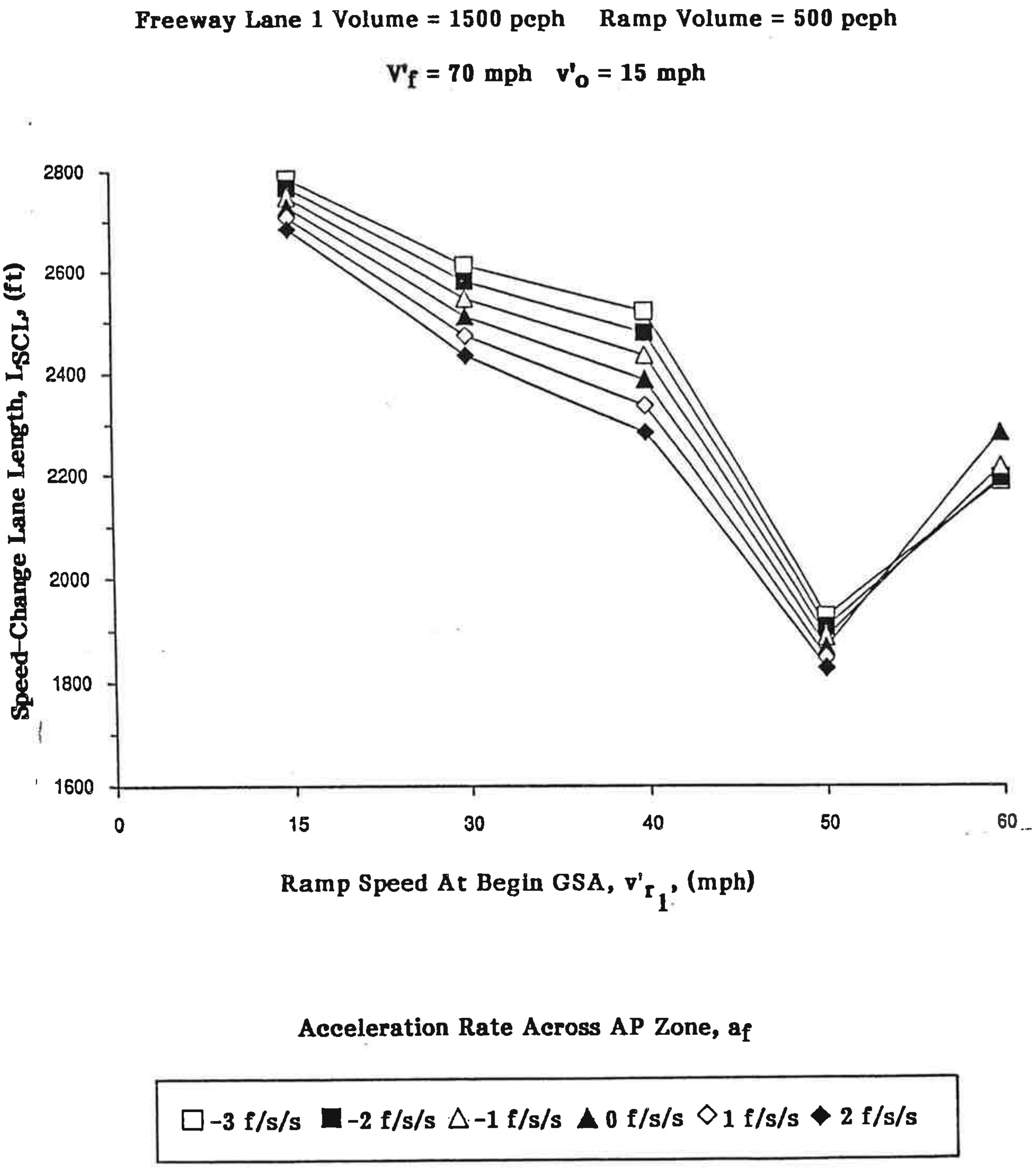


FIGURE 27

EFFECT OF ACCELERATION RATE ACROSS AP ZONE ON ACCELERATION LANE LENGTH

TABLE 7

ACCELERATION VALUES

ΔV * (mph)	a_l (f/s/s)	a_h (f/s/s)	a_o (f/s/s)
0	-2	2	2
10	-1	2	3
20	0	3	4
30	1	3	5
40	2	3	6

---

* Difference between ramp controlling speed and freeway speed.

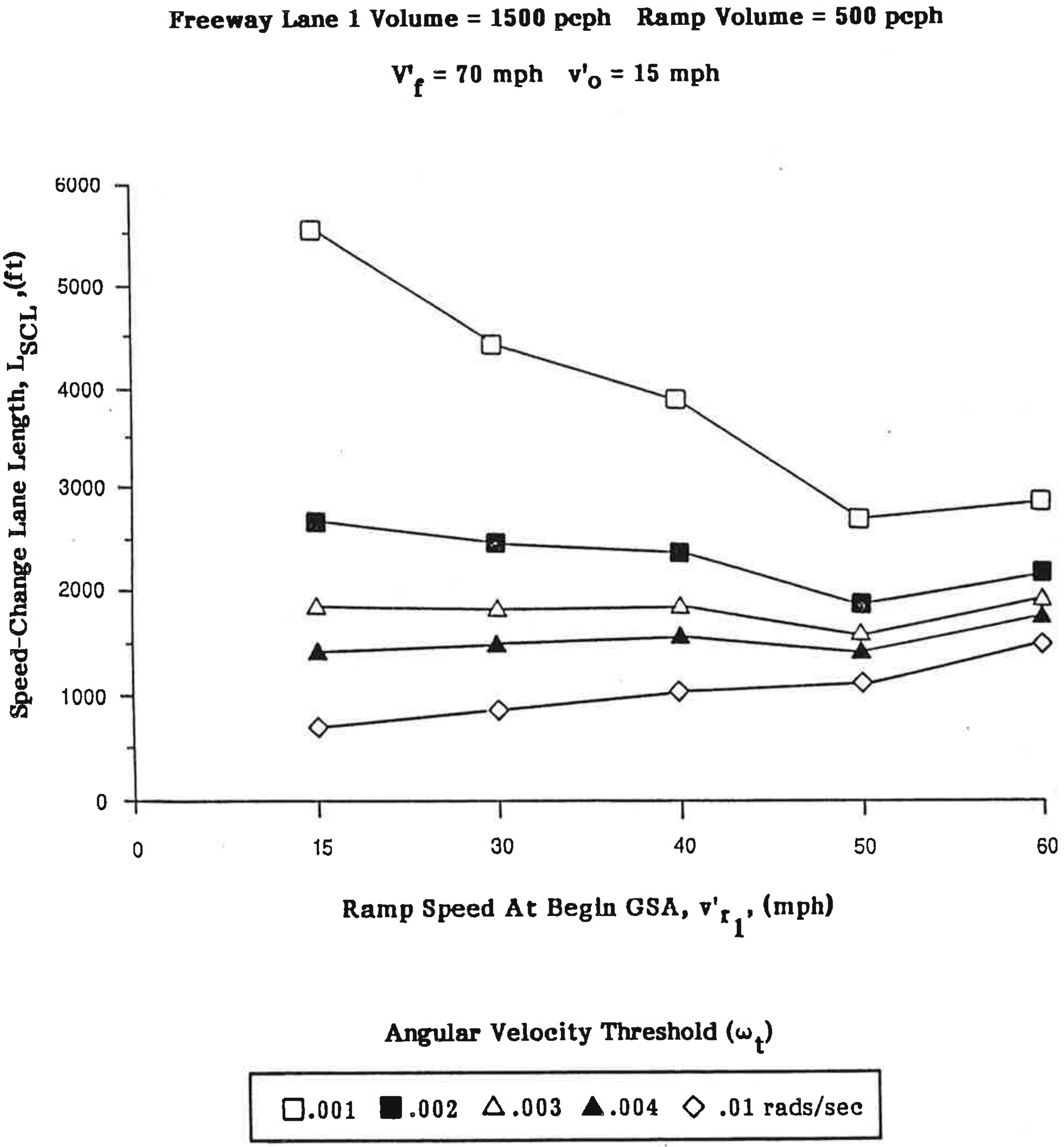


FIGURE 28

EFFECT OF ANGULAR VELOCITY THRESHOLD
ON ACCELERATION LANE LENGTH

value chosen. The range of values in Figure 28 includes those considered to be representative of most drivers plus one value at an order-of-magnitude greater than the others. The exhibit demonstrates that, depending upon the value chosen, the relationship between acceleration lane length and speed differential at the begin GSA can either be the reverse of what is expected, show almost no correlation, or behave as expected. While some values result in unexpected relationships, that does not imply they are wrong. Throughout the range of values, the magnitude of the d_{hr} element decreases continuously for all values of threshold angular velocity, as would be expected. The changing directions of the curves in Figure 28 are the result of the changing relative role in the acceleration lane length that the d_{hr} plays, as the threshold is changed. The possible lengths vary as much as 2,000 feet across the reasonable values for the threshold. The effect is greatest at high speed differential because the value is primarily affected by the d_{hr} component. This analysis shows the need to use the greatest care possible in choosing the angular velocity threshold. The choice of value for design is discussed in a section below.

Car Following Factor. The choice of value for the car following factor (α) also results in a significant, but lesser, impact on the acceleration lane length than does the angular velocity threshold. Figure 29 shows the effect to be relatively constant across all ranges of speed differential. Field data can also be used to select a value for alpha, but accurate assessment of when a minimum car following situation is occurring is difficult at best. The choice of value is discussed below.

Vehicle Lengths. The impact of variation of the length of freeway and ramp vehicles is of interest because it relates to the choice of design vehicle. Figures 30 and 31 show the effect of ramp and freeway vehicle length, respectively, on

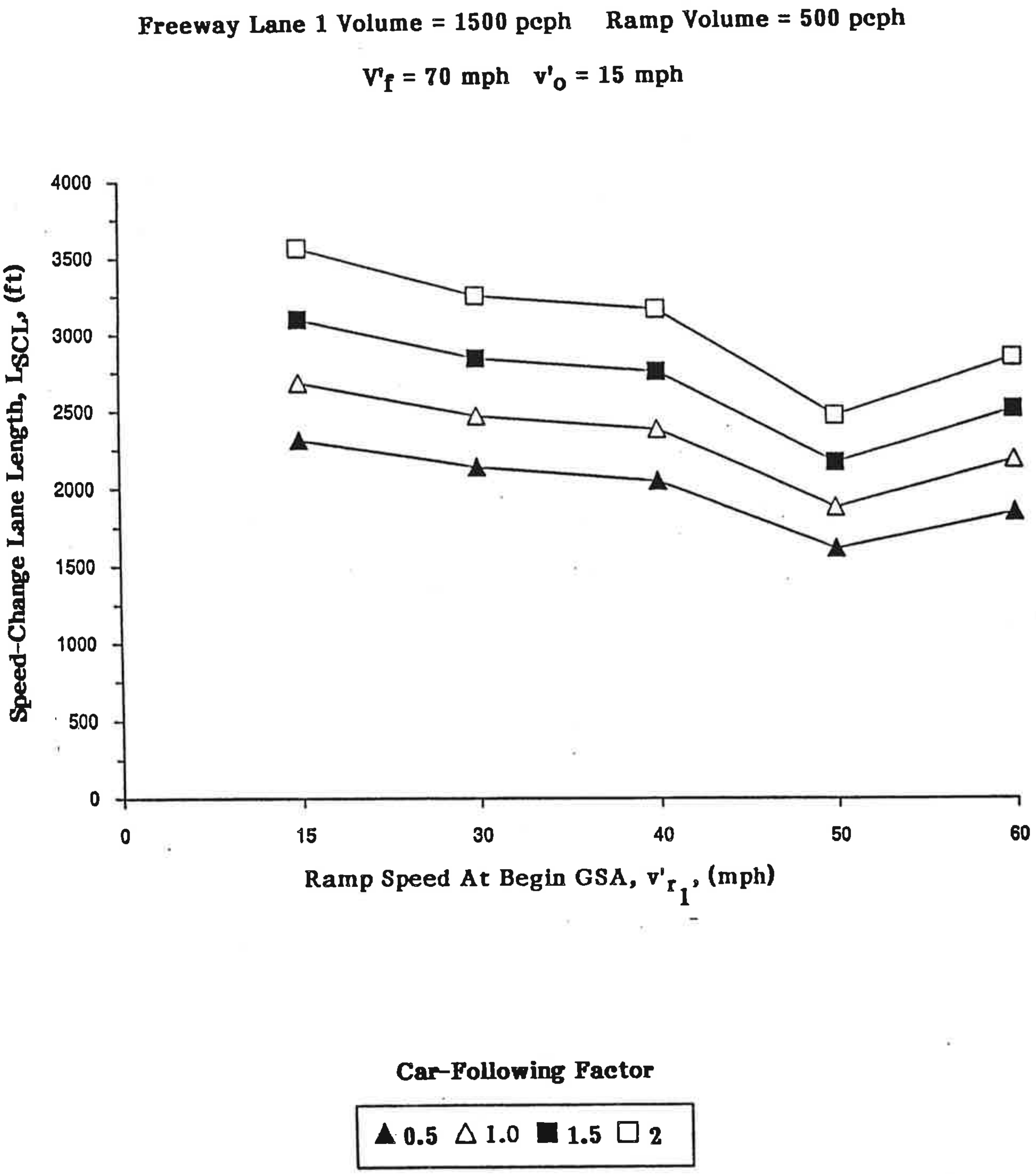


FIGURE 29

EFFECT OF CAR-FOLLOWING FACTOR ON ACCELERATION LANE LENGTH

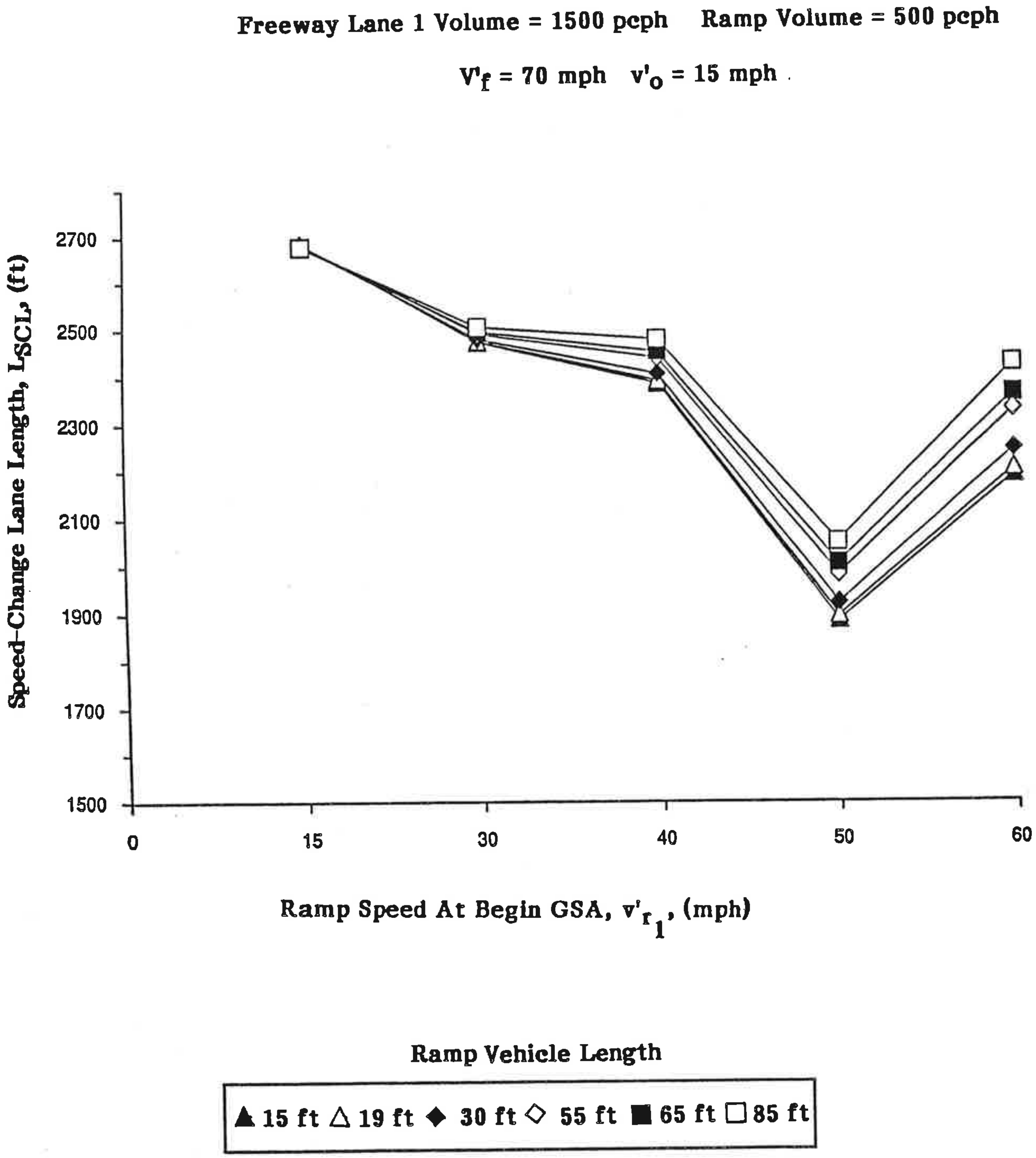


FIGURE 30

EFFECT OF RAMP VEHICLE LENGTH ON ACCELERATION LANE LENGTH

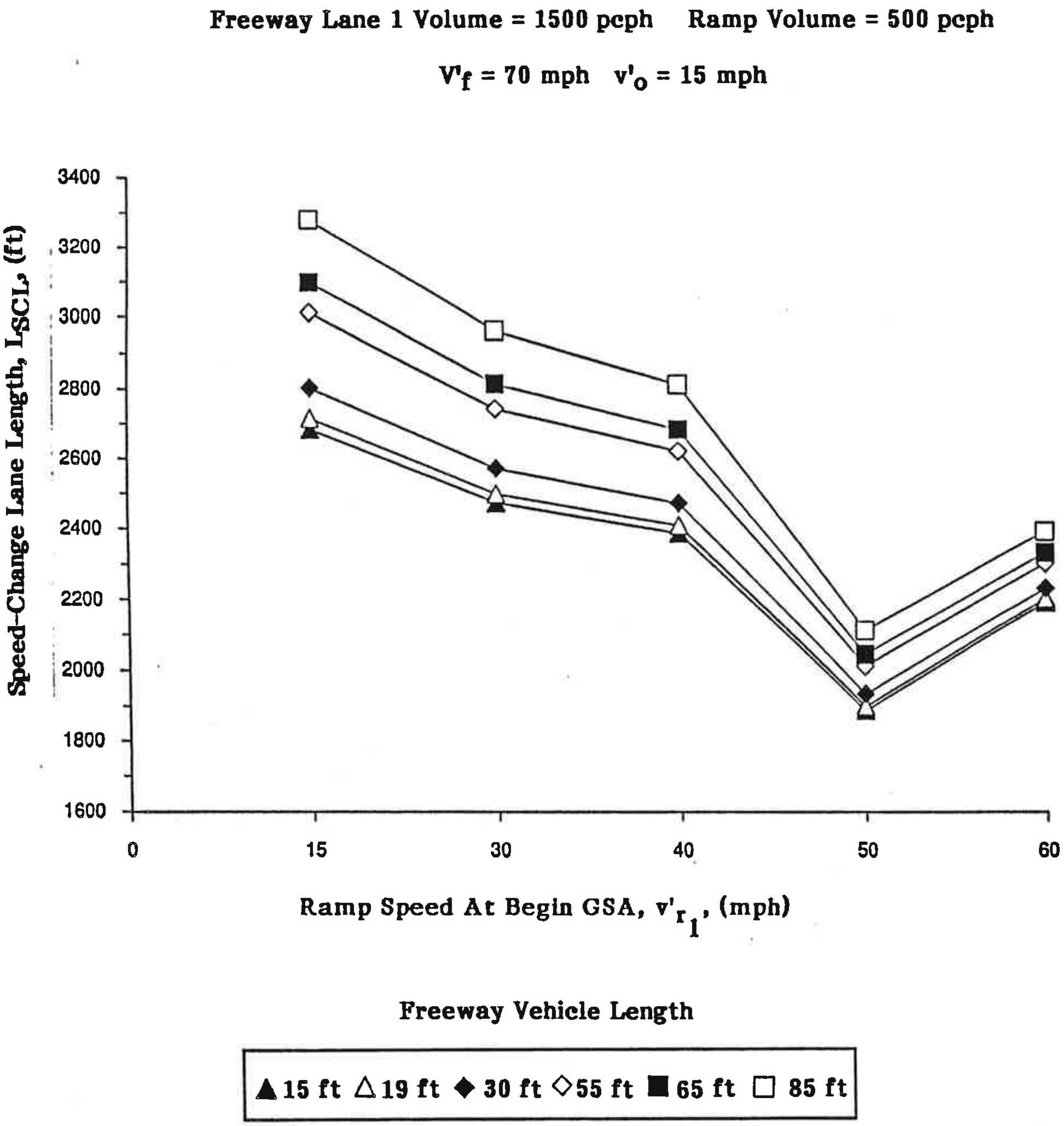


FIGURE 31

EFFECT OF FREEWAY VEHICLE LENGTH ON
ACCELERATION LANE LENGTH

acceleration lane length. The lengths chosen reflect findings of this project, as well as current AASHTO criteria.

The effect of ramp vehicle length only becomes significant at small speed differentials with freeway vehicles. This is because the ramp vehicle length appears in the model only with regard to the adjust position element, which is only significant when the speed differentials are relatively low. The overall range of effects is only about 250 feet. The effect of freeway vehicle length is more significant and is present across the entire range of possible speed differentials. The greatest range of values occur at the high speed differential because the length of the freeway vehicle enters the model primarily through the d_{hr} component. It should be understood, that the selection of a vehicle length for design requires that such a vehicle forms a large proportion of Lane 1 headways.

Design Application

The desire to develop a comprehensive mathematical representation of the dynamics of the entry process, which includes human factors considerations, has resulted in a rather complex model. The challenge is to transform the model so that it can be used in design.

Design Variables. As has been pointed out, there is a need to determine the values which best reflect reality for use in the entry model. Recommendation of these specific values is made in a section below.

The variables in the model may be divided into project specific and project independent factors. They may be further divided into designer chosen and policy-maker chosen. The resulting matrix of variables appears as Table 8. It is important to recognize that the designer, who is working on a particular project may be selecting horizontal and vertical curvatures, as well as grade. The impact of these

TABLE 8

CLASSIFICATION OF MODEL VARIABLES FOR DESIGN

		PROJECT LEVEL	
		PROJECT SPECIFIC	PROJECT INDEPENDENT
DECISION LEVEL	DESIGNER CHOICE	o Operating Speed at Ramp Controlling Condition (v'_o) & At Begin GSA (v'_r) o Grade (associated with acceleration rates)	None
	POLICY -MAKER CHOICE	o Design Vehicles o Design Speeds o Design Volumes	o Driver Attributes ($\dot{\omega}_t$, t_s, α, D', V_f) o Design Vehicle Characteristics (l_f, l_r, a_i)

elements is reflected in the model through associated assumptions on operating speed and acceleration rates. For a particular project, therefore, the designer, within limits, determines the speed on the ramp at the controlling condition and the speeds on the ramp and freeway at the begin GSA. The values for all other variables, or criteria from which the variables are determined, are specified at the policy level. This includes project-specific values for design speeds, design vehicles, and freeway and ramp volumes. All other values for variables in the model are usually not project specific and may be chosen independently, at the policy level.

Thus, by appropriate policy-level decision-making, it is possible to reduce the complexity of the model for the designer to the point where choices are being made regarding the geometric elements at a ramp entry. The model allows the designer the additional flexibility, not included in the current AASHTO guidelines, of trading off between the length of the acceleration lane to be located upstream, versus downstream, of the merging end. The policy maker is now provided with the ability to reflect aspects of the project, as well as the basic dynamics of the merging process, that were not previously possible. At the project level, it is possible to reflect different design vehicles, both on the ramp and Lane 1 of the freeway. It is also possible to reflect volume conditions. At a more basic level, the designer may now account for human factors considerations through selection of driver attributes.

Design Values. Table 9 contains tabulations of the three critical zone lengths which, together, give the total acceleration lane length. The values that appear in Table 4 have been used as the preliminary default values to arrive at these tables. A level condition, and passenger cars as design vehicles, are also assumed. Two parts comprise Table 9:

TABLE 9

CRITICAL ZONE LENGTH TABULATIONS

NCHRP PROJECT 3-35 DESIGN VALUES: SPEED CHANGE LANES

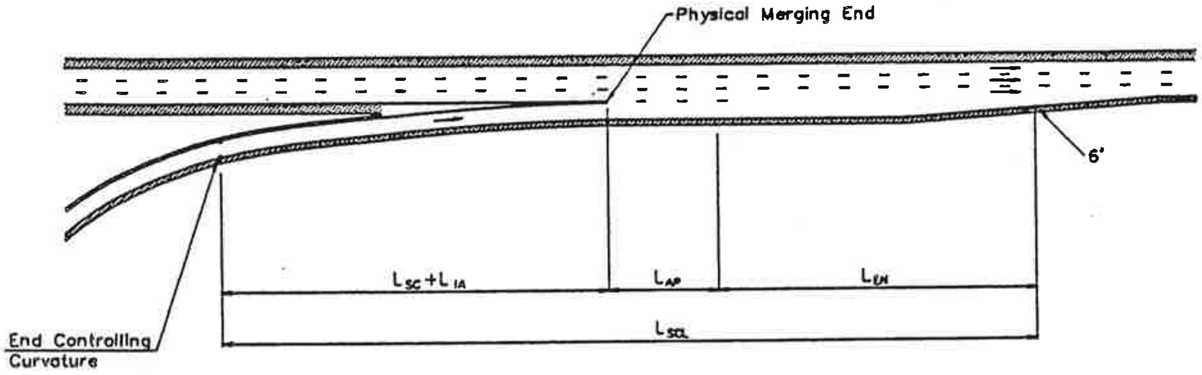
v_r (mph)	$L_{SC} + L_{IA}$ (ft)						L_{AP} (ft)	L_{EN} (ft) MAX RAMP VOLUME (pcph) =		
	v_o (mph)							-	250	500
	0	15	30	40	50	60		(LOS C)	(LOS D)	(LOS E)
0	0	-	-	-	-	-	2	-	1812	2628
15	40	23	-	-	-	-	40	-	1492	2115
30	161	168	45	-	-	-	122	-	1061	1185
40	287	318	296	60	-	-	248	-	937	1032
50	448	512	619	544	75	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-

a) FREEWAY LANE 1 VOLUME = 1500pcph
FREEWAY LANE 1 SPEED = 50 mph

v_r (mph)	$L_{SC} + L_{IA}$ (ft)						L_{AP} (ft)	L_{EN} (ft) MAX RAMP VOLUME (pcph) =		
	v_o (mph)							-	250	500
	0	15	30	40	50	60		(LOS C)	(LOS D)	(LOS E)
0	0	-	-	-	-	-	1	-	1969	2847
15	40	23	-	-	-	-	35	-	1822	2617
30	161	144	45	-	-	-	92	-	1580	2229
40	287	269	196	60	-	-	157	-	1412	1953
50	448	430	389	302	75	-	269	-	1068	1178
60	645	628	626	598	469	90	474	-	991	1083

b) FREEWAY LANE 1 VOLUME = 1500pcph
FREEWAY LANE 1 SPEED = 70 mph

NOTE: FINAL TABLE FOR DESIGN USE WILL HAVE VALUES ROUNDED TO THE NEAREST 25 FEET



a) Freeway Lane 1 Volume = 1,500 pcph and Speed = 50 mph; and

b) Freeway Lane 1 Volume = 1,500 pcph and Speed = 70 mph.

Each of these tables consists of three interrelated parts. The first part allows the designer to determine the combined length of L_{SC} and L_{IA} by assuming values for v'_O and v'_r. The other two parts of the table are entered by moving along the row representing the chosen v'_r. The L_{AP} value is read directly, while the L_{EN} value is dependent upon the ramp volume used. Shown in the table, are the ramp volumes (in pcph) that correspond to the maximum for LOS C, D and E for the given freeway Lane 1 volume. It is not expected that the project design engineer would select the design LOS. In fact, it is likely that most ramps would be designed for some worst case scenario (say LOS E). However, it is possible that the standard for rural conditions, where LOS E is not likely to occur, might be designed for a ramp volume at approximately LOS D. For the ramp volume used in Table 9, it is not possible to attain LOS C.

The designer has the alternative of entering the first part of the table with a desired value for $L_{SC} + L_{IA}$. In this case, the associated v_r for the ramp controlling speed may be found. The designer then proceeds to determine L_{AP} and L_{EN} as described previously.

The format for presenting design values is similar to that appearing in the current AASHTO criteria. To present values to the designer using the AASHTO format would require many more tables than are presently employed, because of the addition of design variables associated with the new model. The final format proposed for the user appears in the companion to this report.

Table 9a is for a freeway speed of 50 mph. As a result, the row for v'_r=60 mph is not applicable. The values for L_{AP} and L_{EN} do not change from v'_r = 40 to

50 mph. This is due to the fact that as the speed differential approaches zero, the model provides very large, unreasonable values for L_{AP} and L_{EN}. It was felt that the values presented in Table 9 for v'_r = 50 mph, were most appropriate. In order to overcome this limit of the model, one must assume that, under the assumptions of the design condition, the driver will adopt a significant, non-zero, speed differential at the begin GSA so as to facilitate entry to the traffic stream. It is recommended that a value of 10 mph be used for that speed differential. Thus, a final user version of the design values for a freeway with a speed of 50 mph would not list ramp speeds at the beginning GSA above 40 mph. Additional example design values for various combinations of model variables are provided in Appendix G.

Comparison with Current AASHTO Values. Table 10 and Figures 32 and 33 provide tabular and graphic comparisons, respectively, between the acceleration lane lengths derived from the proposed entry model and the current AASHTO standards. The AASHTO values were based upon Table X-4 of the Green Book (14). However, due to various differences between the two models, the AASHTO values have been adjusted in order to achieve comparability. A primary difference between the models is that the AASHTO values are based on design speed and the entry model values are based on assumed vehicle operating speeds. Therefore, the AASHTO values were adjusted to represent vehicle operating speed. AASHTO values do not cover operating speeds above 53 mph on the freeway and 44 mph on the ramp. Therefore, it was necessary to extrapolate values to complete the comparison. In addition, AASHTO recommends that the portion of the acceleration lane downstream of the merging end remain above some minimum length, regardless of the speed differential between ramp and freeway. Additionally, the AASHTO values were adjusted to account for the definition of the end of the acceleration

TABLE 10

COMPARISON OF NCHRP 3-35 AND AASHTO VALUES FOR ACCELERATION LANE LENGTH

v_r' (mph)	Acceleration Lane Length (ft) V_f' (mph) 70 3-35	70 AASHTO	60 3-35	60 AASHTO	50 3-35	50 AASHTO
0	--	--	--	--	--	--
15	--	--	--	--	--	--
30	2,387	2,795	2,150	2,070	1,373	1,345
40	2,326	2,795	1,620	2,070	597	1,345
50	1,858	2,795	1,911	2,070	--	--
60	2,204	2,795	--	--	--	--

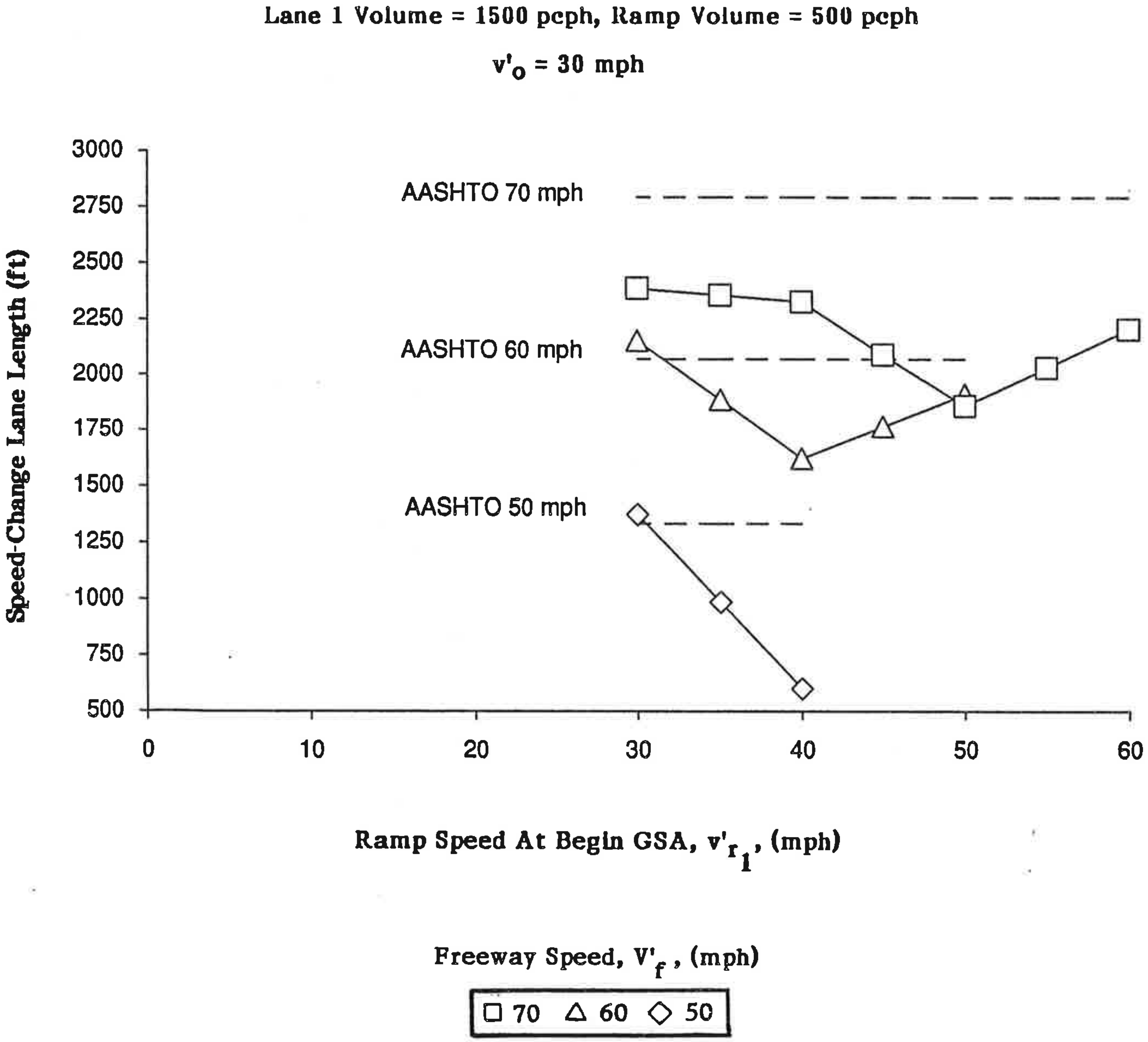
v_o' = 30 mph
Lane 1 Volume = 1,500 pcph
Ramp Volume = 500 pcph

TABLE 10 (CONTINUED)

COMPARISON OF NCHRP 3-35 AND AASHTO VALUES FOR ACCELERATION LANE LENGTH

v_r' (mph)	Acceleration Lane Length (ft) V_f' (mph) 70 3-35	70 AASHTO	60 3-35	60 AASHTO	50 3-35	50 AASHTO
0	--	--	--	--	--	--
15	--	--	--	--	--	--
30	2,162	2,795	1,933	2,070	1,431	1,345
40	2,107	2,795	1,669	2,070	1,628	1,345
50	1,899	2,795	1,941	2,070	--	--
60	2,230	2,795	--	--	--	--

v_o' = 30 mph
Lane 1 Volume = 1,800 pcph
Ramp Volume = 200 pcph



Lane 1 Volume = 1500 pcph, Ramp Volume = 500 pcph

$v'_o = 30$ mph

FIGURE 32

L_{SCL} VALUES COMPARED WITH AASHTO

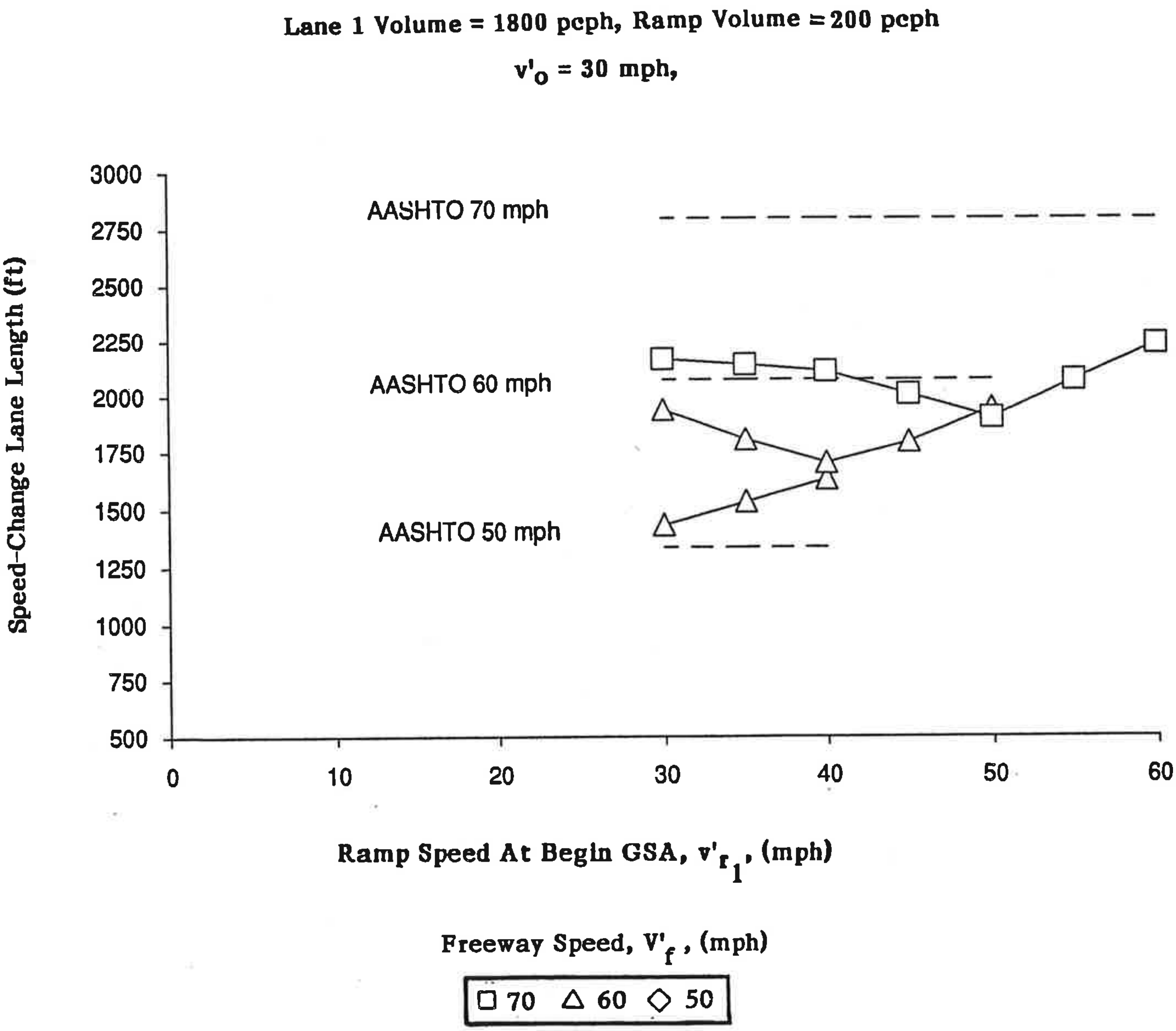


FIGURE 33

L_{SCL} VALUES COMPARED WITH AASHTO

lane, the 12-foot width of the taper according to AASHTO and the 6-foot taper width in the entry model. The values provided in Figure X-68 of the Green Book allow approximately 690 feet for the entry process. This limitation is not reflected in Table X-4, but has been reflected in the comparison values used in Table 10. A detailed description of the methodology used to generate the adjusted AASHTO design values is provided in Appendix G. An alternative comparison is also provided in Appendix G.

One difference that is not accounted for in the comparison values is that AASHTO assumes that the freeway speed, less 5 mph, is reached by the ramp vehicle by the last point along the entry lane at which the width is 12 feet. For the model, no assumption, or constraint, is placed on the speed at the end of the d_{hr} or at the end of the SCL (which is taken as point with a 6-foot width). However, a check of resulting speeds shows that speed differentials on the order of less than 10 mph occur at the end of the d_{hr}, and if the vehicle remains in the ramp lane until the end of the VC zone, the desired freeway entry speed will have been reached. This may be seen in the center section of the tabulations of the example acceleration lane design values located in Table G-6 of Appendix G.

The comparison may be most readily accomplished by studying Figures 32 and 33. The NCHRP 3-35 values resulting for the 70 mph freeway condition are generally below those projected to be associated with the AASHTO criteria, except at high speed differentials between the ramp and freeway vehicles. For a 50 mph speed on the freeway, the lengths generated by the model are generally longer than those used by AASHTO. The differences are fairly significant for speed differentials of 35 mph or greater. These relationships hold for both volume levels shown. The differences seem to result from the varying effect of the speed at the begin GSA, primarily as it affects the d_{hr}. The model's values, however, are of the same order of magnitude as the AASHTO values. Except for the very extremes, the values are within 500 feet of what is currently used by AASHTO.

Entry Model Calibration and Validation

During development of the various components representing the entry model, data were collected at a variety of entrance ramps. These data were used to gain a better understanding of the entry process, calibrate certain key variables identified in the sensitivity analyses, and test the validity of the overall model. Presented here are several of the data used for calibration and validation purposes. The methodology used for the data collection is discussed in Appendix C and the field data is summarized in Appendix D.

As previously discussed, the threshold angular velocity, ω_t, is a critical variable. Variation in the value of threshold angular velocity selected for the model has a significant impact on GSA length and overall acceleration lane length, as shown in Figure 28. Figure 34 shows the distribution of threshold angular velocities based on field measurements of individual vehicles. About 43 percent of the vehicles studied had threshold angular velocities below 0.01 rads/s. This tends to support the theoretical assumption of angular velocities on the order of 0.001 to 0.01 rads/s. The preliminary design value selected, of 0.002 rads/s, represents approximately 15 percent of the field observations, equal to an 85th percentile design condition. Restated, a threshold angular velocity of 0.002 rads/s will ensure that 85 percent of all drivers will accept a gap producing an angular velocity of equal or greater value. Therefore, a value of 0.002 rads/s appears to be reasonable based on the field data and falls within the range of the expected values.

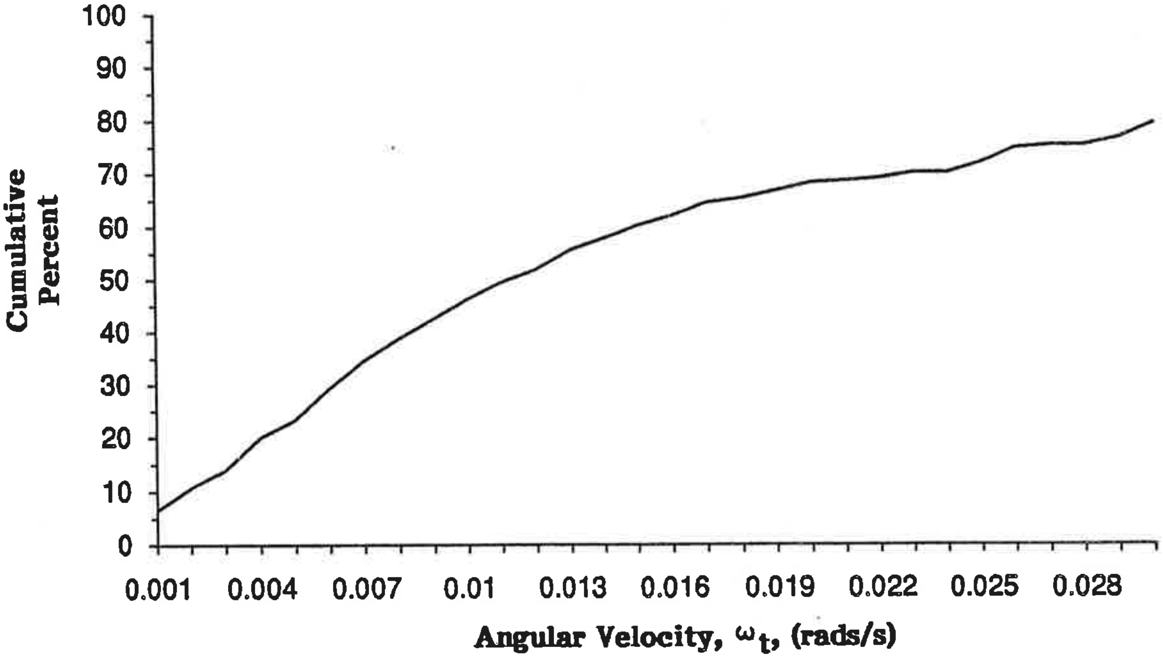


FIGURE 34

DISTRIBUTION OF MEASURED ANGULAR VELOCITY AT MERGE

Figure 35 shows the distribution of the times observed to complete the merge steering maneuver. This maneuver is defined as when the driver steers from the acceleration lane completely onto Lane 1 of the freeway. The 15th, 50th, and 85th percentiles are approximately 1.25, 1.75, and 3.24 seconds, respectively. These observed values compare favorably with the expected range of between 1.5 and 3.0 seconds. The average time spent completing the merge steering maneuver was 2.3 seconds. The average merge time for trucks was also 2.3 seconds. Hence, selecting a value of 2.0 seconds for t_s is reasonable.

Figure 36 presents speed differentials observed at the sites studied. AASHTO has selected 10 mph as an acceptable speed differential, considering accident rates. The 15th percentile of the positive values, considered to represent the preferred design criteria, provides a speed differential of approximately 5 mph. Selection of a higher speed differential as the basis for entry model, however, would provide shorter acceleration lane lengths and uncomfortable speed differentials for too many drivers at merge. Therefore, a 5 mph speed differential is definitely within the range of values observed in the field and would provide reasonable model results.

Several components of the entry model were not calibrated or validated using field data for several reasons. First, depending upon the variable, it was not possible to collect the data required for testing. Second, the data collected did not provide accurate measures of certain variables, especially higher order variables, such as accelerations. The values selected for these variables were based on current knowledge, general field observations, and engineering judgement.

Figure 37 displays a graph of the available entrance length, L_{EN}, at each site, plotted against the observed percent forced merges at that site. Forced merges were defined as any merge which resulted in the braking of lagging vehicles in

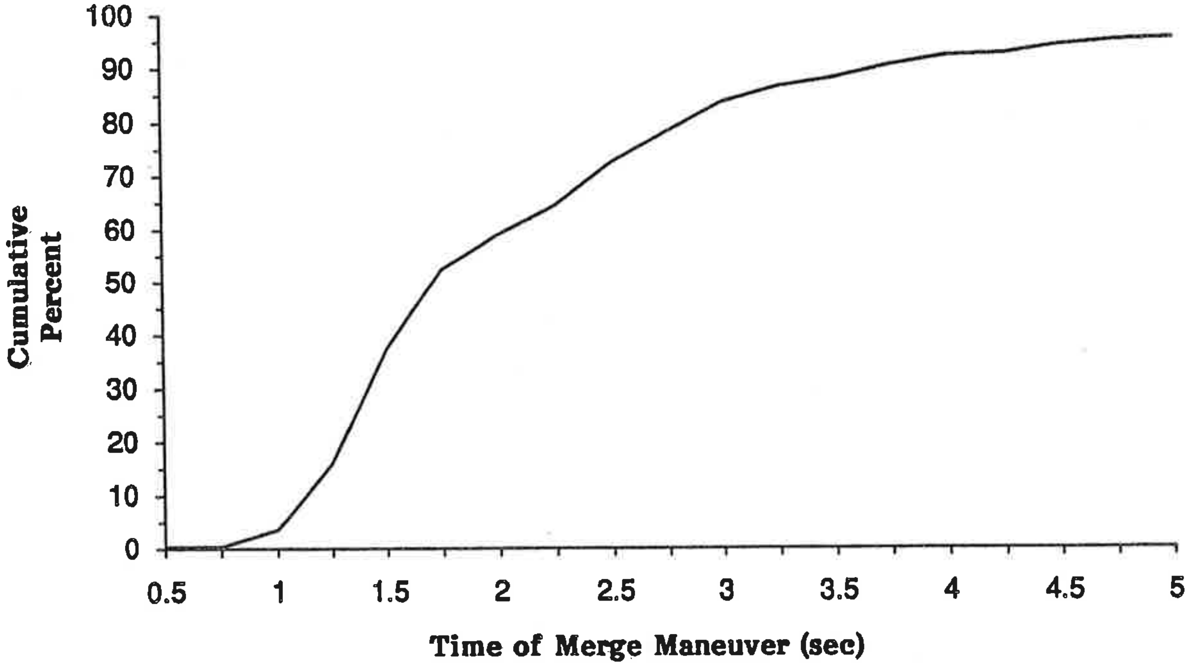


FIGURE 35

DISTRIBUTION OF OBSERVED TIME TO COMPLETE THE MERGE STEERING CONTROL MANEUVER

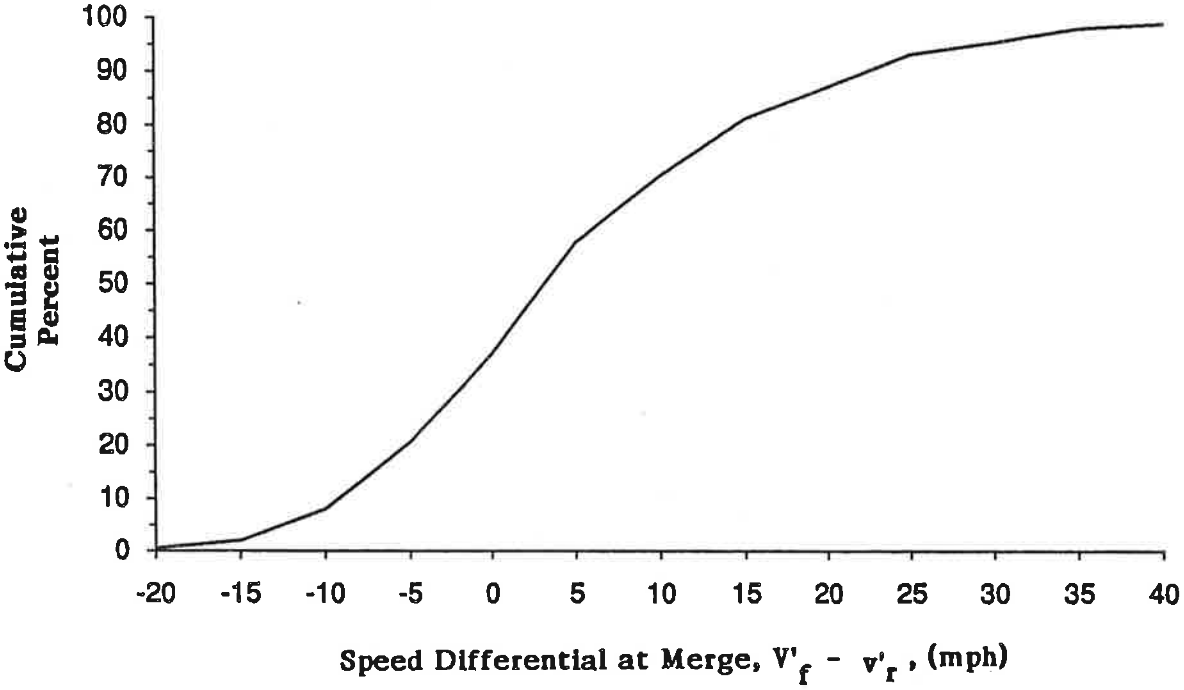


FIGURE 36

DISTRIBUTION OF OBSERVED SPEED DIFFERENCE BETWEEN RAMP VEHICLE AND FREEWAY LANE 1 VEHICLE AT MERGE

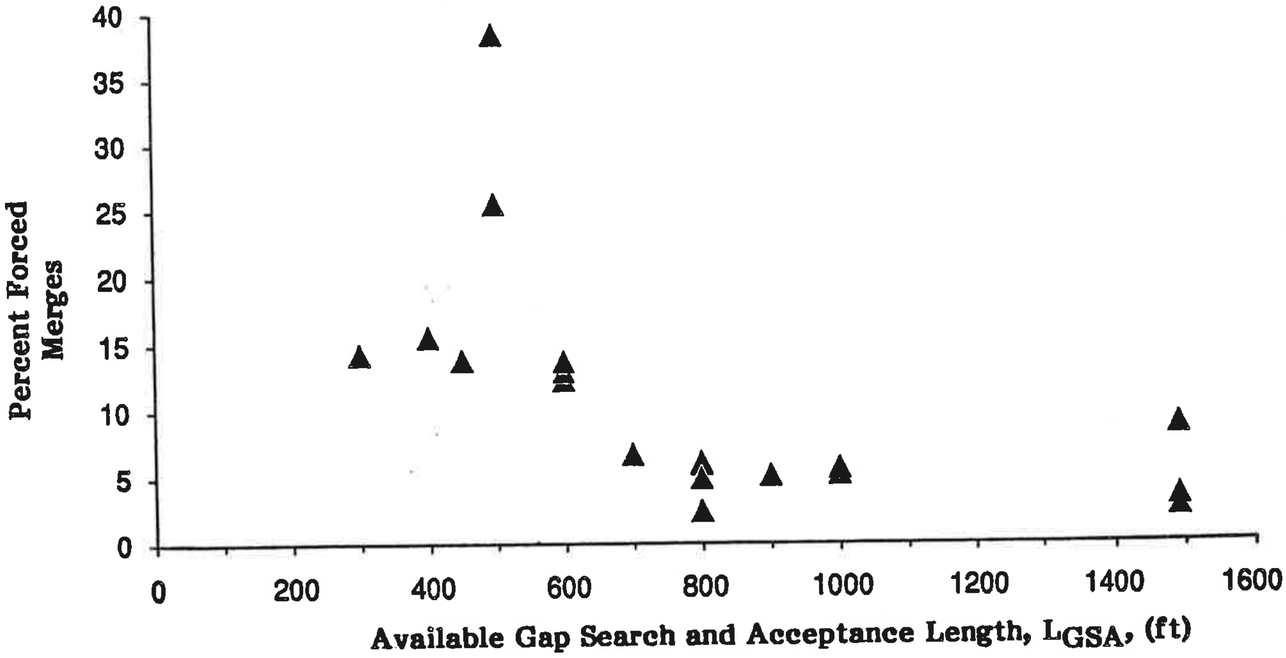


FIGURE 37

RELATIONSHIP BETWEEN PERCENT FORCED MERGES AND AVAILABLE L_{GSA}

Lane 1, or relatively quick lane changes by lagging vehicles, from Lane 1 to a lane to the left. The forced merge data is summarized by site in Appendix D.

Figure 37 shows a definite trend toward a minimum rate of about 5 percent as the available L_{EN} approaches 900 to 1,000 feet. The plot includes a range of ramp controlling speeds, ramp volumes and Lane 1 freeway volumes. The average speed in Lane 1 of the freeways was 50 mph and the average ramp speed at begin GSA was 45 mph. The freeway volumes ranged between 1,200 and 1,500 vph. The ramps were generally low volume. If the average conditions were considered as the design condition, the model would predict the need for a L_{EN} of between 800 and 900 feet, which is reasonable agreement with what this particular measure of effectiveness would suggest is needed.

Figure 38 displays the forced merge data from a different perspective, the speed difference between the freeway and ramp vehicles at merge, plotted against the observed percent forced merges at each site. Figure 38 shows that the frequency of forced merges is not correlated to the speed differential at merge. This suggests that drivers do not merge in response to some threshold speed differential as assumed by AASHTO. Rather, ramp drivers will merge at any speed differential, in response to another element of the freeway Lane 1 vehicle angular velocity.

Overall, entry data collected support the model which describes the entry process. Regression analysis were performed on several components of the model, however, the results provided only fair correlations between predicted and observed values. As described here, however, analysis of certain critical model components provide reasonable results and tend to support the entry model.

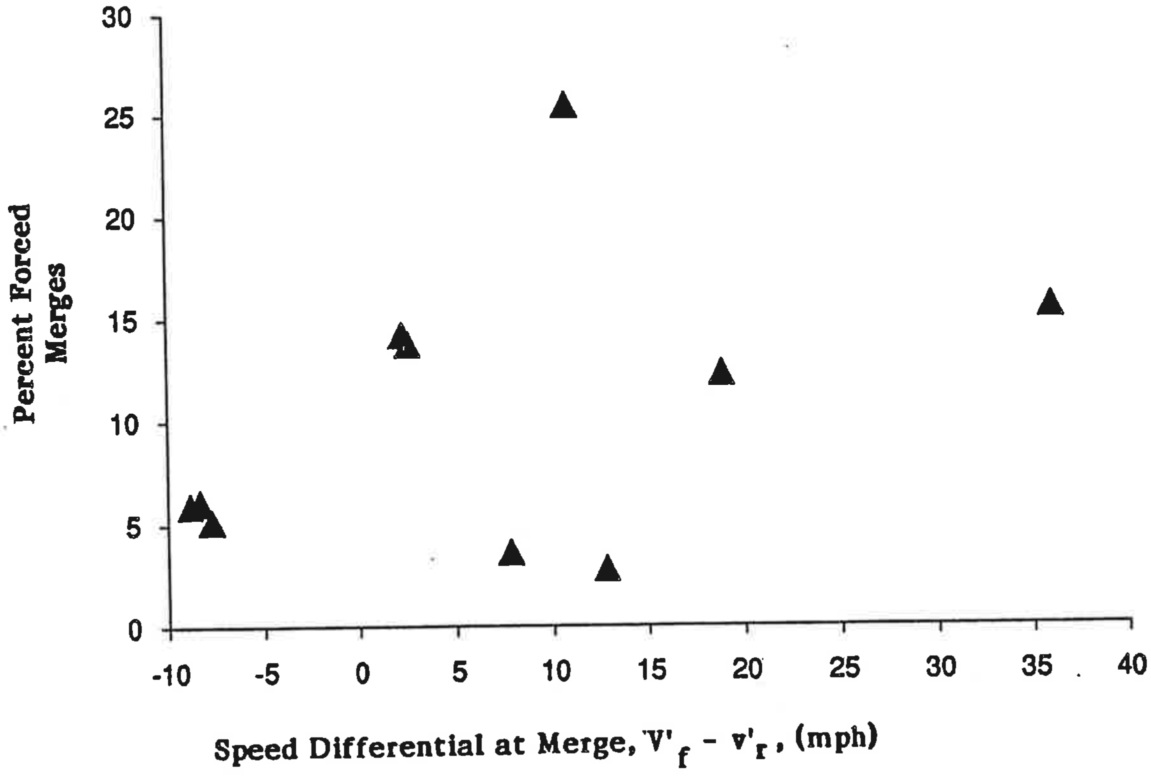


FIGURE 38

RELATIONSHIP BETWEEN PERCENT FORCED MERGES AND SPEED DIFFERENTIAL AT MERGE

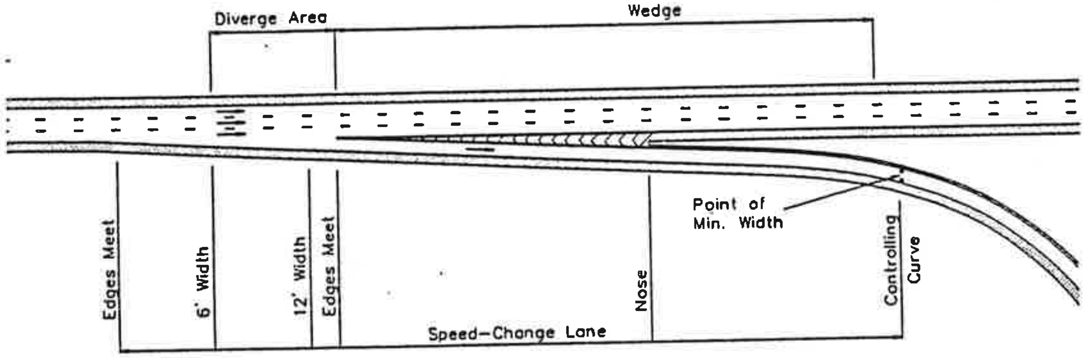
DYNAMICS OF THE EXIT PROCESS

Similar to the entry process, exiting from a freeway onto a ramp requires a series of navigational tasks for the driver. Within each task, the driver must process roadway and traffic information, translating that information into steering and speed control responses. This section outlines the basic driver behavioral tasks which comprise the exit process and formulates the foundation for an exit lane design model.

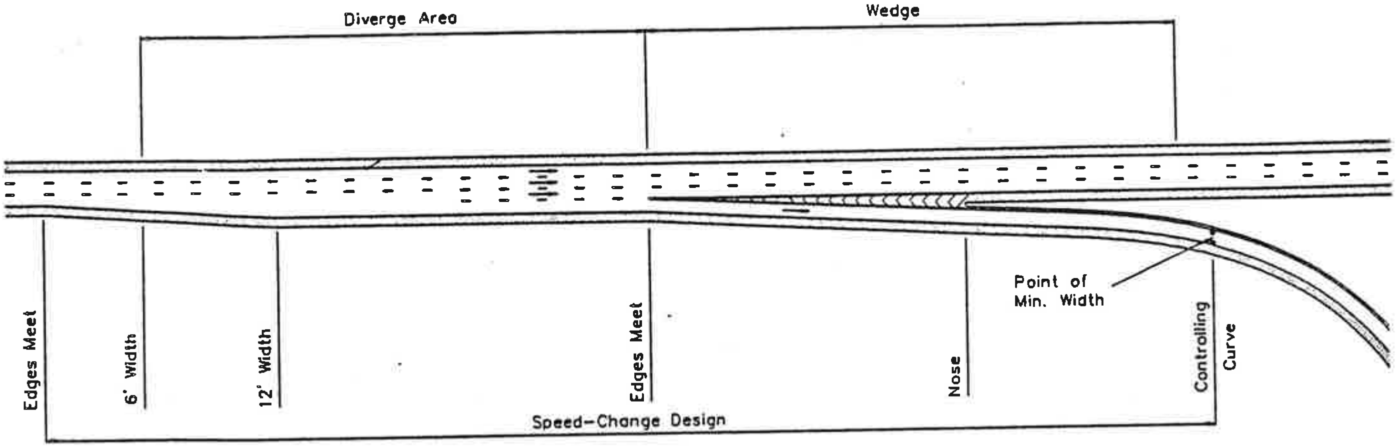
The exit process is more simplistic than the entry process requiring fewer driver tasks to complete the maneuver. The freeway exit process can be broken down into two behavioral tasks required by the driver. First, is the steering maneuver to transition from the mainline onto the exit lane. Second, is the deceleration control on the exit lane in response to some ramp geometry or condition. Within these two basic tasks are several subtasks which the driver must perform as part of the exit process. The following discussion presents the dynamics of the freeway exit process for a single-lane exit ramp. Figure 39 illustrates typical deceleration lane designs.

The Exit Process

As a driver approaches an exit, he first recognizes the taper diverging from the freeway lane. Essentially, he sees a widening of the overall roadway. This recognition is determined mainly by the change in the driver's visual angle subtended by the roadway. If we assume that the roadway is homogeneous in contrast between the median and shoulder, the addition of the deceleration lane simply adds an increment in roadway width, i.e., the visual angle of the roadway eventually increases by at least 12 feet. However, there are also elements of roadway surface texture, edge marking, signing, etc., located in and adjacent to the deceleration



PARALLEL DESIGN



TAPERED DESIGN

FIGURE 39

TYPICAL DECELERATION LANE DESIGNS

lane, will generate a component of angular velocity. The distance at which the deceleration lane may be detected, assuming a tangent section with unobstructed view, is simply the minimum incremental change in the visual angle that the driver can detect. The angular velocity generated is determined by both the speed of travel and the lateral location of the elements. Thus, as drivers approach the beginning of the deceleration lane, a point is reached where the angular velocity approaches their threshold of detection. The field of perceived motion begins to include the deceleration lane. It is at this point in time and distance, that the deceleration lane becomes a cue and stimulus to driver action.

A critical problem for the driver is the determination of the point at which the diverge steering maneuver should begin in order to move onto the deceleration lane. We would hypothesize that the key determinant in an unconstrained operation is either the ramp nose or the ramp curve. The nose defines the beginning of the exit ramp that the driver must negotiate. Similarly, depending upon the design of the ramp curve, it would also provide an essential cue, since at some distance the approaching driver will detect a component of angular velocity of the curve. We would further hypothesize that the cue for the driver to begin a steering maneuver would be the point where the angular velocity of the ramp nose, or curve, reaches the driver's angular velocity threshold. It is at this distance then that we would predict the beginning of the diverge steering maneuver.

In the design of the deceleration lane geometrics, the distance at which angular velocity is detected is critical. The driver must, at this point, begin a steering maneuver that takes him onto the deceleration lane. The driver must then initiate a compensating yaw movement in order to be on a straight course towards the exit ramp. This diverge steering maneuver should be completed prior to the point where the driver must begin the speed change, or deceleration, needed to negotiate the ramp curvature or come to a stop.

Once the driver has completed the diverge steering maneuver, transitioning from the freeway lane to the deceleration lane, the task of decelerating in response to the ramp geometry, or some other ramp condition begins. Essentially, the behavioral dynamics of the deceleration process are similar to those in the steering process. The angular velocity of some component in the driver's visual field, as he is traveling on the ramp, such as the ramp curvature or a queue of stopped vehicles at the ramp terminus, is the key element in determining the deceleration which will occur. In the case of a curved ramp, the driver will decelerate in gear until the angular velocity of the ramp curvature reaches his threshold value. Once the threshold of the driver's angular velocity has been reached, this is a signal to the driver to initiate braking in order to reduce the vehicle's speed to a level which will allow the driver to begin tracking and steer through the curve. Due to the inability of the driver to perform two tasks simultaneously, i.e., curve tracking, and braking, the driver must either perform the braking task prior to entering the ramp curvature or alternate, in a time-share mode, between braking and steering while traveling through the curve. The former process is consistent with most empirical studies.

It is important to keep in mind that the driver will not begin braking until the perceived angular velocity threshold for curve tracking is reached. Prior to that point, the driver will operate on expectancy and decelerate in gear. On a tangent, diamond-type ramp, with little or no curvature, the cue which signals the driver to begin braking is some condition at the ramp terminus. This may be either a stopped vehicle, a stop sign, or a traffic signal. The angular velocity of any of these components in the driver's visual field determines when the object is perceived and, thus, when braking begins. When an exiting vehicle is in a moving queue, following another vehicle at relatively close distance, driver behavior becomes one of car-following and deceleration is controlled by the leading vehicle. In such a case, the leading vehicle is the one of interest for design purposes.

In this discussion, the key elements which define the dynamics of the exit process have been defined. Additionally, the key guidance and control variables used by drivers to perform the exit process have been identified. A more detailed discussion of driver behavior on exit ramps is contained in Appendix F. Additional discussion of angular velocity relating to the exit process is provided in Appendix B. The exit process can be summarized as follows:

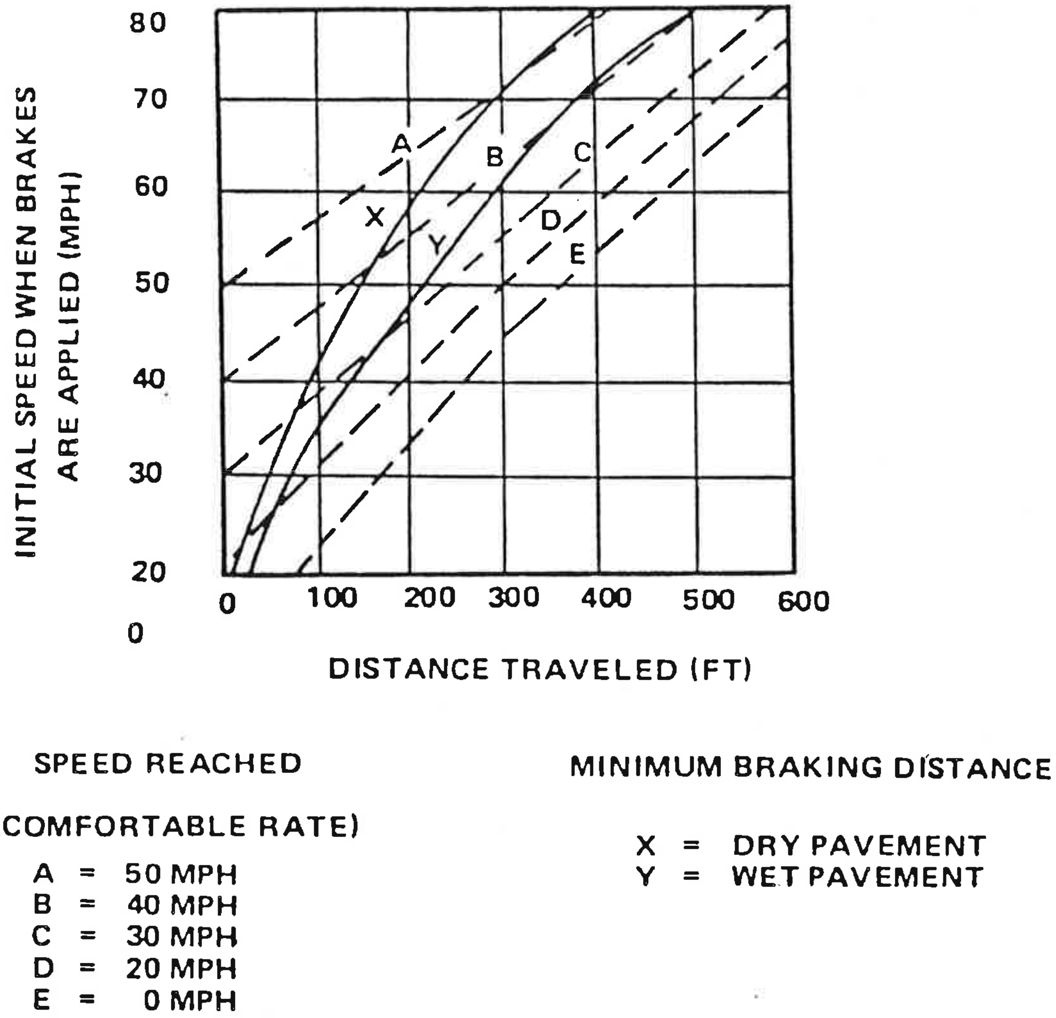
1. The driver determines the beginning of the deceleration lane.
2. The driver detects the position of the vehicle relative to the deceleration lane.
3. The driver begins the diverge steering maneuver from the freeway lane into the deceleration lane when the angular velocity of the ramp nose, or ramp curvature reaches a threshold level.
4. The steering maneuver is completed, placing the vehicle completely on the deceleration lane.
5. The driver decelerates in gear until the angular velocity of the ramp curvature or other ramp condition reaches a threshold level, at which time braking begins.
6. The driver brakes until an appropriate speed is reached to allow for curve tracking and steering in the case of a curved ramp or the driver comes to a stop in the case of a straight ramp.

Review of Existing Exit Models

It was felt that a model for the determination of deceleration lane length at exit ramps should reflect the driver tasks described in the exiting process. As a first step towards the development of the exit model, several existing models were identified and reviewed. These included the current AASHTO (15) model, a model developed by Baker (16), and a model developed for a previous issue of the Urban Highway Design Guide for the Province of Alberta, Canada (17).

Each of the models reviewed were conceptually similar, assuming that the driver would exit the freeway lane at some point at the beginning of the deceleration lane and then decelerate to an appropriate ramp speed. None of the models reflects driver behavior in determining the point at which the exit maneuver begins or the point at which braking begins. In the AASHTO model, the signal for the driver to begin the exit steering maneuver is the initiation of the tapered section of the deceleration lane. Once the steering maneuver has been completed, the driver will decelerate both in-gear and with braking to reach the controlling ramp speed. It is assumed that deceleration in gear will occur for 3-4 seconds, followed by braking at a comfortable rate of 9 f/s/s. Figure 40 shows the braking distances used in the AASHTO model to reach desired ramp speeds. The AASHTO model provides adjustment factors for grades, however, does not provide adjustment factors for heavy vehicles or high volumes.

The Baker model and the Urban Highway Design Guide model are essentially variations of the AASHTO model. The Baker model defines the beginning of the steering maneuver at the 12-foot point on the deceleration lane. At this point, the driver also begins the deceleration process, however, deceleration is not separated into in-gear and braking phases. Rather, an overall deceleration is assumed



Source: AASHTO Green Book (1), Figure II-13, Page 36

FIGURE 40

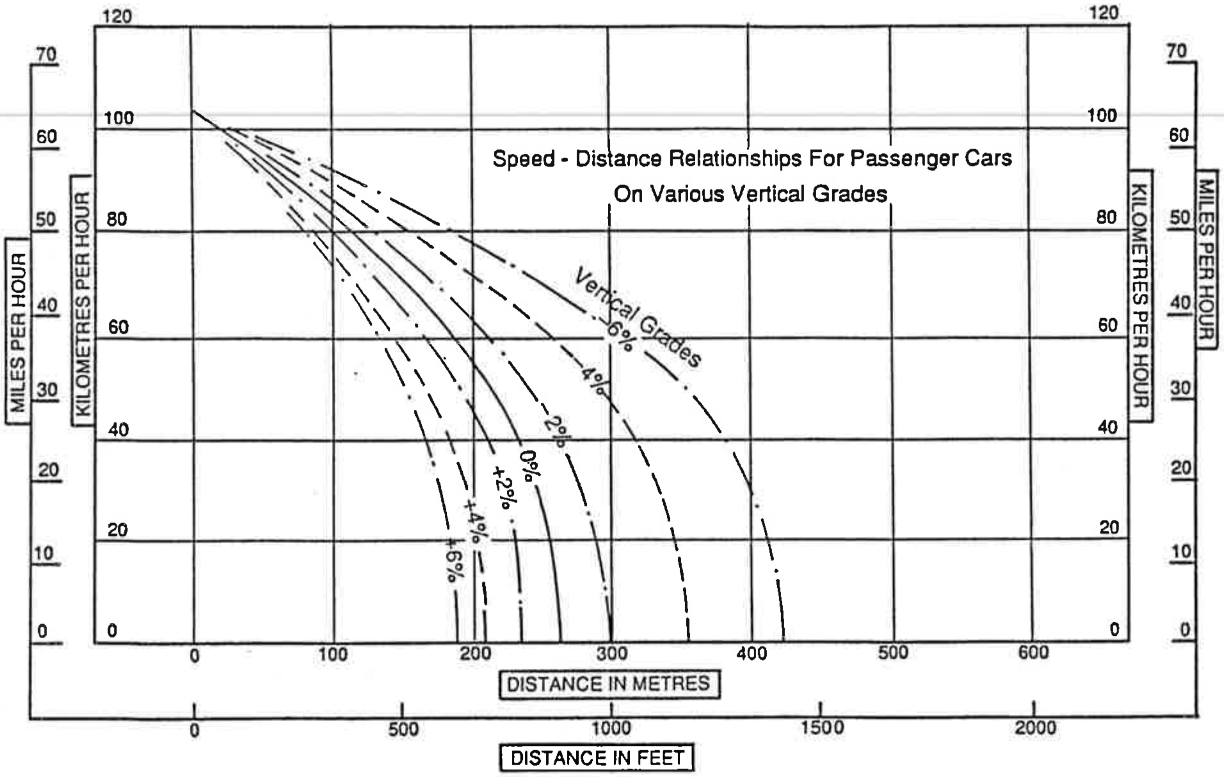
DECELERATION DISTANCES FOR PASSENGER VEHICLES APPROACHING INTERSECTIONS depending upon initial speed and grade. The speed-distance relationships used by Baker to determine deceleration distance are shown in Figure 41.

The Urban Design Guide model essentially follows the AASHTO concepts, however, additional control criteria are offered in order to locate the deceleration lane with respect to the exit wedge. The exit steering maneuver occurs at the 6-foot point on the deceleration lane, followed by deceleration, both in-gear and with braking, if necessary, prior to the nose of the exit wedge. Several examples of this process are shown in Figure 42. According to the Urban Design Guide model, it is assumed that the driver will decelerate to a speed 12.5 or 35.0 percent less than the freeway speed, prior to reaching the nose of the exit. The selection of the percentage of deceleration is dependent upon the ramp curvature or conditions. Additional deceleration would be required past the nose in order to reach the ramp controlling speed. Deceleration lane length adjustments for grades are handled similarly to the AASHTO model and two-lane exits are also reflected.

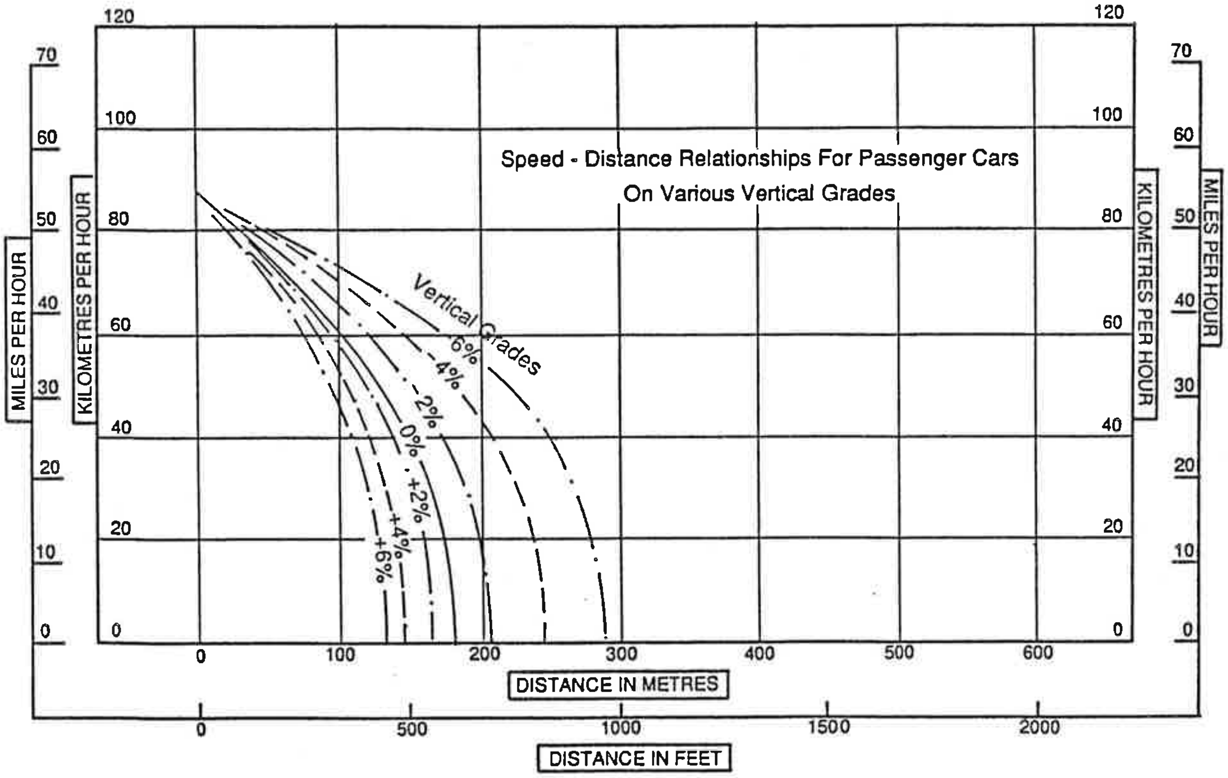
After review of each of the models described above, it was concluded that none of the models adequately reflect the dynamics of the exit process. All three models are based on deceleration requirements only and do not reflect driver behavior in the exit process. It was felt that in order to develop an appropriate exit model, all the elements of the exit process, both operational and behavioral, need to be considered. Not only could such a model provide a more realistic view of the exit process, but it could also provide the designer with greater flexibility in designing the deceleration lane.

Design and Operational Considerations

As previously stated in the discussion on the entry process, any inconsistencies or unexpected elements, along the deceleration lane or exit ramp will disrupt the



Initial Speed = 65 mph



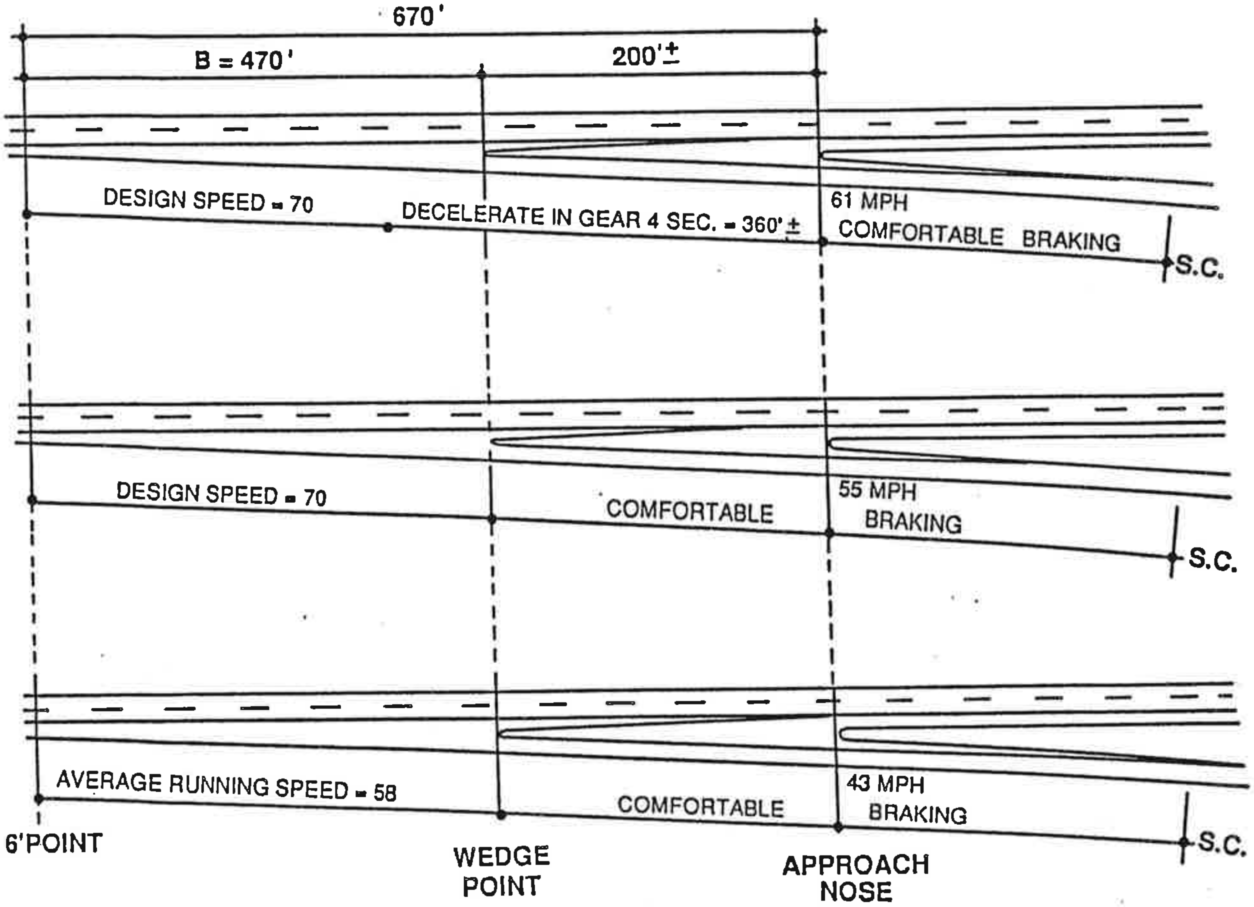
Source: Baker (3)

Initial Speed = 55 mph

Figure 41

NORMAL DECELERATION

(INITIAL SPEEDS 65 and 55 mph)



Source: **Urban Highway Design Guide (17), Figure 6-7, page 69**

FIGURE 42

URBAN DESIGN GUIDE MODEL

ability of the driver to process the required information with which to perform the exit process. In the exit process, however, the driver is leaving the major traffic stream and its complexities. Thus, exiting reduces the task load on the driver, eliminating many relative speed and position tracking tasks.

There are two potential critical overload problems for the exiting driver. One is the identification of the exit and the physical diverge of the deceleration lane. The initial cue to location of the exit is the angular velocity of the ramp curvature or divergence angle. If a driver has made the cognitive decision that the approaching exit is the appropriate one, the task becomes one of locating the diverging ramp and steering from the mainline onto the deceleration lane. Therefore, it is desirable to design the exit wedge area which provides a high degree of visibility to the driver and minimizes information which is both unnecessary and unwanted. In this respect, it is clear that flat geometry in the exit area is simpler for the driver to deal with. The driver does not have to process a high order angular velocity vector as in the case of sharp curvature. Further, flat geometry at the exit allows for a direct extension of the deceleration lane onto the ramp proper and, hence, requires little significant steering control in a critical area. Once the driver has entered the deceleration lane, the driving task essentially involves speed control. Furthermore, a tangent, diamond-type ramp eliminates any further need for steering control.

The second potential overload problem faced by the exiting driver is potential conflict with other vehicles on the deceleration lane or ramp. If traffic flow is relatively high (LOS C or worse), the driver must time share between the exit process and car following. Given moderate flow turbulence, the amount of time available to the driver to respond to the exit diverge will be reduced. There is a reasonable likelihood that a portion of the total time available for the diverge maneuver will be lost in the car following task. This time-sharing requirement could result in turbulence on the freeway, as exiting vehicles reduce their speed while still on the mainline in order to increase the time available to detect and respond to the exit diverge. To minimize this undesirable effect a clearly delineated exit and well-defined taper should be designed. A proper design utilizing pavement markings effectively will tend to "draw" the driver onto the deceleration lane and out of the traffic stream. This may be especially important in urban areas, where exits are frequent, higher freeway volumes are present, and signing can be ambiguous.

Visibility and environmental factors will also affect a driver's perception and response to the exit. In general, anything that reduces the brightness or contrast of the exit lane or the exit diverge will reduce the time and distance within which the driver can detect and track the exit. The most likely effect of reduced visibility is to lead drivers into the ramp controlling curve at a higher speed than desirable or to incur deceleration on the freeway prior to entering the deceleration lane. Similarly, environmentally-induced degradation, rain, fog, etc., might also cause drivers to reduce their speed prior to exiting the freeway lane. Appropriate lighting and delineation of the exit ramp and the deceleration lane may compensate to some degree for these adverse effects.

There are essentially two classes of freeway exit users, the familiar and the unfamiliar driver. The familiar driver requires minimal time for search and location of the appropriate point of initiation of the diverge maneuver, and overloading is generally unlikely. The unfamiliar driver faces the potential overload problems discussed earlier.

The conflicts among exiting drivers depends in part on the characteristics of the exit and familiarity of drivers. If there is a small angle of divergence of the exit ramp and there is a long deceleration lane, a driver has considerable latitude as to where he may initiate the diverge steering maneuver. In part, this is a matter of how "conservative" a driver is and in part (and more likely) the variation in angular velocity threshold among drivers. In either case, when there are several drivers exiting, there will be some variation in the distance at which the diverge steering maneuver is initiated. If the deceleration lane is long relative to the angle of divergence of the ramp, it is possible for a trailing driver to diverge from the freeway ahead of a more conservative driver. This is likely to occur in high volume off-ramps. One way that such conflicts may be minimized is to provide the shortest possible deceleration lane length coupled with a high degree of taper.

Human Factor Considerations

Similar to the entry process, however, angular velocity is the key component of the exit process which defines driver response. Unlike the entry process, the driver bases his decision to act, either diverge from the freeway, or begin braking, on the angular velocity created by geometric elements of the exit which are stationary relative to the exiting driver. It is the driver's threshold angular velocity which determines when action will be taken.

Time-sharing of driver tasks must also be considered in the exit process. In design of the exit ramp, it is desirable to minimize the amount of time-sharing which must occur during the exit process. This translates into greater driver efficiency during the exit process and could result in shorter distance requirements for the deceleration lane.

The length of a deceleration lane is constrained by the ability of a normal driver to decelerate at an acceptable rate. Drivers prefer deceleration rates, while braking, between 6 and 10 f/s/s. Higher rates are considered uncomfortable to the driver and cause poor driver performance on the ramp, thereby, reducing safety.

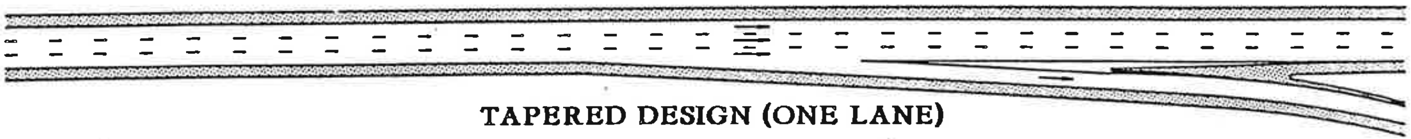
Parallel vs. Taper Design Considerations

Currently, AASHTO provides both a parallel and taper design for the deceleration lane. Figure 43 shows typical designs for single deceleration lanes. One design type is not seen as differing significantly from the other. As stated previously, however, the flatter geometry of the diamond-type exit ramp is easier to navigate than a curved design. It follows that a taper deceleration lane is consistent with the diamond-type exit. Its design involves a simpler linear divergence from the freeway lane. The taper design provides the driver with continuity of divergence and hence orients the driver onto the ramp with a minimal amount of steering control. The parallel design will produce discontinuity of angular velocity at the ramp junction. Although such a change is manageable by the driver, continuity in angular velocity is preferable.

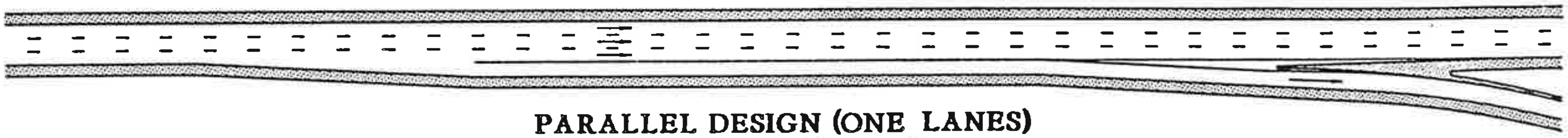
Two-Lane Exit Ramps

The previous discussion on the exit process was based on a single-lane exit ramp. The basic components of the exit process, however, can also be applied to two-lane exit ramps. Figure 43 also illustrates taper and parallel type designs for two-lane exit ramps from AASHTO.

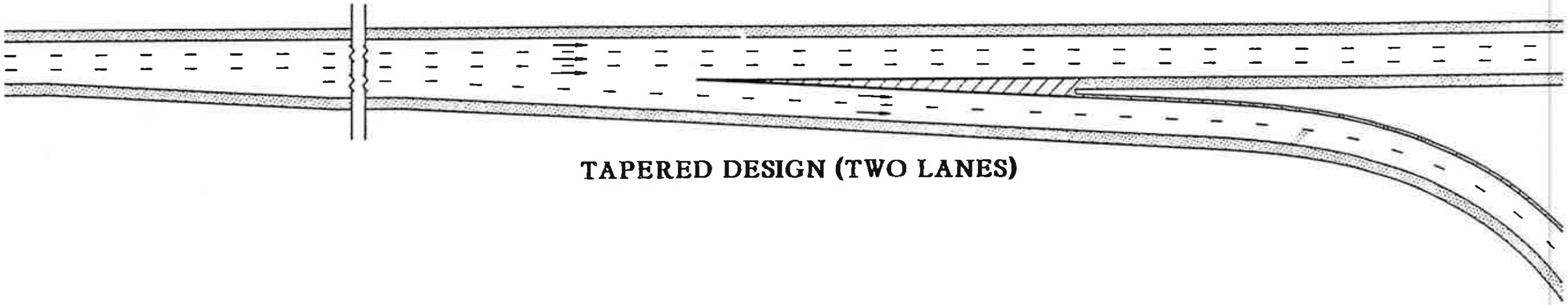
In the taper design, the driver on the outside, or auxiliary, lane has already left the mainline and needs only decelerate in response to the exit geometry or conditions. The inside deceleration lane is used the same way as a single-lane exit ramp. The driver must steer from the freeway mainline onto the deceleration lane



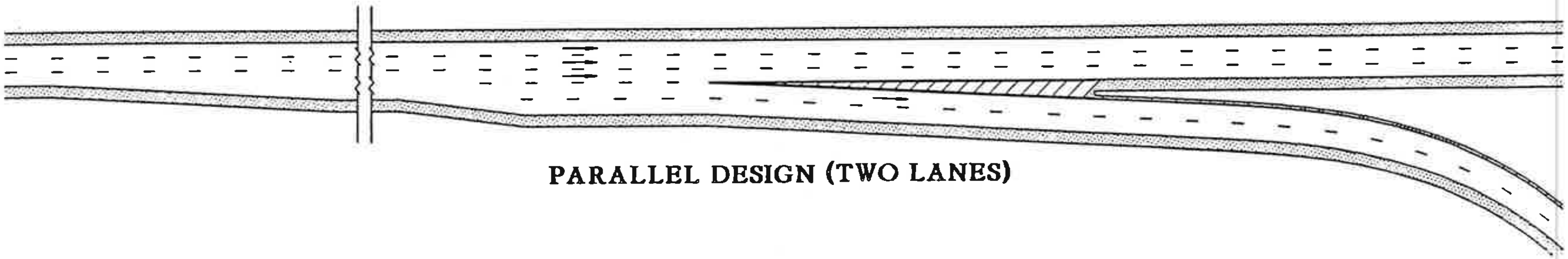
TAPERED DESIGN (ONE LANE)



PARALLEL DESIGN (ONE LANES)



TAPERED DESIGN (TWO LANES)



PARALLEL DESIGN (TWO LANES)

FIGURE 43

TYPICAL TAPERED AND PARALLEL DESIGNS
OF ONE AND TWO- LANE EXIT RAMPS

and decelerate accordingly. Therefore, the length of the deceleration lane is based on the requirements of those drivers on the inside lane who must perform two driving tasks. A two-lane design would require additional information to the driver well upstream of the exit in order to provide for proper operation.

The parallel type design operates similarly to the taper design, however, the drivers in both exiting lanes must now perform both the steering and deceleration tasks.

The driver on the outside or auxiliary lane faces a more difficult task in determining when to initiate the diverge steering maneuver since his visibility of those components of the exit which normally signal the beginning of the deceleration lane, could now be obstructed by exiting vehicles in the adjacent or inside lane. Therefore, it is reasoned that the parallel type design would not operate as effectively as the taper type design of two-lane exit.

A Model of Deceleration Lanes

Framework. Based on the exit process dynamics and human factor considerations described earlier, the deceleration lane was divided into the following zones as illustrated in Figure 44.

1. Diverge Steering Zone (DS) which defines the distance upstream from the exit wedge at which the driver's angular velocity threshold is reached and the steering maneuver to exit the freeway is initiated.
2. Steering Control Zone (SC) in which the driver steers and positions the vehicle from the freeway lane onto the deceleration lane.
3. Deceleration In-Gear Zone (DG) in which the vehicle decelerates prior to braking.

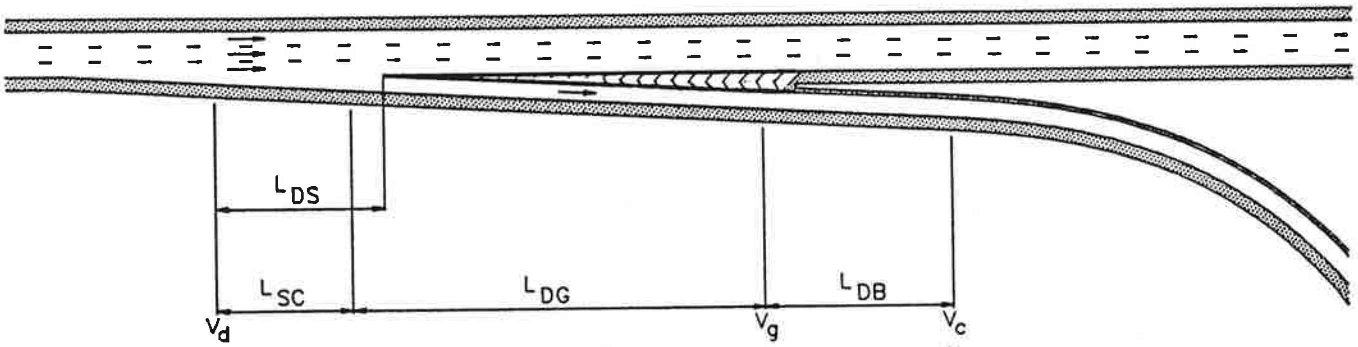


FIGURE 44

EXIT MODEL FRAMEWORK

4. Deceleration While Braking Zone (DB) in which braking occurs in order to decelerate to an appropriate speed controlled by the ramp geometry, traffic conditions, or the ramp terminus. The length of the DB is defined as the distance upstream from the speed control point at which the angular velocity of the driver reaches a threshold and braking occurs.

Two geometric design cases were considered during development of the exit model. These included a tangent or diamond-type exit ramp and a curvilinear exit ramp, such as a loop or outer connector. The tangent exit ramp is most frequently referred to in the following discussion for purposes of simplicity and brevity. The basic model was, however, developed for both design types and was predicated on a level exit ramp to the right.

Mathematical Model

The mathematical components which describe the exit model zones were developed using established speed-distance relationships and data obtained from field studies. Only a brief discussion of the development of the mathematical relationships will be presented here. A more detailed derivation of the exit model equations is presented in Appendix B. The basic equations for the exit model are listed in Table 11. Definition of the exit model nomenclature is given in Table 12.

Diverge Steering Zone (DS). The DS zone is not actually a separate component of the exit lane, rather, it defines the point upstream from the exit wedge at which the driver will begin the diverge steering maneuver, or essentially, the beginning of the speed-change lane. As shown in Figure 44, the DS zone extends from the wedge of the exit upstream, a distance L_{DS}. The DS zone includes the entire steering control zone. As described previously, a driver will take no action to exit the freeway until his angular velocity threshold has been reached. Therefore, the

TABLE 11

EXIT MODEL EQUATIONS

Deceleration Lane Length, L_{SCL}

$$L_{SCL} = L_{DG} + L_{DB} + L_{SC}, \text{ or } L_{SCL} = L_{DS}, \text{ whichever is greater} \qquad (1)$$

Steering Control Zone, L_{SC}

$$L_{SC} = V_d t_S \qquad (2)$$

Diverge Steering Zone, L_{DS}

$$L_{DS} = \sqrt{\frac{V_d}{\omega_t}\left(h+y'\right) - \left(h+y'\right)^2} - \frac{y'}{\tan\alpha} \qquad (3)$$

Deceleration In-Gear Zone, L_{DG}

$$L_{DG} = V_d t_g - \tfrac{1}{2} D_g t_g^{\,2} \qquad (4)$$

Deceleration While Braking Zone, L_{DB}

$$L_{DB} = \sqrt{\frac{aV_g}{\omega_t} - a^2} \qquad (5)$$

$$V_g = \sqrt{V_d^{\,2} - 2L_{DG}D_g} \qquad (6)$$

$$D_b = \frac{V_g^{\,2} - V_c^{\,2}}{2L_{DB}}, \quad D_b \leq \hat{D}_b \qquad (7)$$

TABLE 12

EXIT MODEL NOMENCLATURE

Variable	Definition	Unit
a	Lateral width at braking focal point	ft
D_b	Braking rate	f/s/s
$\hat{D}_b$	Maximum desirable braking rate	f/s/s
D_g	Deceleration rate in gear	f/s/s
h	Lateral distance from driver eye in Lane 1 of freeway to the right edge of pavement	ft
L_{DB}	Distance from ramp controlling point at which braking must begin	ft
L_{DG}	Distance traveled while decelerating in gear	ft
L_{DS}	Distance from nose of exit gore at which driver begins to diverge	ft
L_{SC}	Distance traveled during steering control maneuver to exit freeway	ft
L_{SCL}	Total speed-change lane (deceleration) length	ft
t_g	Time spent decelerating in gear	sec
t_s	Time spent executing steering control maneuver	sec
V_c	Speed at ramp controlling point	f/s
V_d	Speed at the beginning of the diverge maneuver	f/s
V_f	Freeway speed prior to diverge	f/s
V_g	Speed at end of deceleration in gear, when braking begins	f/s
y'	Width of wedge, freeway edge to ramp edge, at a point on which the exiting driver is focused	ft
ω_t	Angular velocity threshold.	rads/s
α	Angle of ramp divergence.	degrees

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, V_d = f/s and V'_d = mph.

beginning of the DS zone is a function of the speed at which the driver is travelling and his angular velocity threshold. The DS zone is considered to begin at the 6-foot point on the tapered section of the deceleration lane. This is so that deceleration will not begin until the vehicle has completely left the freeway lane.

The driver's perspective of the exit wedge as he approaches is illustrated in Figure 45. As the driver approaches, the roadway is diverging at a rate determined by the angle of divergence, alpha, of the exit wedge. This may most often be the nose. The driver's eye is focused on a point of the exit wedge. The width of the exit wedge at this point is defined as y'. Based on the diagram in Figure 45, it was possible to formulate an equation for the distance L_{DS}. This formula, for a tangent exit ramp, is given as Equation 1. The variables h, y', and ω_t are constants. The values of y' and ω_t were developed through field studies and will be discussed later in the report. The speed V'_d, at which the driver is travelling at the beginning of the DS zone was considered to be equal to the freeway running speed. No differential with mainline speed was assumed, based on the desire to minimize deceleration on the freeway and on field data which showed this generally to be the case.

Steering Control Zone (SC). As illustrated in Figure 44, the SC zone begins at the same point as the DS zone. The distance required to complete the steering maneuver, L_{SC}, is given by Equation 6. The time required to complete the steering maneuver was assumed to range from 1.5 to 3.0 seconds, based on previous research (18) and field studies. Field data was used to more accurately define this value since at a speed of 60 mph (88 f/s) the SC zone could range from 132 to 264 feet.

Deceleration In-Gear (DG) and While Braking (DB) Zones. In order to understand the DG and DB components of the exit model, it is necessary to discuss them together, since they are not independent. As defined previously, and

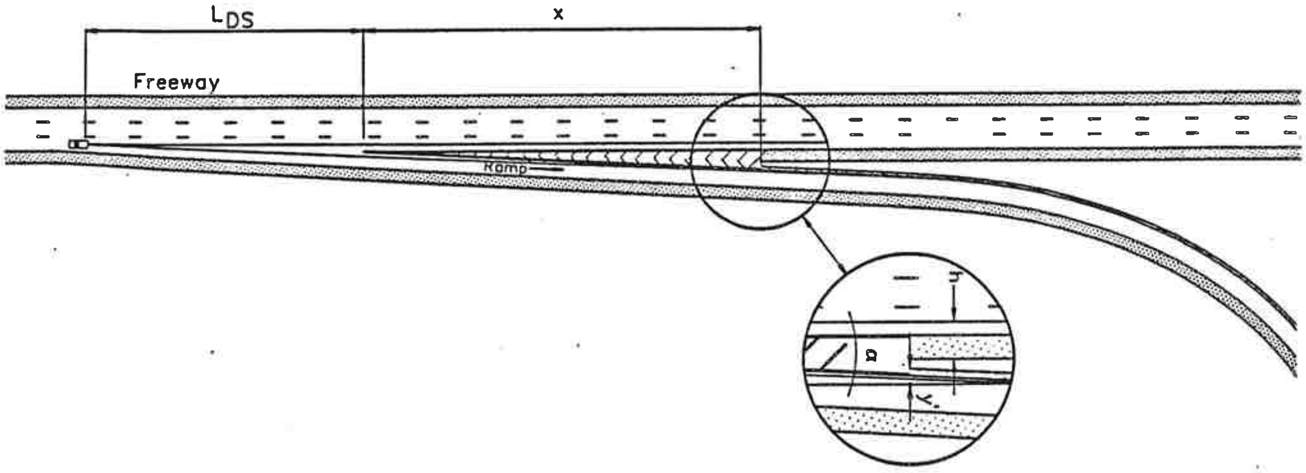


FIGURE 45

DRIVER PERSPECTIVE—EXIT WEDGE

illustrated in Figure 44, deceleration in-gear will not begin until the driver has completely left the freeway lane, or in other words at the end of the SC zone. The basis for this assumption was also the desire to maintain a relatively high speed for the ramp vehicle through the SC zone, thus, reducing any potential impacts on following freeway vehicles. Depending on the location of the speed controlling point on the ramp, the driver will decelerate in-gear until the driver's angular velocity threshold has been reached and braking must occur. Therefore, the total deceleration of the vehicle is a combined process between in-gear and braking. Equations 2 through 5 in Table 11 can be used to determined L_{DG} and L_{DB}.

An iterative process is used to calculate L_{DG} and L_{DB}, as summarized below:

Step 1: Calculate L_{DG} using Equation 2 assuming the time spent in-gear , t_g, is 3.0 seconds.

Step 2: Calculate the velocity V_g, at the end of the L_{DG}, using Equation 3.

Step 3: Calculate L_{DB}, using Equation 4.

Step 4: Calculate the deceleration rate, D_b (using Equation 5), which would be required to reach the controlling speed, V_c. If D_b is greater than a threshold value of $\hat{D}_b$ = 10 f/s/s, return to Step 1 and recalculate L_{DG} using a longer time spent in-gear.

The threshold value for the deceleration in braking rate, $\hat{D}_b$, was set at 10 f/s/s, based on the maximum braking rate considered comfortable for drivers. The result of this iterative process is to minimize the total deceleration distance required. Theoretically, at low differences in speed between the freeway and ramp, it is possible that no braking will occur and only deceleration in-gear will be necessary to reach the controlling ramp speed.

The total length of the deceleration lane then is the sum of SC, DG, and DB zones. The total deceleration lane length, however, cannot be shorter than the length of the DS zone. The DS zone is used as a geometric control to determine the location of the beginning of the exit lane on the freeway and its lower limit is governed by the SC zone.

Model Attributes

In this section the model for determination of exit lane length is analyzed in terms of its sensitivity to variation in the key input variables. The values selected for each varible were considered most reasonable for the purpose of testing the exit model. The speeds which were selected are intended to reflect design speed, rather than some lower operating speed. Throughout the sensitivity testing, it was assumed that under normal conditions, drivers tended to decelerate in gear for 3 seconds. This constraint was based on current AASHTO deceleration lengths which are based on a three-second period for deceleration in-gear.

> "For determination of deceleration lengths, a value of three-seconds is assumed as that while decelerating without the use of brakes, which time is sufficient for most drivers to size up the situation and apply brakes. A somewhat longer period of time may be utilized by some drivers who choose to decelerate gradually and are not hurried" (19).

Deceleration Lane Length Components Figure 46 shows the total deceleration lane length (L_{SCL}) by component for various diverge speeds for an assumed ramp controlling speed of $V'_c = 0$ mph (e.g., a ramp ending at a stop sign). The length of the DG zone, (L_{DG}) is the most sensitive to variations in diverge speeds, ranging from approximately 1,000 feet at 70 mph to 100 feet at 50 mph. Figure 46 also indicates that the length of the SC and DB zones vary little with diverge speed. The

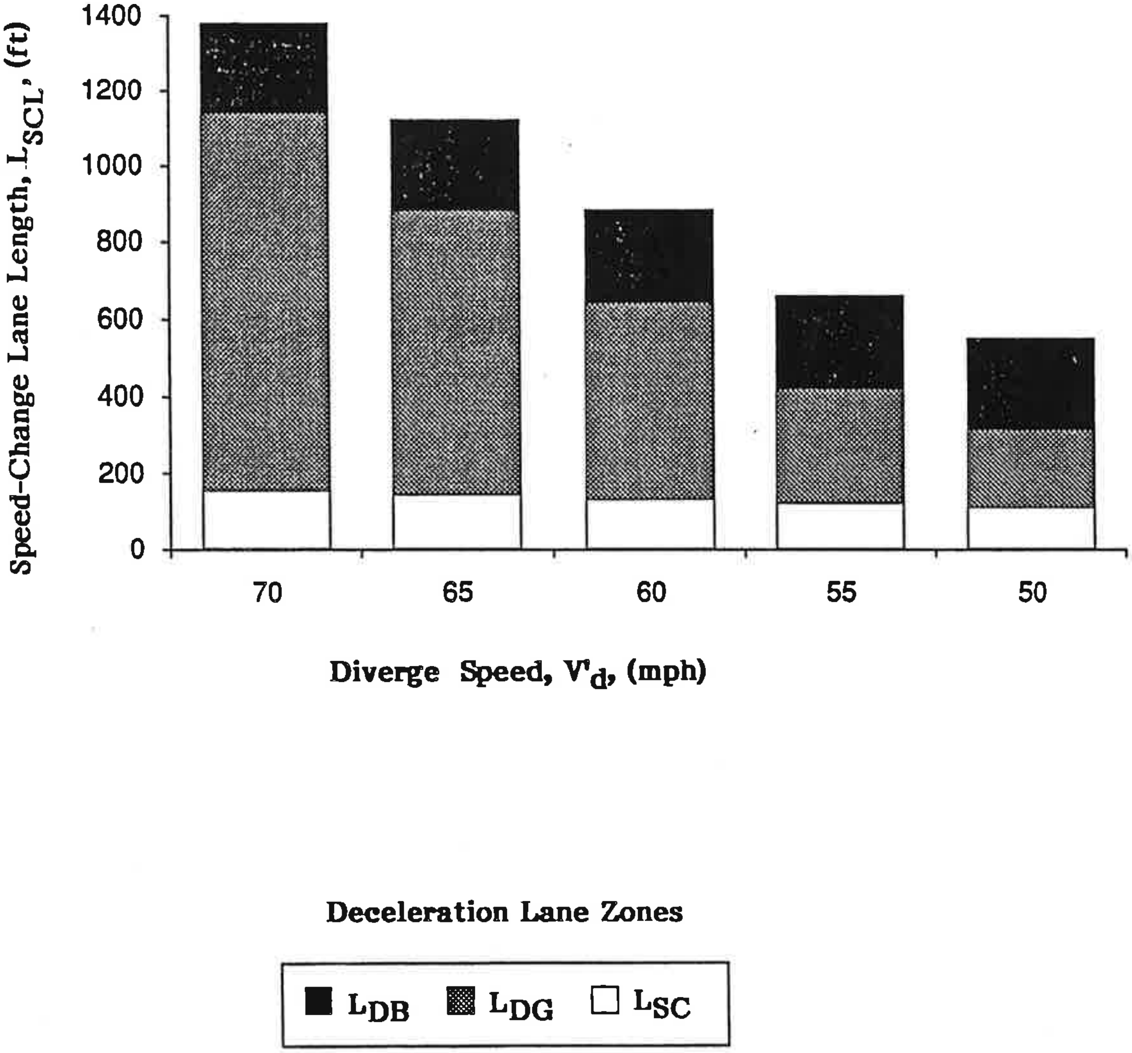


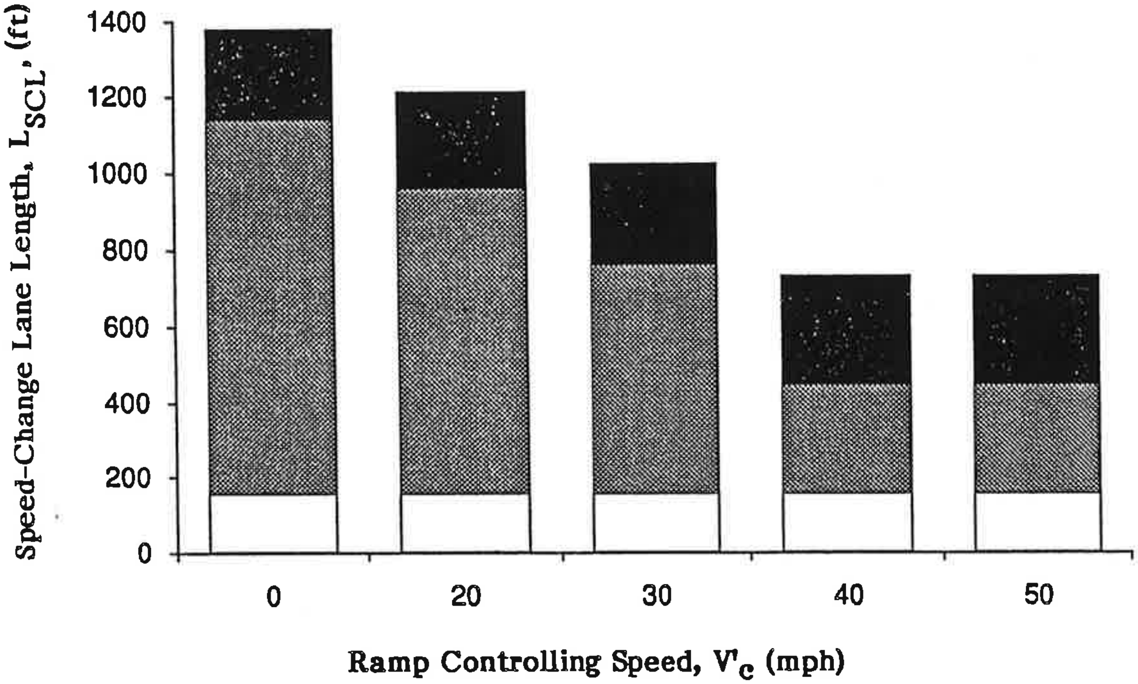
FIGURE 46

VARIATION OF EXIT LANE COMPONENTS BY DIVERGE SPEED total deceleration lane length varies by approximately 800 feet across the range of speeds.

Figure 47 shows the variation of total deceleration lane length by component for various ramp controlling speeds. A diverge speed of 70 mph was selected for this illustration. Again, only the DG zone shows any significant variation in length across the range of ramp speeds. Interestingly, the length of the DB zone increases slightly with increasing ramp speed or as the speed reduction which the driver must complete becomes smaller. This is due to the fact that a lower braking rate is required to reach the appropriate speed. Figure 47 also indicates that the total deceleration lane length decreases as the amount of speed reduction necessary decreases, but then levels off. This is due to the constraint placed on the model to allow the driver three seconds to decelerate in-gear prior to braking. If this constraint were not placed on the model and the deceleration in-gear time could go to zero seconds, the deceleration lane length required for a V'_c = 50 mph would be less than for V'_c = 40 mph.

The distance, L_{DS}, upstream from the exit wedge at which the deceleration lane must begin varies significantly with diverge speed, however, is constrained by the length of the SC zone. The driver must be capable of executing the steering maneuver from the freeway to the deceleration lane prior to the exit wedge.

<u>Angle of Divergence.</u> The angle at which an exit ramp diverges from the freeway only affects the length of the DS zone, (L_{DS}), and not the total deceleration lane length. Figure 48 illustrates the relationship of L_{DS} with the angle of divergence. For a given angle of divergence, L_{DS} varies at most 90 feet with changes in diverge speed. However, there is a significant variation in L_{DS} as angle of divergence varies. For a 70 mph diverge speed, L_{DS} can vary by nearly 400



Deceleration Lane Zones

■ L_{DB} ▨ L_{DG} ☐ L_{SC}

FIGURE 47

VARIATION OF EXIT LANE COMPONENTS BY RAMP-CONTROLLING SPEED

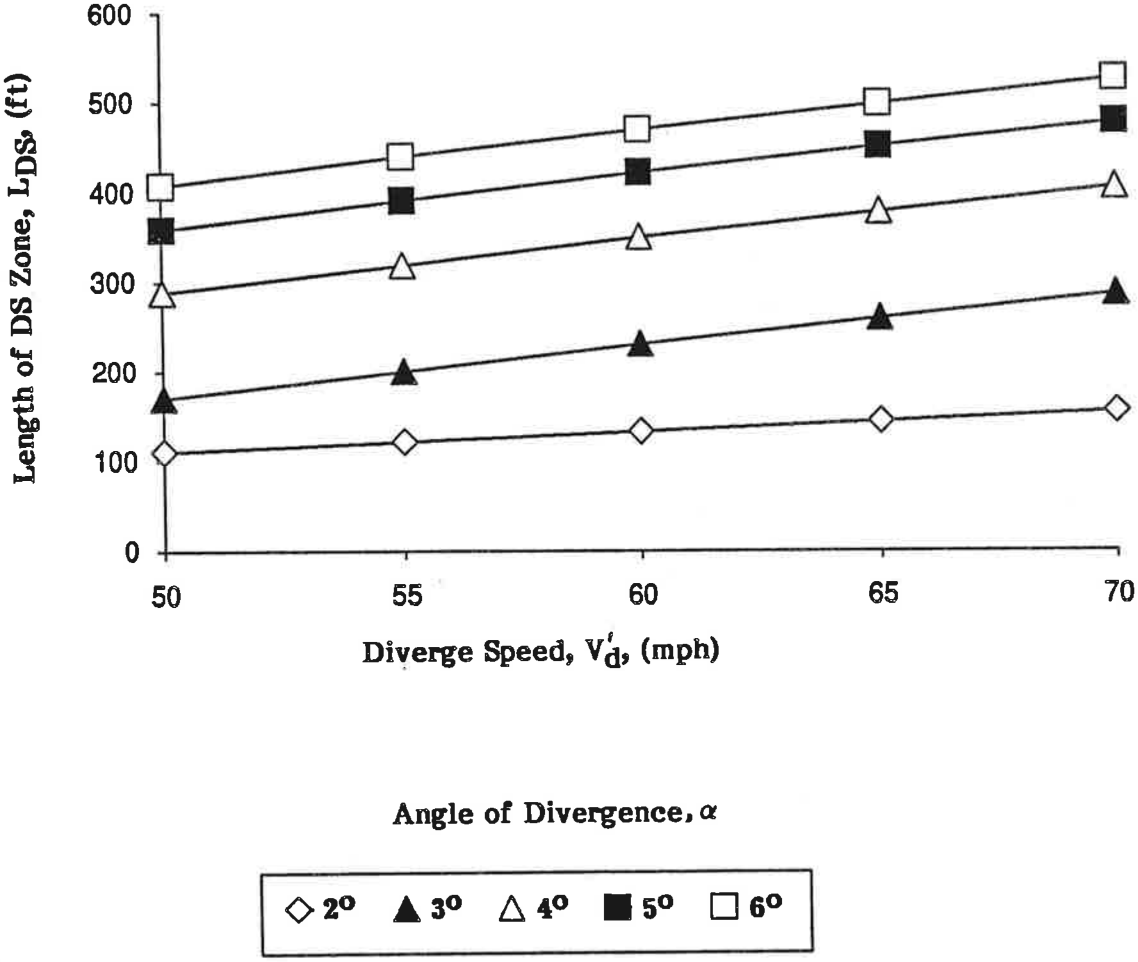


FIGURE 48

EFFECT OF ANGLE OF DIVERGENCE ON DS ZONE LENGTH feet for angles of divergence ranging from 2 to 6 degrees. Thus, the greater the diverge angle, the farther away from the exit ramp a driver will begin to leave the freeway. The current AASHTO policy recommends angles of divergence of between 2 and 5 degrees. Therefore, the exit model is sensitive to ramp geometry as would be desired, and the angle of divergence provides the designer with one means of reflecting this sensitivity in the deceleration lane.

Exit Wedge Width. The width of the exit wedge at the driver's focal point, y', also only affects the length of the DS zone and not the total deceleration lane length. Figure 49 shows the effect of varying y' across a range of diverge speeds. In general, the distance L_{DS} varies approximately 153 feet over the range of y' tested. The variation in L_{DS} for diverge speeds ranging from 50-70 mph is slight, 100 feet, regardless of the value of y' selected. Although Figure 49 indicates that a mid-range value of y' would provide satisfactory model results, field testing of this variable was performed, and is discussed later in this section.

Figure 50 shows the relationship between L_{DS}, y', and the angle of divergence. In this illustration, y' and angle of divergence have a significant effect on L_{DS}, especially at higher values of both variables. Therefore, although the angle of divergence would be determined by the designer, the selection of y' will be very important.

Angular Velocity Threshold. Similar to the entry model, the choice of the threshold value of angular velocity is a difficult one because of the problem of obtaining accurate field measurements. As discussed previously, earlier theoretical models suggest that values between 0.010 and 0.001 rads/s are reasonable. In the exit model, both the DS zone and the total deceleration lane length, the DB zone in particular, are sensitive to the value of $\dot{\omega}_t$ selected. As shown in Figure 51, L_{DS}

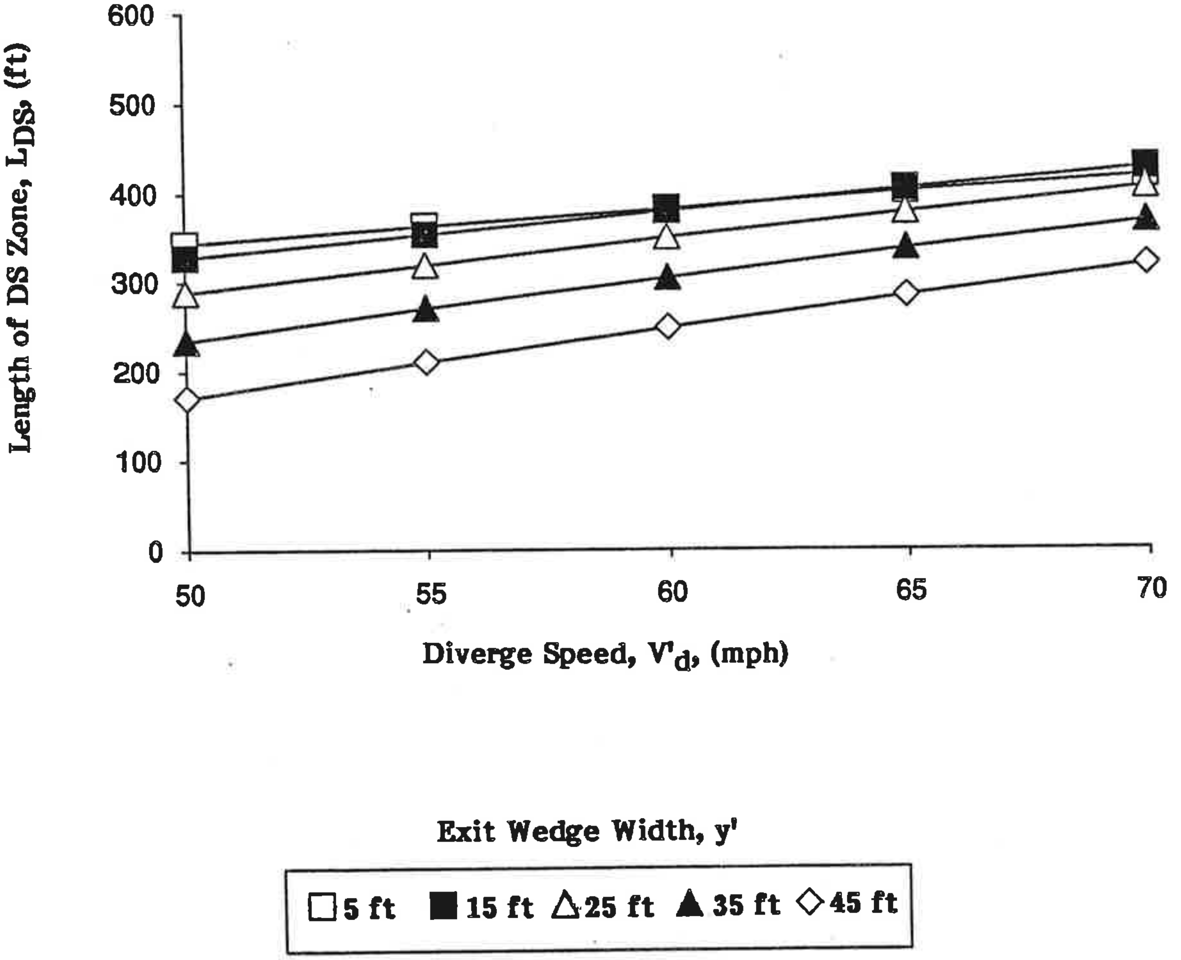


FIGURE 49

EFFECT OF EXIT WEDGE WIDTH AT THE DRIVER'S FOCAL POINT ON LENGTH OF DS ZONE

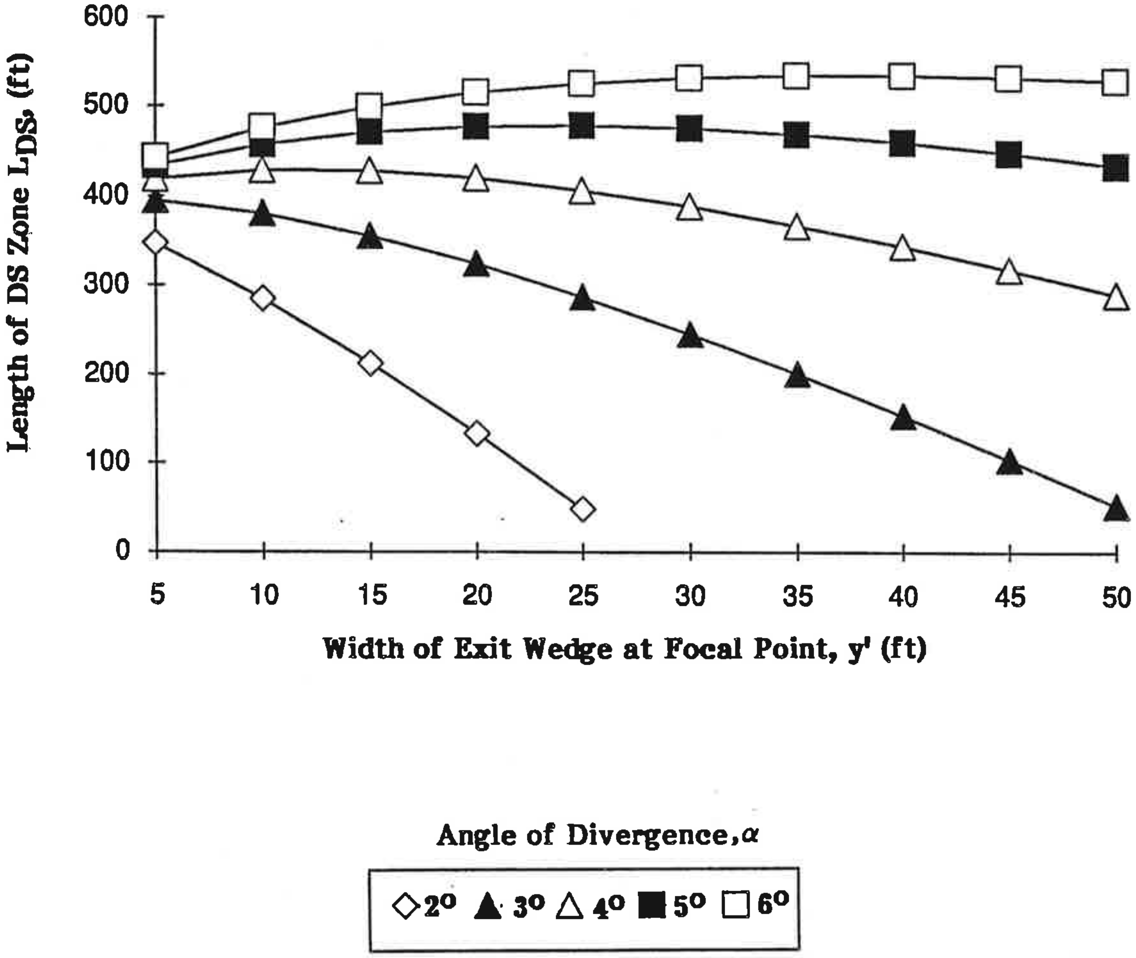


FIGURE 50

COMBINED EFFECT OF EXIT WEDGE WIDTH AND ANGLE OF DIVERGENCE ON DS ZONE LENGTH

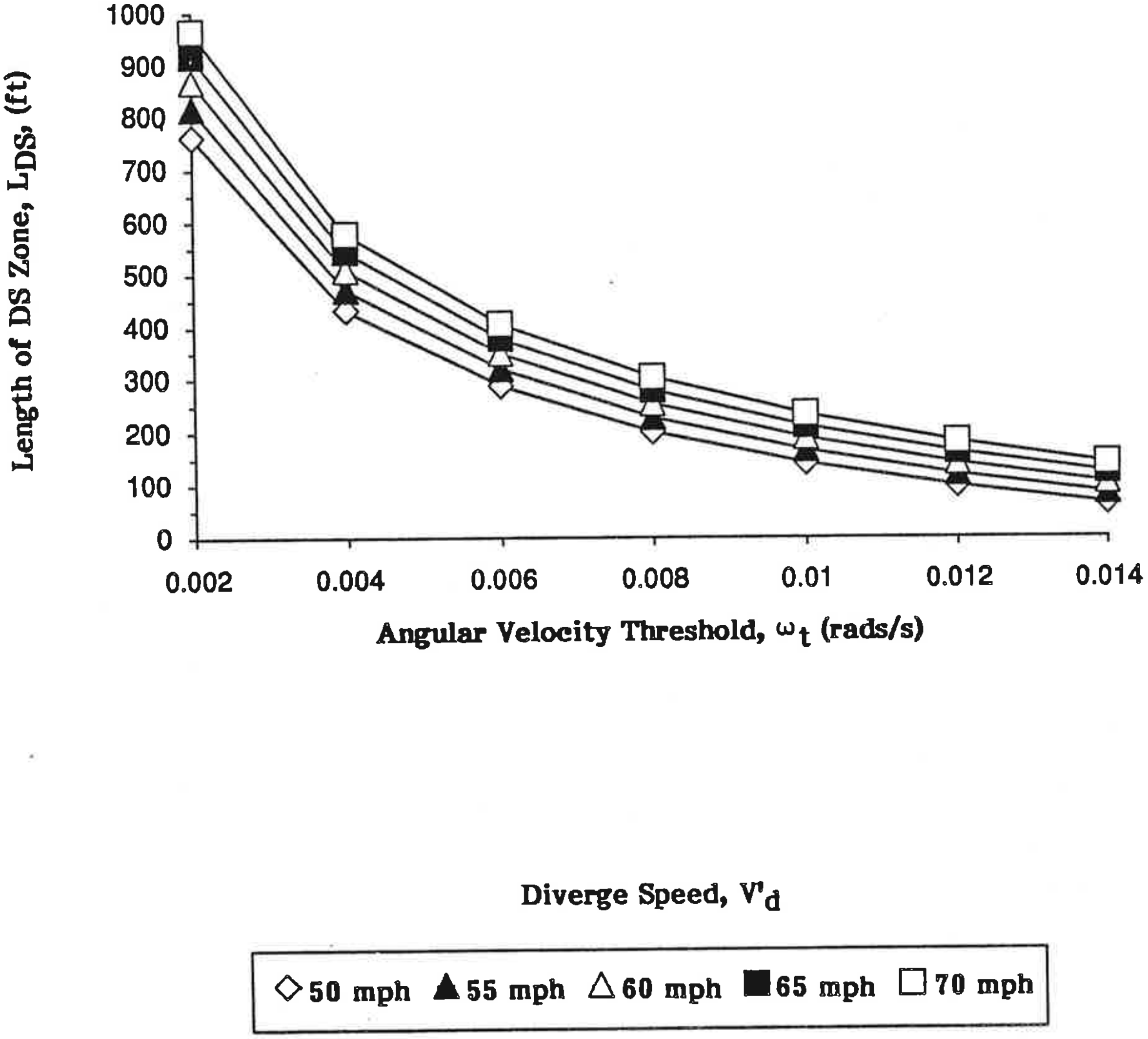


FIGURE 51

EFFECT OF THRESHOLD ANGULAR VELOCITY ON DS ZONE LENGTH varies significantly with angular velocity, especially at low values, between 0.002 and 0.006 rads/s. Diverge speed has little effect on the threshold angular velocity and L_{DS}. The effect becomes less significant at higher values of ω_t. The range of values for L_{DS} across the threshold values tested is nearly 800 feet. This indicates that great care must be taken in choosing the angular velocity threshold for the DS zone.

The threshold angular velocity also affects the total deceleration lane length, although to a lesser degree, as shown in Figure 52. As the diverge speed decreases, the variation in the deceleration lane length with respect to the threshold angular velocity also decreases. The large variation of L_{SCL} among diverge speeds, however, is somewhat misleading since the majority of the deceleration lane length is contained in the DG zone as previously shown in the component analysis. The actual effect of variation in the angular velocity threshold is on the DB zone.

Deceleration Rates. As previously discussed in the model component analysis and illustrated in Figures 46 and 47, at moderate to high speed differentials between the diverge speed and ramp controlling speed, the DG zone is the critical component of the total deceleration lane length. For smaller speed differentials, the DG zone is approximately as long as the DB zone. The factor which greatly influences L_{DG}, is the rate at which vehicles decelerate while in gear. This rate is dependent upon grade and vehicle type. Figure 53 shows the variation of deceleration lane length with several normal deceleration in-gear rates. These rates represent passenger cars on level grade. Figure 53 shows that as diverge speeds increase, deceleration lane lengths are significantly affected by deceleration rates.

In the discussion of the exit process and human factor considerations, it was suggested that drivers prefer to brake at rates between 6 and 10 f/s/s. In the exit

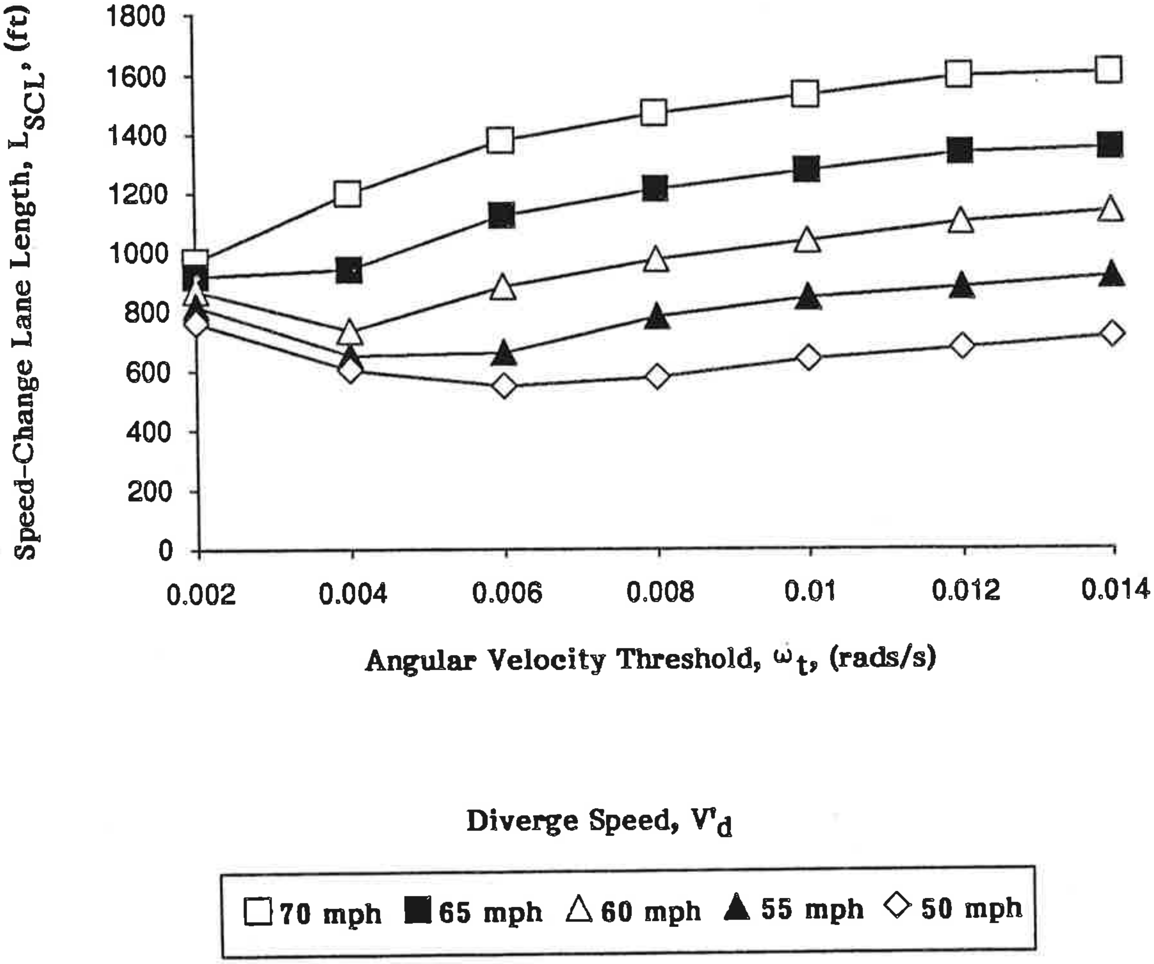


FIGURE 52

EFFECT OF THRESHOLD ANGULAR VELOCITY ON DECELERATION LANE LENGTH

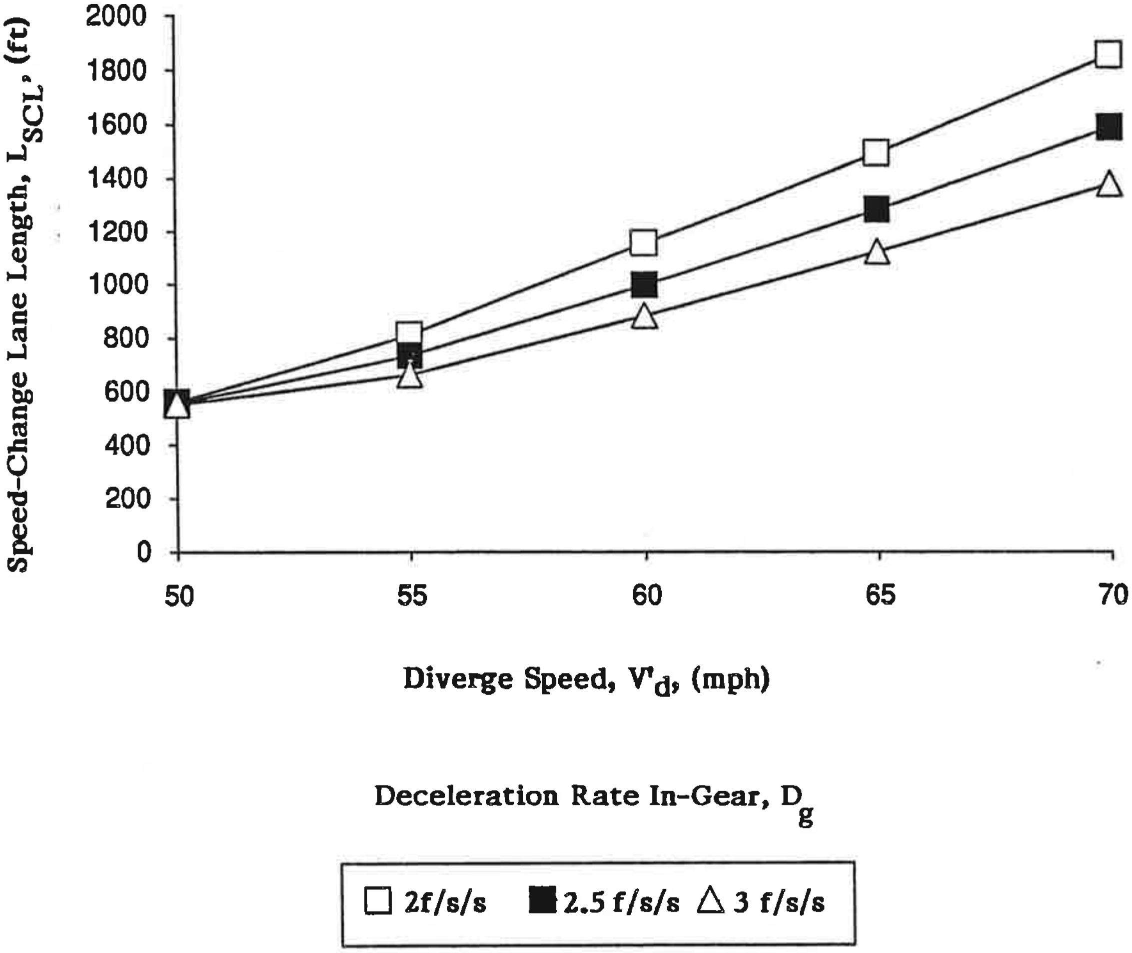


FIGURE 53

EFFECT OF DECELERATION IN-GEAR RATE ON DECELERATION LANE LENGTH

model, a maximum threshold braking rate, $\hat{D}_b$, was defined. This maximum threshold value is the key to the overall deceleration lane length. The amount of deceleration in-gear is dependent upon the braking rate which must be achieved in order to reach the ramp controlling speed. In Figure 54 the pattern of variation in the deceleration lane length for different braking rates does not change as diverge speed changes. The range of resulting deceleration lane length, across the range of maximum values tested is approximately 200 feet.

Based on the human factors considerations, it is appropriate to select a constant value for the maximum braking rate, $\hat{D}_b$, especially since grade and vehicle type should have little or no effect. The in-gear deceleration rates, however, may be included as a variable in the model, thus providing a means of reflecting vehicle type and grades.

Lateral Width at Braking Focal Point. The lateral width, a, used in calculating L_{DS} is analogous to the exit wedge width, y'. They both describe the width of some distance object which generates a component of angular velocity relative to an approaching driver. As discussed, the exit wedge width, y', determines the distance at which a driver will begin the steering maneuver to diverge from the freeway. Similarly, the lateral width determines the point from the controlling ramp curvature or condition will cause the driver to begin braking. The location of this point, and therefore, the associated lateral width, however, are very difficult to measure in the field, based upon observed driver behavior. Figure 55 presents the analysis results showing how deceleration lane lengths vary with lateral width. The results show that selection of the proper value for, a, will have a significant effect on the deceleration lane lengths generated by the exit model. The effect is greatest at higher diverge speeds.

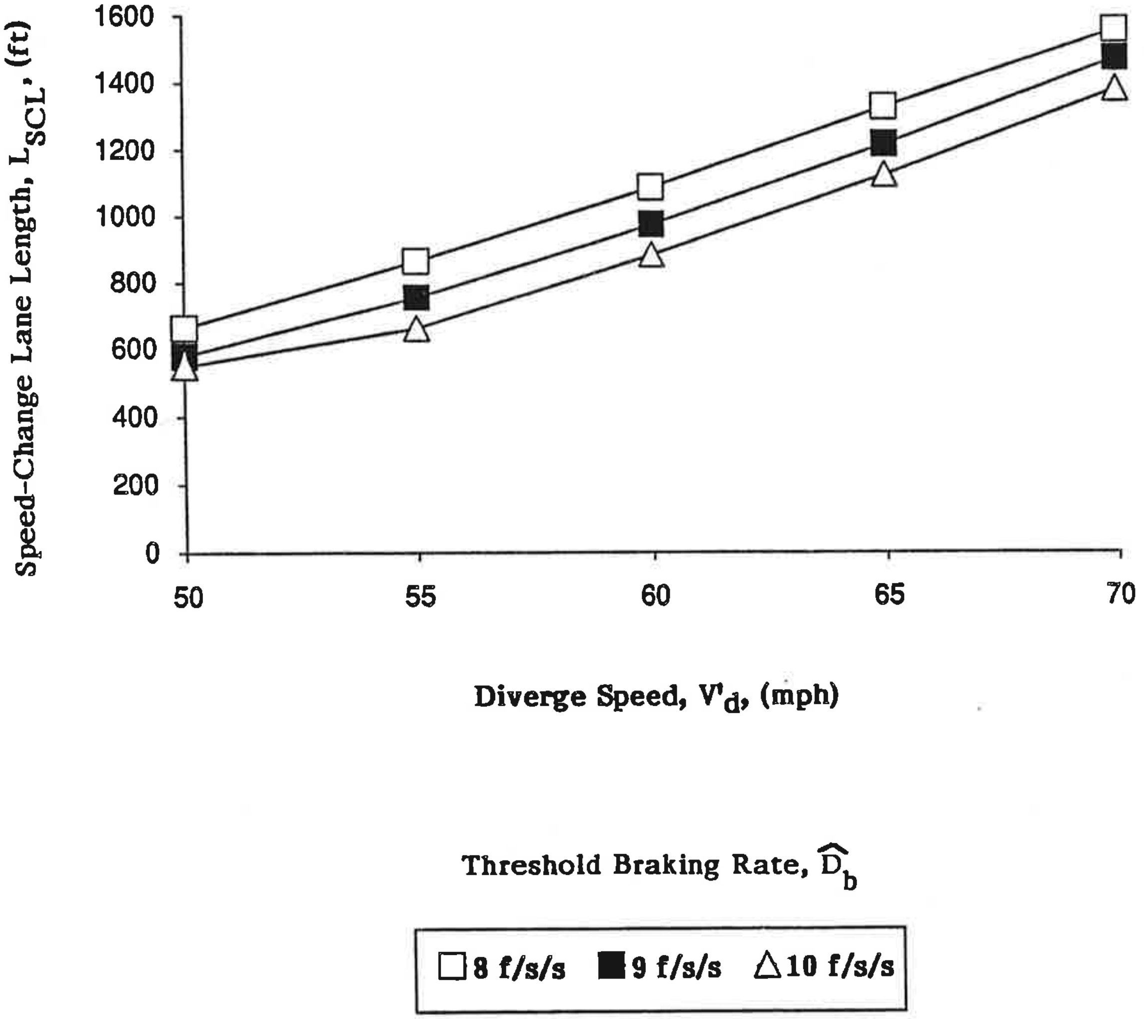


FIGURE 54

EFFECT OF THRESHOLD BRAKING RATE ON EXIT LANE LENGTH

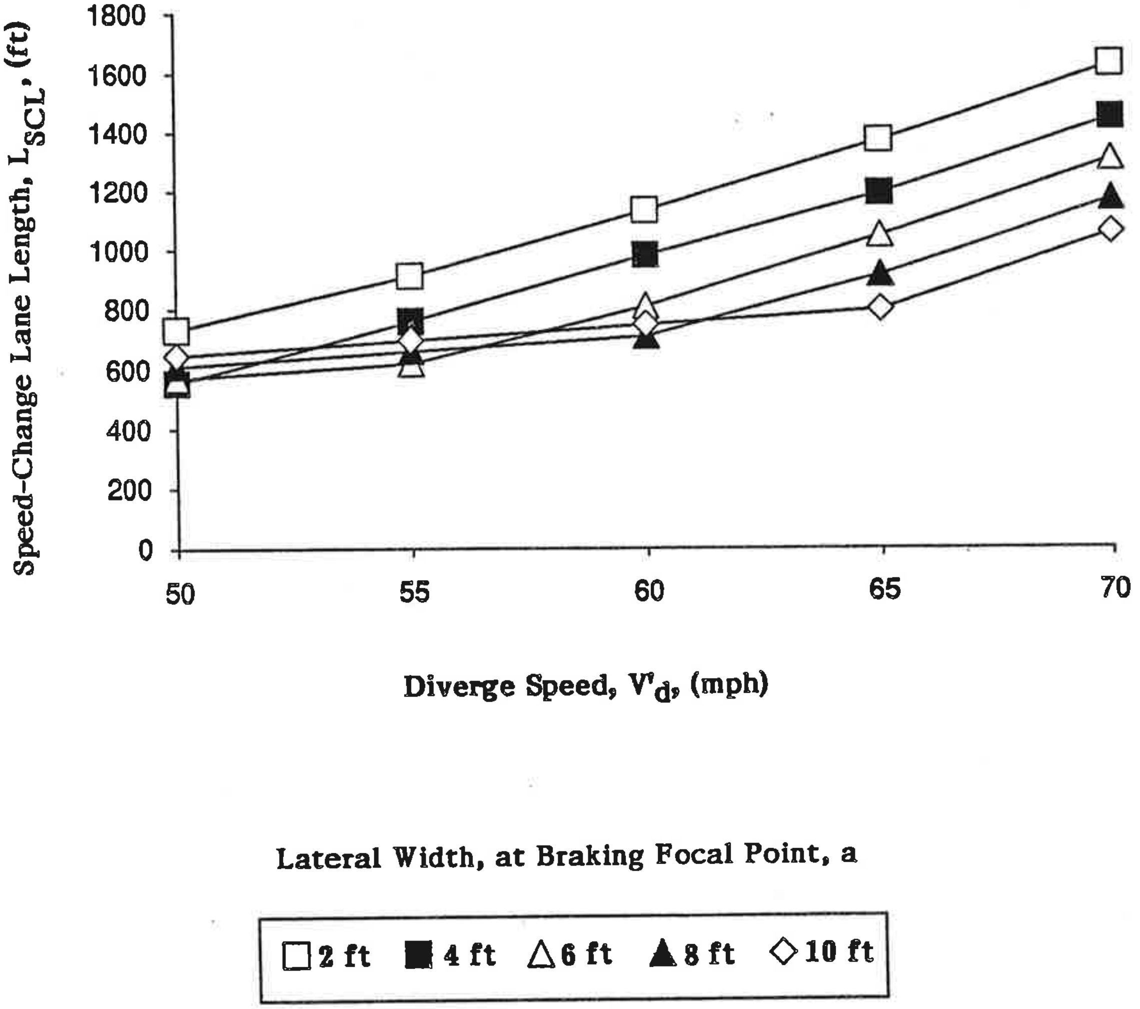


FIGURE 55

EFFECT OF LATERAL WIDTH AT BRAKING FOCAL POINT ON EXIT LANE LENGTH

Design Application

Design Variables. As noted in the discussion of the exit model attributes, it is necessary to define each variable so as to provide a working design model, while also providing adequate flexibility to reflect certain design conditions. Similar to the design variables recommended for the entry model, the variables in the exit model are defined as either project specific or project independent. Project independent variables would include w_t, t_g, t_{sc}, y', h, a, and D_b. The values of these variables would be set at the policy level for the designer. At the project level, the designer controls the geometry and speed on the ramp. The designer selects the appropriate horizontal and vertical curvature and grade based on assumptions of desired freeway and ramp speeds and deceleration rates. Different design vehicles would be reflected by varying deceleration rates. Therefore, the designer would be required to select values for D_g, , and V'_d, essentially the freeway operating speed. The ramp controlling speed, V'_c, will also be designer determined because it will be a function of the ramp geometry or condition. Table 13 presents preliminary values for the project independent variables and also default values for the project specific variables.

Design Values. Based on the preliminary and default values presented in Table 13, design values for the deceleration lane length were calculated. Table 14 presents the design values for freeway speeds of 70, 60, and 50 mph, and ramp controlling speeds ranging from 0 to 60 mph. Table 14 includes the total deceleration lane length, L_{SCL} and the length of the DS zone, L_{DS}, for given freeway and ramp speeds. Based on the known or assumed freeway operating speed, V'_d, and controlling ramp speed, V'_c, the designer is able to determine from the

TABLE 13

EXIT MODEL VARIABLES

Variable	Definition	Unit	Value
a	Lateral width at braking point	ft	6
D_g	Deceleration rate in-gear	f/s/s	3.0
$\hat{D}_b$	Maximum desirable deceleration rate in braking	f/s/s	10
h	Distance from driver eye to freeway lane edge	ft	9
t_g	Time spent decelerating in gear	sec	3.0
t_s	Time spent executing steering control maneuver	sec	3.0
V_c	Speed at ramp controlling point	f/s	Varies
V_d	Speed at the beginning of the diverge maneuver	f/s	Varies
y'	Width of wedge, freeway edge to ramp edge, at the driver's focal point	ft	25
ω_t	Angular velocity threshold	rads/s	0.004
α	Angle of ramp divergence.	degrees	Varies

TABLE 14

PROPOSED DESIGN VALUES FOR DECELERATION LANES (ANGLE OF DIVERGENCE = 4°)

V'_c (mph)	L_{SCL} (ft) V'_f (mph) 70	60	50
0	1,113	728	628
15	1,035	728	628
30	825	728	628
40	825	728	433
50	825	599	433
60	631	509	--

V'_c (mph)	L_{DS} (ft) V'_f (mph) 70	60	50
All	578	509	433

tables, the total deceleration land length required, as well as the minimum distance upstream from the exit wedge at which the deceleration lane must begin.

As discussed previously, the limited variation in L_{SCL} with controlling ramp speed is a direct result of constraining the time in which a driver decelerates in-gear, t_g, to at least three seconds. If this constraint were removed and t_g allowed to drop to one or even zero seconds, L_{SCL} would have greater variation with ramp speeds. Table 15 which provides a component analysis of the exit model for different freeway speeds, illustrates the impact of constraining the deceleration in-gear element of the model. The component analysis is based upon the default values provided in Table 13. The total deceleration lane length is the sum of L_{SC}, L_{DG}, and L_{DB} or L_{DS}, whichever is greater, and is based on the assumption that deceleration will not begin until after the steering control maneuver is completed.

Comparison with Current AASHTO Values. The component analysis results contained in Table 15 also provide a comparison between the current AASHTO design values and those generated from the exit model. The AASHTO values presented in the comparison were extrapolated from Table X-6 in the Green Book. An additional length of 125 feet was added to the AASHTO values to reflect the distance required by the driver to leave the freeway. The methodology used to adjust the AASHTO deceleration lengths for comparative purposes is discussed in Appendix G. Also, in Appendix G is an alternative comparison between the AASHTO and exit model design values.

For most freeway and ramp speeds the model deceleration lane lengths are longer than the AASHTO values. The difference between the exit model and AASHTO values increases with increasing ramp speed. These longer lengths are due to several reasons inherent to the exit model. First, the model is constrained by the

TABLE 15

EXIT MODEL COMPONENT ANALYSIS

V'_d = 70 mph

V'_c (mph)	L_{DS} (ft)	L_{SC} (ft)	t_g (f/s/s)	L_{DG} (ft)	V'_g (mph)	L_{DB} (ft)	D_b (f/s/s)	L_{SCL} (ft)	AASHTO Length (ft)	L_{SCL} as % of AASHTO (%)
0	578	154	6.5	605	45.7	354	9.8	1,113	915	122
15	578	154	5.5	521	58.8	360	9.7	1,035	905	114
20	578	154	4.5	433	60.8	366	9.7	953	895	106
25	578	154	3.5	342	62.9	372	9.7	868	875	99
30	578	154	3	295	63.9	375	9.2	825	845	98
40	578	154	3	295	63.9	375	7.1	825	745	111
45	578	154	3	295	63.9	375	5.9	825	705	117
50	578	154	3	295	63.9	375	4.6	825	605	--

V'_d = 60 mph

V'_c (mph)	L_{DS} (ft)	L_{SC} (ft)	t_g (f/s/s)	L_{DG} (ft)	V'_g (mph)	L_{DB} (ft)	D_b (f/s/s)	L_{SCL} (ft)	AASHTO Length (ft)	L_{SCL} as % of AASHTO (%)
0	509	132	3	251	53.9	345	9.1	728	765	95
15	509	132	3	251	53.9	345	8.4	728	735	99
20	509	132	3	251	53.9	345	7.8	728	725	100
25	509	132	3	251	53.9	345	7.1	728	695	105
30	509	132	3	251	53.9	345	6.3	728	675	108
35	509	132	3	251	53.9	345	5.3	728	625	116
40	509	132	3	251	53.9	345	4.1	728	565	129
45	509	132	3	251	53.9	345	2.8	728	505	144
50	509	132	5	404	49.8	--	--	536	425	--

V'_d = 50 mph

V'_c (mph)	L_{DS} (ft)	L_{SC} (ft)	t_g (f/s/s)	L_{DG} (ft)	V'_g (mph)	L_{DB} (ft)	D_b (f/s/s)	L_{SCL} (ft)	AASHTO Length (ft)	L_{SCL} as % of AASHTO (%)
0	433	110	3	207	43.9	311	6.7	628	625	100
15	433	110	3	207	43.9	311	5.9	628	600	105
20	433	110	3	207	43.9	311	5.3	628	575	109
25	433	110	3	207	43.9	311	4.5	628	545	115
30	433	110	3	207	43.9	311	3.6	628	505	124
35	433	110	8	492	33.7	--	--	602	455	132
40	433	110	5	330	39.8	--	--	440	395	111
45	433	110	4	270	41.8	--	--	433	325	133
50	433	110	3	207	43.9	--	--	433	--	--

assumption that drivers must decelerate in-gear for a minimum of three seconds. During this period, the driver recovers from the diverge steering maneuver, determines his position relative to the ramp controlling condition, and prepares to apply brakes.

Second, the minimum deceleration lane length for a given freeway speed is equal to the distance from the exit wedge at which the driver begins to diverge the freeway or the DS zone. In the exit model, L_{DS} is independent of ramp speed. Hence, for small speed differentials, the exit model provides surplus length in which to decelerate to the appropriate ramp speeds. However, the exit model does provide the necessary deceleration lane length to permit drivers to exit the freeway with a minimum amount of deceleration on the freeway.

Exit Model Calibration and Validation

Data on the exit process was collected at 12 exit ramps representing a variety of geometric and traffic conditions. The characteristics of these sites and the data collected are summarized in Appendix D. Data from seven of the 12 sites was used to calibrate and test the validity of several elements of the exit model and select the values for key variables.

An initial assumption in the development of the exit model stated that the speed of an exiting vehicle during the diverge steering maneuver was constant. Therefore, the speed of the vehicle during the diverge, V'_d, equals the freeway speed, V'_f. Figure 56 presents the distribution of observed speeds prior to and during the diverge steering maneuver. These data indicate that the reduction in speed during the diverge maneuver is normally less than two mph, regardless of the initial speed, thus supporting the model assumption. However, the data also provide evidence that a significant percentage of drivers reduce their speed while still on

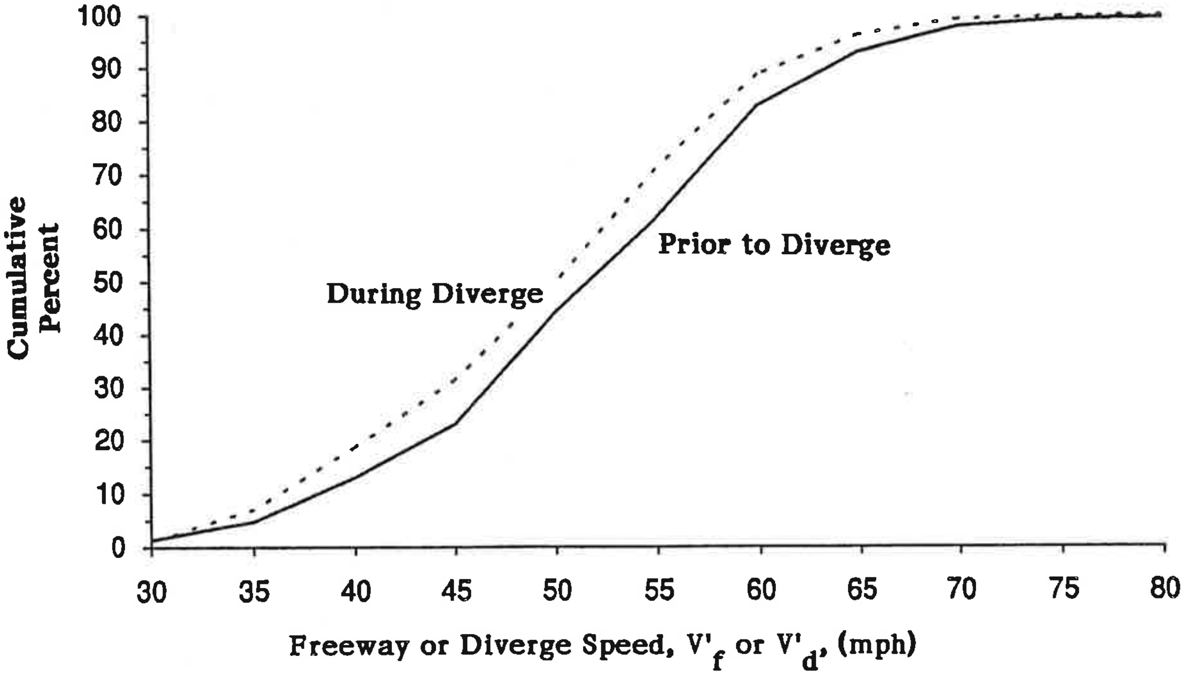


FIGURE 56

DISTRIBUTION OF OBSERVED SPEEDS PRIOR TO AND DURING THE DIVERGE MANEUVER the freeway, prior to beginning the diverge maneuver. The average speed of exiting vehicles across all sites prior to the diverge maneuver was approximately 52 mph as shown in Appendix D. Figure 56 indicates a similar value for the 50th percentile of vehicle observed. These speeds appear lower than normal freeway operating speeds and suggest that deceleration on the freeway is occurring. This is especially true for short deceleration lanes. For exit ramps greater than 1,000 feet in length, the values of V'_f ranged from 54 to 59 mph. On shorter exit ramps, V'_f ranged from 40 to 50 mph.

As in the entry model, a critical element in the exit model is the threshold angular velocity which determines L_{DS} and L_{DB}. The angular velocities measured in the field at selected sites are summarized in Figure 57. These data indicate that of the vehicles observed, 70 percent of the diverge maneuvers occur at angular velocities below 0.008 rads/sec. The 15th percentile, considered to be the design condition, occurs at between 0.004 and 0.005 rads/s. The average angular velocity measured was approximately 0.008 rads/sec. Based on these data, selection of 0.004 rads/sec as the threshold angular velocity is appropriate for design purposes.

Another critical element in the exit model is the minimum of 3.0 seconds assumed for the time spent decelerating in-gear. Field observations showed an unweighted average of 4.0 seconds and 5.7 seconds when weighted by site. On the shorter exit ramps, the average ranged from 3.7 to 4.1 seconds. This suggests that a minimum deceleration in-gear does indeed exist, with a magnitude of 3 to 4 seconds. Figure 58 give the distribution of the overall observed data. The 85th percentile is approximately 5.0 seconds. Therefore, although the 3.0 second minimum does constrain the model it is a reasonable assumption.

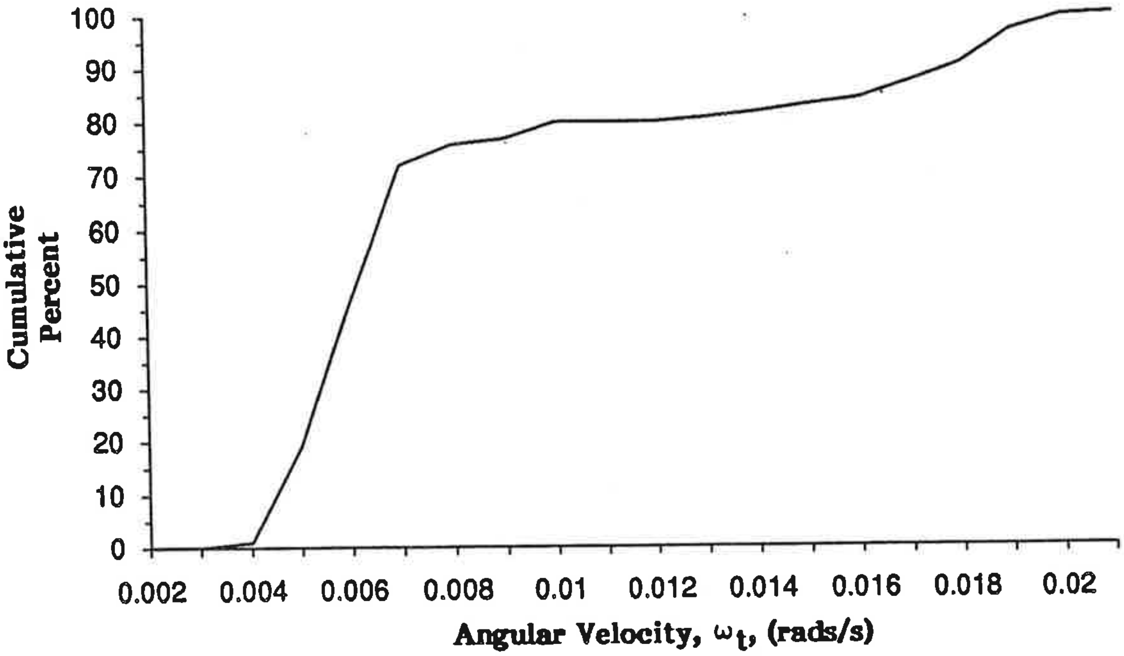


FIGURE 57

DISTRIBUTION OF OBSERVED ANGULAR VELOCITIES
AT DIVERGE

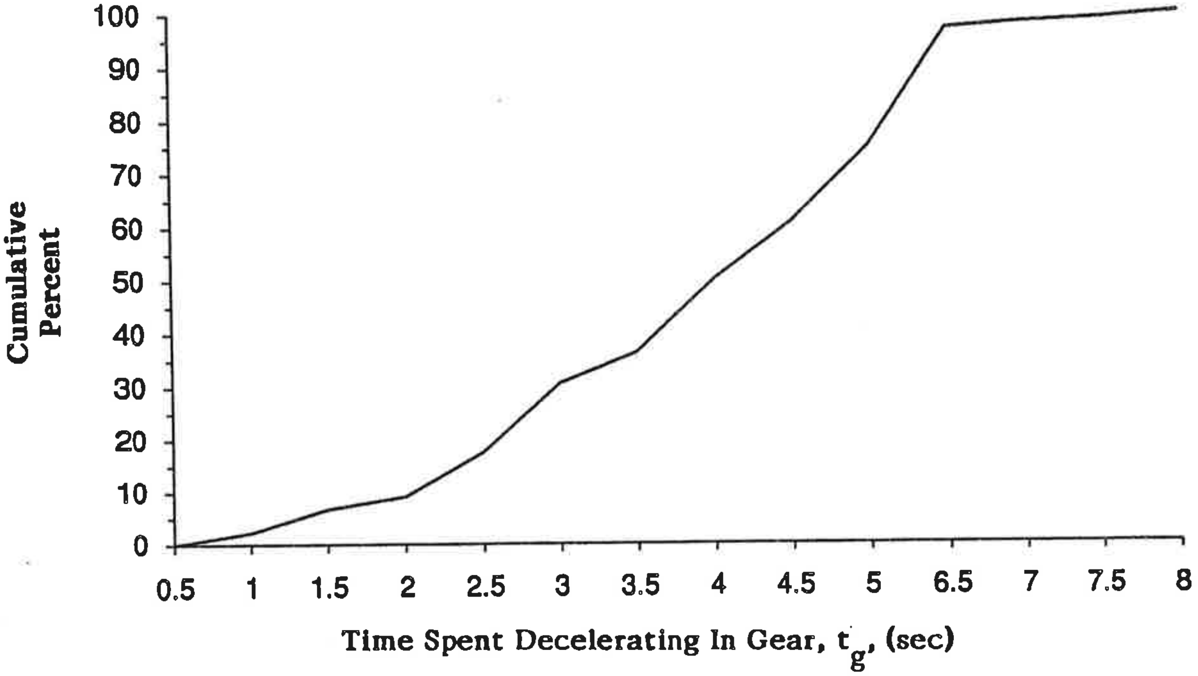


FIGURE 58

DISTRIBUTION OF OBSERVED TIME DECELERATING IN GEAR

Although the length of the SC zone is not a major part of the total deceleration lane length, results of field observations were used to determine the time necessary to complete the diverge steering control maneuver. Figure 59 shows that more than 85 percent of the drivers observed complete the steering maneuver in 2.5 seconds or less. The average value of t_s in the overall data was 1.6 seconds. Figure 60 summarizes the distribution of the t_s data for the trucks observed. A greater percentage of trucks, nearly 85 percent, completed the steering maneuver in approximately 1.5 seconds or less. This indicates that trucks are not the controlling factor for the SC zone component of the exit model.

Finally, the validity of the DS component of the exit model was tested against actual field data. The results are summarized in Figure 61. These data indicate that the DS component of the exit model does a fairly good job predicting L_{DS}. The 50th percentile of the observed data shows that the exit model under predicts L_{DS} by approximately 25 feet, while the 85th percentile shows an overprediction of nearly 75 feet. These errors are considered very reasonable given the complexity of the exit model.

Model Refinements

During the development and testing of the exit model, the effects of grade, trucks, and volume were considered. In order to provide a flexible model to the designer, it was important to be capable of reflecting these effects.

Unlike the entry model, variation in traffic volume was not considered to have a significant effect on the exit process and, therefore, was not reflected in the exit model. Moderate to high traffic freeway volumes would reduce the time available to the driver to search and detect the exit ramp, due to car following effects. There is no method for predicting the magnitude of this time loss. However, it is

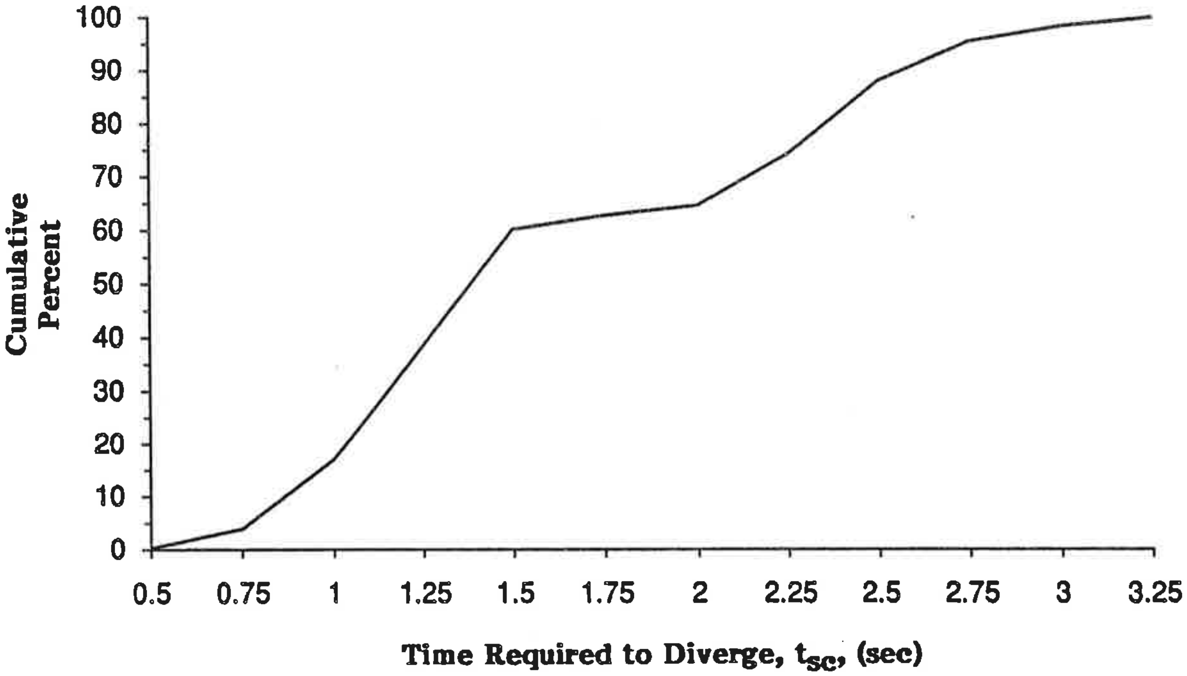


FIGURE 59

DISTRIBUTION OF OBSERVED TIME REQUIRED TO COMPLETE THE DIVERGE STEERING MANEUVER (ALL VEHICLES)

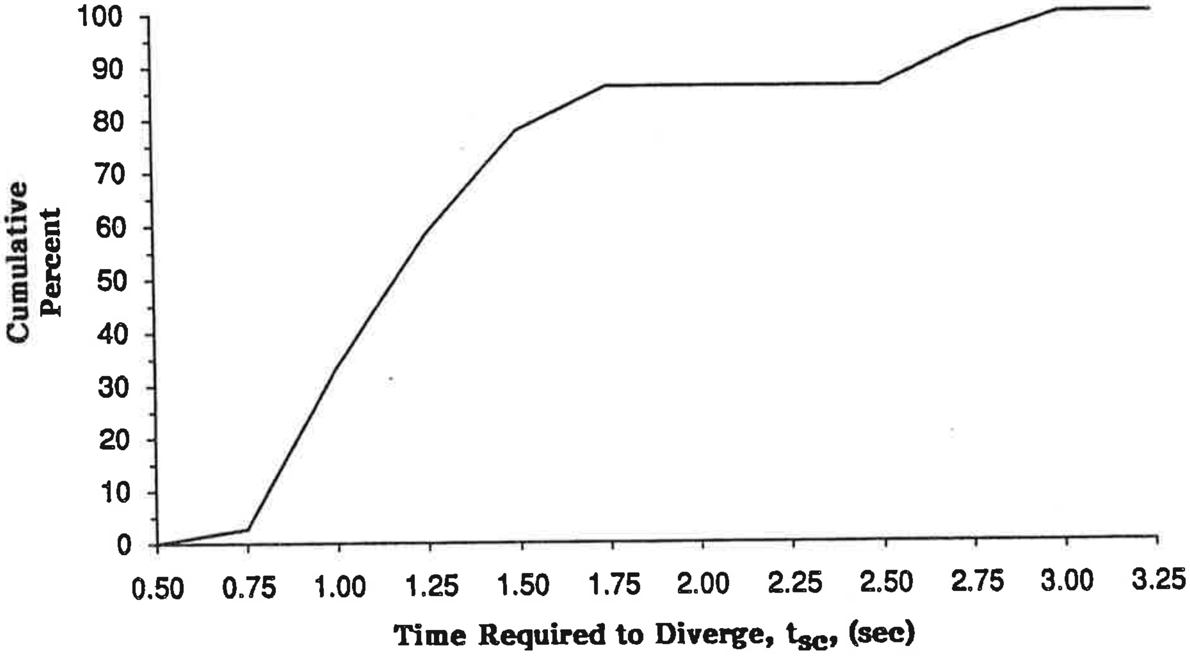


FIGURE 60

DISTRIBUTION OF OBSERVED TIME REQUIRED TO COMPLETE THE DIVERGE STEERING MANEUVER (TRUCKS ONLY)

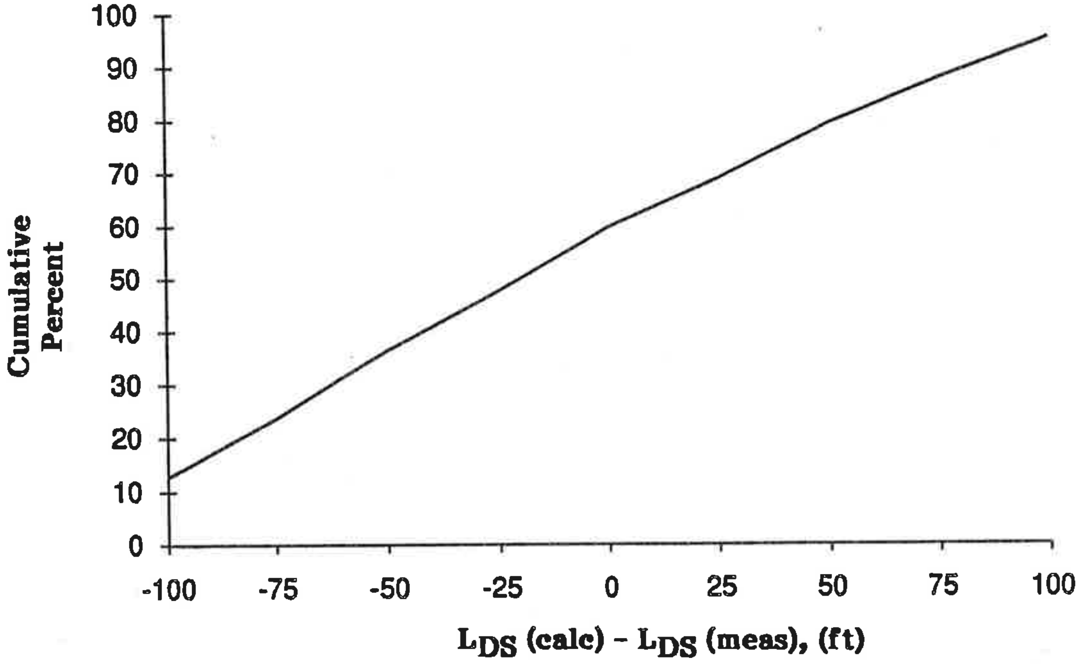


FIGURE 61

DIFFERENCE BETWEEN CALCULATED AND OBSERVED DS ZONE LENGTHS assumed only to be significant as volumes approach capacity. As volumes increase on the exit ramp, control of deceleration becomes more and more a response to vehicles ahead and not to the ramp geometry. Therefore, an exiting driver still requires a certain distance to decelerate to an appropriate ramp speed regardless of the ramp volume. The effect of increased ramp volumes is to change the cues which most drivers will use. The lead vehicle of a cue becomes the prime determinant of the queue's operational characteristic. It is this lead vehicle for which the model applies.

Grades and trucks are both reflected in the exit model through the in-gear deceleration rate. Since the maximum braking deceleration rate of 10f/s/s is based principally on driver comfort it is unlikely that grade or vehicle type would cause it to vary. The effects of grades and trucks would best be reflected through the use of different in-gear deceleration rates. Table 16 presents in-gear deceleration rates for passenger cars on various grades. Unfortunately, the same information has not been found to be readily available for trucks.

An initial goal of this research was to determine the operational advantages and disadvantages of parallel versus tapered lanes. Of the 12 exit ramps at which data were collected, only one, Deerfield Road, was a parallel design. Therefore, a good comparison between the two design types could not be performed. As was discussed earlier in this report, it was hypothesized that the major difference between parallel and taper lanes was in the steering control maneuver to leave the freeway. A driver steering onto a parallel lane was required to perform a more complex steering manevuer than on a taper lane. Therefore, it is assumed that the length of the SC zone would be longer for the parallel lane. The field data collected at the Deerfield Road site tend to support the assumption when compared with the

TABLE 16

EXIT MODEL DECELERATION RATES FOR PASSENGER CARS

Grade %	In-Gear Deceleration Rate (f/s/s)
-6	2
-4	2
-2	3
0	3
+2	4
+4	5
+6	6

sites with taper lanes. The average value of t_s at Deerfield Road is approximately 3.0 seconds, nearly twice the average value for other sites. The effect on the deceleration lane length would be small, however, keeping in mind the weight which the SC zone carries. No other operational differences were found in the limited comparison. Therefore, based on the data from this study, except for simplifying the steering control task for the driver, the taper and parallel designs were considered to operate in a similar fashion.

3. INTERPRETATION, APPRAISAL, AND APPLICATION

RESEARCH RESULTS

The results of this research project are essentially threefold. First, a high degree of understanding of the entry and exit processes was developed through the compilation and review of previous research results, and more importantly, through field observation and data collection at freeway entries and exits. The descriptions of the entry and exit processes presented in this report are considered the most detailed to date. It has long been known that entry to and exit from a freeway involve a series of driver tasks; however, this research represents the first time that these tasks have been identified and described in a comprehensive manner.

Perhaps the most important result of this research was the understanding of driver behavior, which occurs during the entry and exit processes. Previously, the entry process was more or less based on the need of a driver to accelerate to a speed 5 to 10 mph below the freeway speed, in order to enter the freeway. Once this speed requirement was met, the merge could take place. As a result of this research, it is now understood that it is not only the speed differential between the ramp and freeway vehicles, but also the position of the vehicles relative to each other and the availability of a suitable gap in the freeway traffic, which determines when the merge will occur.

The exit process defined in this research, is similar to the processes currently described by AASHTO and others. Once the driver has exited the freeway, a deceleration must occur in order to reach some appropriate speed on the ramp. This research, however, was able to define when and how this deceleration would occur.

The second primary result of this research was the representation of the various components of the exit and entry processes mathematically. The entry and exit models, which were developed, are very complex. However, this is reasonable, considering the complexity of the processes themselves. Both models do a good job of representing driver behavior, and provide reasonable speed-change lane lengths for design application. Additionally, the entry and exit models take into account geometric and traffic conditions, which are important factors which should be provided to the designer.

Finally, the models which were developed were translated into specific design values which can be used by designers of freeway acceleration and deceleration lanes. One objective of this research was to provide designers with a more flexible and powerful tool for speed-change lane design. This research has resulted in design guidelines which offer greater sensitivity to geometric and traffic conditions. Additionally, the designer is provided more criteria than the current guidelines for the proper placement of the acceleration and deceleration lanes on the freeway. A brief summary/comparison of the NCHRP 3-35 and AASHTO models is provided in Table G-1 of Appendix G. The User Design Guidelines document, which accompanies this report, provides useful information for the designer.

Future Research

The research results are complete and the design values generated by the research are recommended for adoption as new AASHTO policy. Additional research would be valuable to further understand the processes which occur at freeway entries and exits. Such research could be used to provide greater amounts of data to further calibrate the entry and exit models and to address unusual conditions such as two-lane ramps, left-hand ramps, or poor weather. In particular, further research into the angular velocity threshold of drivers is important, considering the key role that this element plays in both models. Since driver behavior and characteristics are represented in both design models, consideration of future driver attributes should be made. Initial research into the effects of an aging driver population on transportation and safety has already been performed by NCHRP 26. Additional research in this area should be undertaken and the results used to update the entry and exit models as necessary. Also, more information on acceleration and deceleration rates, especially for the current truck fleet, is needed. Such information could be used in the equations for the entry and exit models to recalculate design values if future vehicle or driver characteristics change from those used in this research.

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APPENDIX A

GLOSSARY OF TERMS

Acceleration Lane - The length of pavement between a freeway entrance ramp and the freeway mainline in which a vehicle transitions from the ramp speed to a speed appropriate for entry onto the freeway. In addition, the acceleration lane, also referred to as the speed-change lane, provides a length in which both ramp and freeway vehicles can adjust their speed and position to allow the ramp vehicle to find a suitable gap in which to merge.

Adjust Position Zone - L_{AP}, the length needed for the ramp vehicle to reject the initial lag and adjust position relative to the Lane 1 freeway vehicle which forms the intial rejected lag. The zone begins when the ramp vehicle arrives at the point where the gap search and acceptance may begin. (See Figures 6, B-2).

Angular Velocity Threshold - w_t, the maximum angular velocity of some element in the driver's field of vision which provides a stimulus for some driver action. In the entry process, the angular velocity generated by a trailing freeway vehicle will determine whether a ramp vehicle will merge. A ramp driver will only merge into a freeway gap when the angular velocity of the freeway vehicle is at or below the threshold of the driver. In the exit process, the angular velocity generated by some geometric element of the exit ramp will cue the driver to either diverge from the freeway or begin braking. (See Figures 45, B-1, B-3, B-4).

Critical Gap or Headway - The minimum gap or headway which a ramp driver will consider as acceptable in which to merge.

Deceleration In-Gear Zone - L_{DG}, the length in which a driver will decelerate in-gear until the appropriate speed is reached or the driver must begin braking. (See Figures 2, 46).

Deceleration Lane - The length of pavement between the freeway mainline and the exit ramp, in which a vehicle can transition from the freeway speed to a speed appropriate for the ramp geometry and conditions.

Deceleration While Braking Zone - L_{DB}, the length in which a driver will brake in order to reach a speed determined by the ramp geometry, the ramp terminus, or traffic conditions. (See Figures 2, 44).

Diverge Steering Zone - L_{DS}, the distance upstream from the exit wedge at which the driver will begin to exit the freeway. (See Figures 2, 44, B-3, B-4, F-1, F-2).

Edges Meet - The point at which the pavement edges of the freeway lane and the speed-change lane meet. (See Figure 4).

Entry Zone - L_{EN}, the length of the acceleration lane in which the merge occurs. This zone consists of two subzones, the d_{hr} and the visual clear zone, L_{VC}. (See Figure 14).

Exit Wedge Width - As a driver approaches an exit ramp, an element in the driver's visual field, in particular the exit wedge, generates an angular velocity. The corresponding width of the exit wedge at which the driver is focused is y'. (See Figure 45, B-3, B-4).

Gap Search and Acceptance Zone - L_{GSA}, the total length in which the merging vehicle adjusts its position relative to the freeway Lane 1 vehicle if necessary, and also searches and accepts for an available gap. (See Figures 1, 6, 14).

Initial Acceleration Zone - L_{IA}, the distance a ramp vehicle travels while accelerating to reduce the speed differential between the ramp vehicle and the freeway vehicles to an acceptable level to complete the merge process. (See Figures 1, 14).

Lateral Width at Braking Focal Point-a, - As a driver travels along a deceleration lane, an element on the lane or the ramp, such as the beginning of ramp curvature, a traffic signal or a stopped vehicle, will generate a component of angular velocity in the driver's visual field which will act as a stimulus for braking. This lateral width is similar to the exit wedge width in driver response.

Merging End - The physical nose of the exit wedge at which the ramp driver can begin the gap search and acceptance process. (See Figure 4).

Merge Steering Control Zone - L_{MSC}, the length in which the driver transitions from the acceleration lane onto Lane 1 of the freeway. This distance is not considered part of the acceleration lane length. (See Figure 1).

Speed-Change Lane - SCL, the length of pavement between the freeway mainline and the freeway ramp to allow for transition from one facility to the other. Also referred to as either acceleration or deceleration lanes.

Steering Control Zone - In the entry process, the distance required to steer from the ramp curve to the flatter geometry of the acceleration lane. (See Figures 1, 14). In the exit process, the distance in which an exiting driver transitions from the right lane of the freeway to the deceleration lane. (See Figures 2, 44).

Visual Clear Zone - L_{VC}, the distance which provides a buffer between the end of the gap search and acceptance zone, L_{GSA}, and the end of the acceleration lane, allowing the driver to complete the merge process without slowing due to the effect of the approaching end of the acceleration lane. (See Figures 1, 14).

Wedge - The area in which the ramp merges or diverges from the freeway. Also known as the gore. (See Figures 4, 5).

APPENDIX B

DERIVATION OF EQUATIONS

ENTRANCE MODEL

Gap Search and Acceptance Zone, GSA

Initial Assumptions and Delay Definition. The GSA model is a microscopic model for the gap-search and acceptance process of a vehicle traveling from a ramp and merging into the freeway right (shoulder) lane. The objective of this model is to determine the length needed to travel at a constant speed and to merge into the freeway stream in which the constant speed is V_f. The merging driver is assumed to travel along the GSA section of the acceleration lane until a suitable gap is found, or to continue to the end of the GSA where the merging process is aborted and the driver decelerates to a stop. The merge, it is assumed, begins at some point along the GSA. The GSA process begins with a positioning of the ramp vehicle opposite the initial lagging vehicle so that trailing headways may be considered. The derivation of this model follows the discussion below, of the more basic driver entry task.

Delay to merging vehicles is caused by the freeway flow which creates the need to travel at a constant speed and to conduct the gap-search at a lower speed; ($v < V_f$) rather than to accelerate and merge much faster, if no freeway traffic were present. Therefore, it is possible to accept a previously suggested approach (Blumenfeld & Weiss (7)) and to define the delay as the relative time difference between a vehicle on the mainstream and a merging vehicle. Thus:

$$d = \left(1 - \frac{v}{V_f}\right)t \qquad \text{(B-1)}$$

Where,

d = delay to the merging vehicle, sec.

v = constant speed on the acceleration lane, f/s.

V_f = constant speed on the freeway right lane, f/s.

t = travel time along the GSA section of the acceleration lane, sec.

It is possible to define β as:

$$\beta = 1 - \frac{v}{V_f} \tag{B-2}$$

and it follows that:

$$d = \beta t \tag{B-3}$$

Delay Component and Additional Assumptions. One can assume that the total delay to each driver on the acceleration lane is composed of three parameters: the geometric delay (g), the traffic delay (d), and some random delay (e). The geometric delay is caused, at times, by restricted geometry which necessitates travel at a lower speed on the acceleration lane, even if no traffic is present on the freeway right lane.

The random delay is the result of some drivers merging at a point along the second half of the acceleration lane, even though an appropriate gap or lag was available and could be accepted when traversing the first half of the acceleration lane. This may be explained by the need of some drivers to accelerate in comfort outside the freeway lane.

The GSA model is concerned with traffic delay only. That is, it is assumed that other delay components are equal to zero since all drivers are rational drivers and will accept the first available gap (after the initial acceleration maneuver is completed) and that no severe adverse geometry (steep grade or sharp curvature) exists on the acceleration lane.

It is further assumed that traffic in the freeway shoulder lane behaves by the Poisson process, i.e., the gaps (headways) are exponentially distributed as described by the Erlang distribution. Finally, it is assumed that the volume on the ramp is low and no queues are formed along the acceleration lane.

MODEL FORMULATION

The average traffic delay, d_S, for stationary vehicles having a fixed critical gap (headway), T, which accept gaps in a major stream with a flow of vehicles per unit time is given as:

$$d_s = \frac{1}{\lambda}\left(e^{\lambda T} - \lambda T - 1\right) \qquad \text{(B-4)}$$

Note that gaps smaller than the critical gap are assumed to be rejected by all drivers (at a particular site), and longer gaps accepted. However, since the freeway right-lane volume relative to the driver moving in the acceleration lane is affected by the speed differential between the ramp vehicle and the freeway traffic, (parameters defined above) Equation B-4 is adjusted accordingly, as discussed by Polus and Livneh (8), and is given as:

$$d_s = \frac{1}{\lambda\beta}\left(e^{\lambda\beta T} - \lambda\beta T - 1\right) \qquad \text{(B-5)}$$

Where,

d_S = average traffic delay to a merging vehicle, sec.

λ = volume in right lane, vps.

β = relative speed differential (Note Equation B-2).

T = critical headway for merging vehicles, sec.

The travel time on the acceleration lane from the end of the initial acceleration maneuver to the moment of merge (along the GSA section) is given by:

$$t = \frac{d_s}{\beta} \qquad \text{(B-6)}$$

or

$$t = \frac{1}{\lambda\beta^2}\left(e^{\lambda\beta T} - \lambda\beta T - 1\right) \qquad \text{(B-7)}$$

where all the parameters have been defined above. Note that the ramp volume is assumed to be low. The distance then, that a ramp vehicle would travel in the GSA zone before accepting a gap and beginning to merge is given as:

$$d_h = \frac{v_r}{\lambda\beta^2}\left(e^{\lambda\beta T} - \lambda\beta T - 1\right) \qquad \text{(B-8)}$$

Where,

d_h = distance traveled while seeking and accepting a headway, ft.

v_r = average speed of ramp vehicle across GSA zone, f/s.

The volume in the right lane of the freeway is defined as,

$$\lambda = \frac{k\lambda'}{3600N} \qquad \text{(B-9)}$$

Where,

λ = volume in right lane, pcps

λ' = total freeway volume, pcph

k = right-lane distribution factor.

N = number of freeway lanes.

The assumed velocity of the ramp vehicle, across the GSA zone, v_{r_1}, can be described by:

$$v_{r_1} = \sqrt{v_o^2 + 2a_oL_{IA}} \qquad \text{(B-10)}$$

Where,

v_{r_1} = speed of ramp vehicle across GSA zone, f/s.

v_o = speed of ramp vehicle at end of ramp controlling curve, f/s.

a_o = initial acceleration rate of ramp vehicle in IA zone, f/s/s.

L_{IA} = length of IA zone, ft.

Effect of Ramp Volume on Acceleration Lane Length

Increased volume on a ramp will impact, or increase, the distance traveled by a ramp vehicle while seeking and accepting a headway. This distance traveled was previously defined as d_h. In order to reflect this ramp volume effect in the entry model, a factor was developed. The development of this factor is described below.

The traffic delay to a vehicle on an acceleration lane is caused by both the traffic in Lane 1 of the freeway and by the tendency of drivers to remain on the acceleration lane longer than necessary. The former delay can be defined empirically, however, the latter delay is difficult to approximate. The delay to a ramp vehicle caused by freeway Lane 1 traffic is described by Equation B-5 and is based on a low ramp volume. From queueing theory the traffic delay to a ramp vehicle, including ramp volume effects is given as:

$$d_q = d_s + \frac{\sigma^2 + d_s^2}{2\left(\frac{1}{p} - d_s\right)} \qquad \text{(B-11)}$$

Where,

d_q = average delay to a merging vehicle with ramp volume effect, sec.

d_s = average delay to a merging vehicle without ramp volume effect, sec.

σ^2 = variance of time spent in a queue, sec^2.

p = ramp volume, vps.

The second term in Equation B-11, represents the ramp volume effect. Having defined the delay with and without the effects of ramp volume, a factor, f_{hr} can be defined as the ratio of the delays, or,

$$f_{hr} = \frac{d_q}{d_s} \qquad \text{(B-12)}$$

This factor when multiplied by the distance d_h, produces the distance traveled by a ramp vehicle searching for and accepting a headway as impacted by ramp volume. This distance is defined as d_{hr}.

Approximation of the Value of f_{hr}. Because of the highly theoretical nature of the models for d_h and d_s, the relationship which produces f_{hr} results in unrealistic values at the boundary conditions for the model. Since the model was considered sufficiently sound to provide reasonable estimates of the factor for most conditions that would be encountered in design, it was deemed necessary to arrive at a predetermined set of values for the factor, f_{hr}, using the theoretical relationships that could be applied for design purposes. This was accomplished by calculating the factor for a range of speed differentials and volume combinations and then selecting values for f_{hr} which were considered representative for the normal design conditions.

Table B-1 displays several tables which were generated for this purpose. It can be seen that the values for f_{hr} were relatively small and consistent for low ramp volumes and low speed differentials. These values increase substantially as either ramp volume, or speed differential is increased. These values also increase with increasing freeway Lane 1 volume, but to a lesser degree.

Table 6 (in the main body of this report) shows the values which were selected for use in the model. Only two levels of speed differential were considered necessary, recognizing the theoretical nature of the relationships being used, and considering the variations which resulted. The table also indicates that the classification as high speed differential occurs for situations where the difference between the speed in Lane 1 of the freeway is at least 30 mph greater than that assumed for the begin GSA point.

TABLE B-1

TEST VALUES FOR f_{hr}

Freeway Lane 1 Volume (pcph)	f_{hr} Ramp Volume (pcph)			
	200	500	800	1,000
1,000	1.2	1.7	2.2	2.6
1,200	1.3	1.8	2.5	--
1,500	1.3	2.1	--	--
1,800	1.4	--	--	--

V'_f = 70 mph
v'_{r_1} = 0 mph

Freeway Lane 1 Volume (pcph)	f_{hr} Ramp Volume (pcph)			
	200	500	800	1,000
1,000	1.1	1.3	1.5	1.7
1,200	1.1	1.3	1.6	--
1,500	1.1	1.4	--	--
1,800	1.2	--	--	--

V'_f = 70 mph
v'_{r_1} = 30 mph

TABLE B-1 (CONTINUED)

TEST VALUES FOR f_{hr}

Freeway Lane 1 Volume (pcph)	f_{hr} Ramp Volume (pcph) 200	500	800	1,000
1,000	1.3	1.9	2.8	3.6
1,200	1.4	2.2	3.5	--
1,500	1.5	2.7	--	--
1,800	1.7	--	--	--

V'_f = 50 mph
v'_{r_1} = 0 mph

Freeway Lane 1 Volume (pcph)	f_{hr} Ramp Volume (pcph) 200	500	800	1,000
1,000	1.1	1.3	1.4	1.6
1,200	1.1	1.3	1.5	--
1,500	1.1	1.3	--	--
1,800	1.1	--	--	--

V'_f = 50 mph
v'_{r_1} = 30 mph

The Critical Headway

The critical headway which defines the acceptability of a freeway gap depends on the angular velocity threshold of drivers at a particular site and the volume of traffic in the right freeway lane. Figure B-1 shows the components of the angular velocity created by a lagging freeway vehicle as a ramp vehicle is merging. As the freeway vehicle approaches the ramp vehicle, the angle θ, as viewed by the merging driver becomes larger. More simply stated, the freeway vehicle, as perceived by the merging driver, is becoming larger as it approaches. Mathematically, angular velocity is defined as the change in the angle θ over time or $d\theta/dt$. It is possible to define the velocity vectors of approaching vehicles relative to the merging driver. This has been done by Michaels (20) and Drew (5). Essentially, the driver can evaluate the angular velocity which is the first order motion vector relative to the ramp driver. This angular velocity can be quantitatively described by a simple first order differential equation:

$$\omega = \frac{(D+O)(V_f - v_r)}{L_T^2} \qquad \text{(B-13)}$$

Where,

ω = angular velocity, rads/s.

D = width of lagging freeway vehicle, ft.

O = lateral offset between freeway vehicle and ramp vehicle, ft.

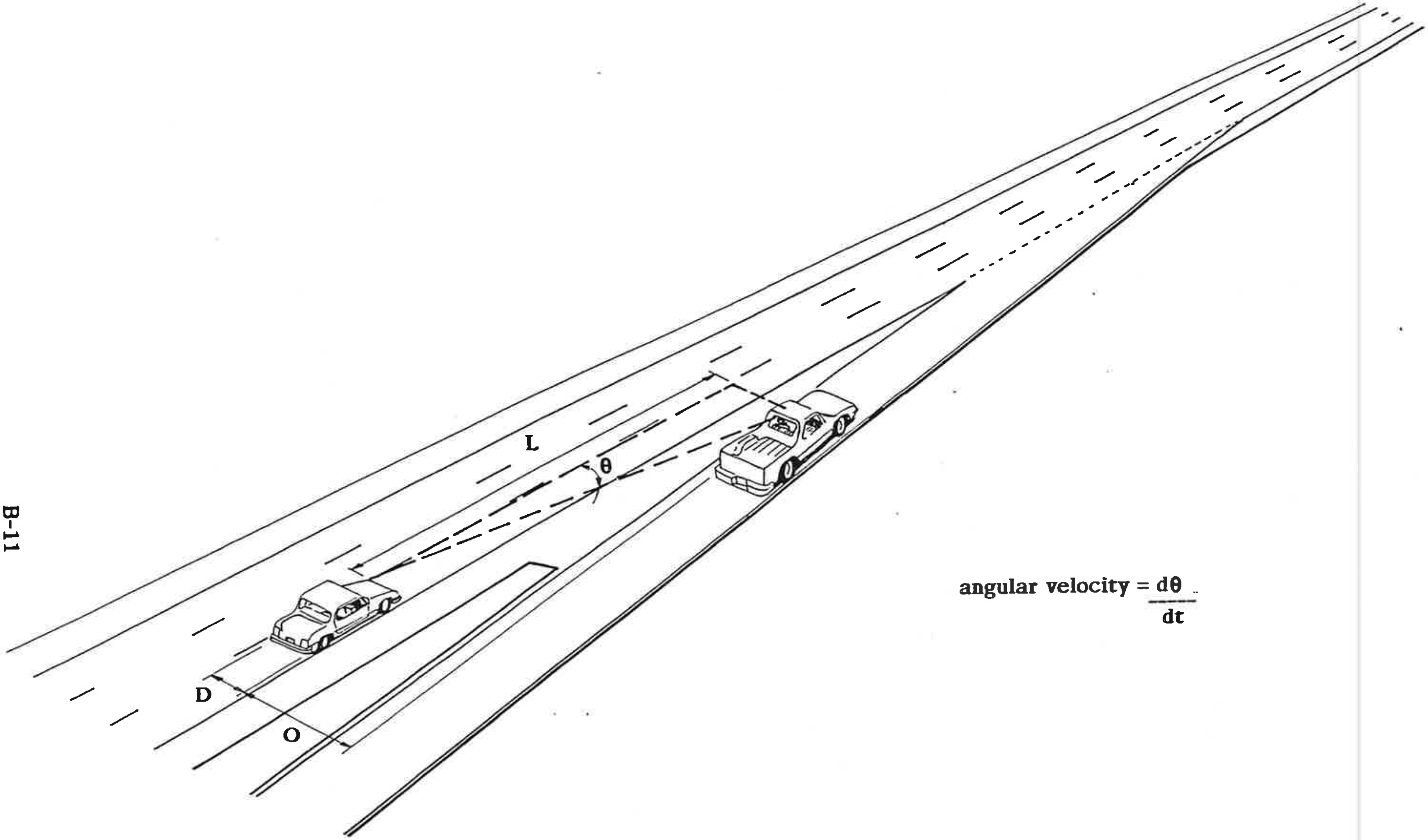
V_f = speed of freeway vehicle, f/s.

v_r = speed of ramp vehicle, f/s.

L_T = longitudinal distance between the two vehicles, ft.

Rearranging gives:

$$L_T = \sqrt{\frac{(D+O)(V_f - v_r)}{\omega}} \qquad \text{(B-14)}$$



angular velocity = $\frac{d\theta}{dt}$

Figure B-1
COMPONENTS OF ANGULAR VELOCITY
IN THE ENTRY PROCESS

It is assumed that a merging vehicle enters into the freeway lane as soon as the lead vehicle has passed. However, in order to smooth the continuity of the model for small speed differentials ($V_f - v_r > 0$) and account for safety and car following of drivers in a traffic stream, two additional terms are added to Equation B-13, and the minimum headway in the freeway traffic stream which will result in an acceptable gap for the merging driver can simply be described as:,

$$L_H = L_T + F + l_f \qquad \text{(B-15)}$$

Where,

L_H = minimum headway in freeway traffic stream, ft.

L_T = longitudinal distance between the merging vehicle and ramp vehicle, ft.

F = length to reflect car following distance, ft.

l_f = length of leading vehicle in the freeway traffic stream, ft.

The length associated with car following effects, F, is defined as:

$$F = \alpha V_f \qquad \text{(B-16)}$$

Where all parameters are as defined above and α is the car following steering control and safety parameter.

The critical time headway, T, is then defined as:

$$T = \frac{L_H}{V_f} \qquad \text{(B-17)}$$

The distance required to search for and accept this freeway headway is based on the assumption that the speed of the ramp vehicle at the beginning of the GSA is at least 10 f/s slower than the speed of the freeway vehicle.

Field data showed that many ramp vehicles arrived at the beginning of the GSA zone with a speed differential of 10 f/s or less. Depending upon the location of the freeway lagging vehicle, the ramp vehicle either accelerated slightly to extend its distance in front of the lagging freeway vehicle, maintained speed, or decelerated slightly in order to fall back to become opposite the lagging vehicle so that trailing headways could be considered. Whereas the equations presented previously only cover the actual gap search and acceptance process, additional relationships are necessary to represent the adjustment process. The absolute distance traveled by the ramp vehicle during the adjustment process is a function of speed and the distance traveled relative to the freeway vehicle. The adjustment process is diagrammed in Figure B-2. The ramp vehicle drops back a distance L_o relative to the freeway vehicle (noted as vehicle 2 in Figure B-2) during the time period $t = t_2 - t_1$. Based on this adjustment process, the absolute distance traveled by the ramp vehicle can be represented as:

$$d_r = v_{r_1} t + \frac{1}{2} a_1 t^2 \qquad \text{(B-18)}$$

Where,

d_r = absolute distance traveled by ramp vehicle, ft.

v_{r_1} = average speed of ramp vehicle access GSA, f/s.

t = time spent completing adjustment process, sec.

a_1 = acceleration/deceleration rate of the ramp vehicle, f/s/s.

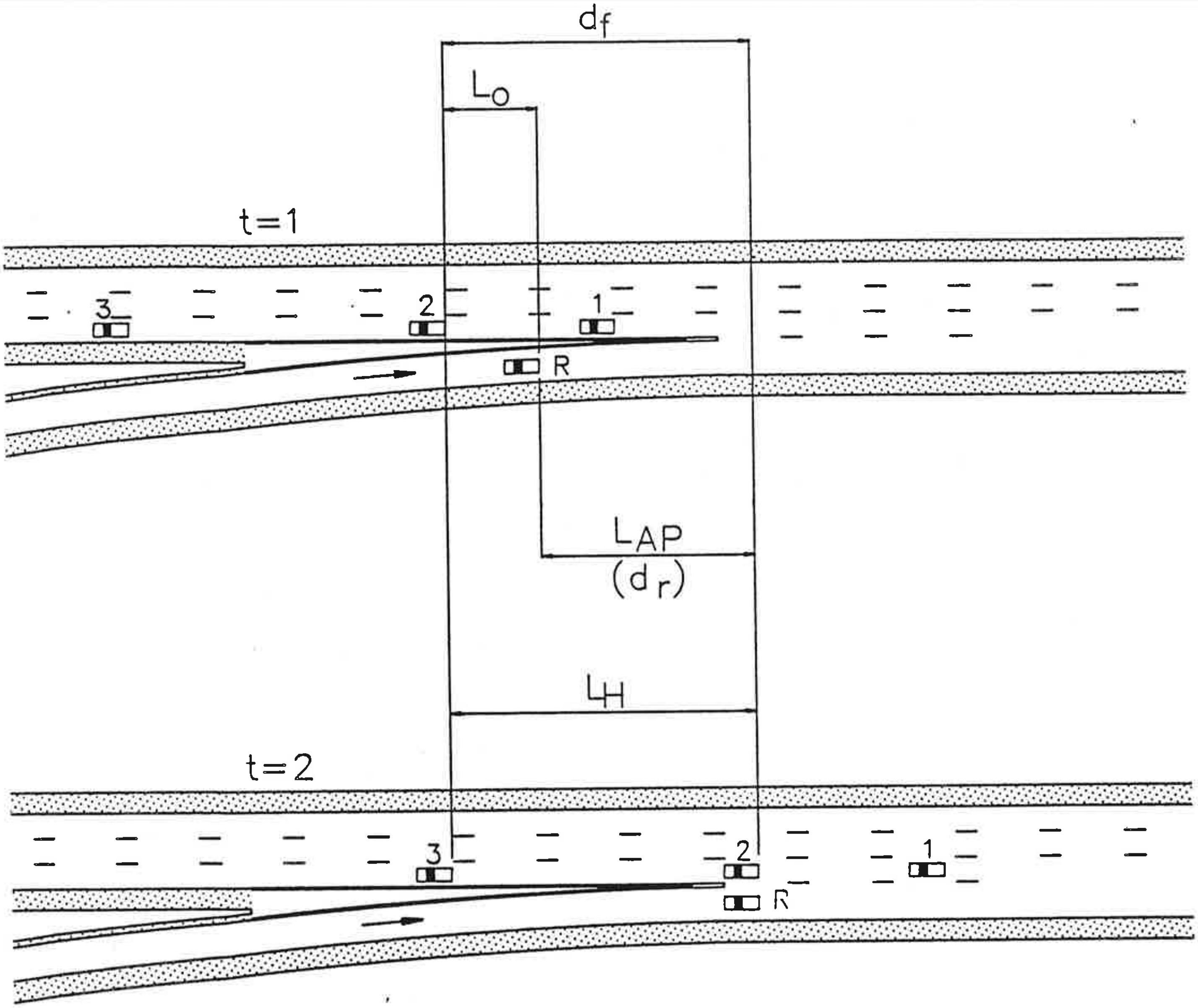


FIGURE B-2

MERGE ADJUSTMENT PROCESS

This distance will be referred to as the "adjust position" length (L_{AP}). The absolute distance traveled by the freeway vehicle during the adjustment process can be similarly be written as:

$$d_f = V_f t + \frac{a_f t^2}{2} \tag{B-19}$$

Where,

d_f = absolute distance traveled by trailing freeway vehicle, ft.
V_f = speed of trailing freeway vehicle, f/s.
t = time spent during adjustment process, sec.
a_f = acceleration/deceleration rate of the freeway vehicle, f/s/s.

The difference between the absolute distances traveled by the ramp and freeway vehicles is:

$$\Delta d = d_f - d_r \tag{B-20}$$

Equation B-20 can be rewritten as:

$$\Delta d = \left(V_f t + \frac{a_f t^2}{2} \right) - \left(\upsilon_{r_1} t + \frac{a_1 t^2}{2} \right) \tag{B-21}$$

Simplifying,

$$\Delta d = \Delta V t + \frac{\Delta a t^2}{2} \tag{B-22}$$

Where,

$\Delta V = V_f - \upsilon_{r_1}$, f/s.
$\Delta a = a_f - a_1$, f/s/s.

Rearranging Equation B-22

$$\Delta V t + \frac{\Delta a t^2}{2} - \Delta d = 0 \qquad \text{(B-23)}$$

Equation B-23 can then be solved using the quadratic solution.

$$t = \frac{-\Delta V \pm \sqrt{\Delta V^2 + 2\Delta a \Delta d}}{\Delta a} \qquad \text{(B-24)}$$

In order to yield a rational term the following conditions are assumed.

$$\Delta a \Delta d \geq 0 \qquad \text{(B-25)}$$

$$\Delta V^2 \geq 2(\Delta a \Delta d) \qquad \text{(B-26)}$$

Solving for the positive root of Equation B-24, since t must be positive, yields

$$t = \frac{2\Delta d}{\Delta V + \sqrt{\Delta V^2 + 2\Delta a \Delta d}} \qquad \text{(B-27)}$$

Equation B-27 may now be used to solve Equation B-18 to arrive at a value for L_{AP}.

Initial Acceleration Zone, IA

The length required to accelerate from an initial ramp speed controlled by a curve, or some other ramp condition, can be described by the principles of motion.

$$L_{IA} = \frac{v_{r_1}^2 - v_o^2}{2a_o} \qquad \text{(B-28)}$$

Where,

L_{IA} = initial acceleration distance, ft.

v_{r_1} = ramp vehicle speed at the end of the IA zone or beginning of GSA zone, f/s.

v_o = initial ramp vehicle speed at the end of the controlling curve or other condition, f/s.

a_o = initial acceleration rate of the ramp vehicle in the IA zone, f/s/s.

Visual Clear Zone, VC

The VC zone is defined as the distance from the end of the acceleration lane needed by a driver to either implement a forced merge or decelerate to a stop. At some point along the speed-change lane, if a driver has not merged, he must force his vehicle into an otherwise unacceptable freeway gap or begin to decelerate. Michaels (21) has suggested that drivers will respond to a change in the angular velocity of an object in the driver's visual field. Michaels defined this distance by:

$$L = \sqrt{\frac{a v_r}{\omega_t} - a^2} \qquad \text{(B-29)}$$

If we assume that the second term in the radical is much less than the first term, the length of the VC zone can be described by,

$$L_{VC} = \sqrt{\frac{a v_{r_3}}{\omega_t}} \qquad \text{(B-30)}$$

Where,

L_{VC} = length of visual clear zone, ft.

a = lateral distance between the driver and a distant point in the driver's foveal field, ft.

v_{r_3} = speed of the ramp vehicle at the end of the GSA zone, f/s.

ω_t = angular velocity threshold, rads/s.

The distance required to abort the entry process or decelerate to a stop is given as:

$$L_{AZ} = \frac{v_{r_3}^2}{2a_A} \qquad \text{(B-31)}$$

Where,

L_{AZ} = length of abort zone, ft.

v_{r_3} = average velocity across the abort zone, f/s.

a_A = average deceleration rate, f/s/s.

EXIT MODEL

Diverge Steering Zone, DS

The equation representing the distance from the exit wedge at which a driver will initiate the exit steering maneuver is given below.

$$L_{DS} = \sqrt{\frac{V_d}{\omega_t}\left(h+y'\right)-\left(h+y'\right)^2} - \frac{y'}{\tan\alpha} \qquad \text{(B-32)}$$

Where,

L_{DS} = distance from nose of exit wedge at which a driver begins to diverge from the freeway, ft.

V_d = velocity of freeway vehicle at the beginning of the diverge maneuver, f/s.

ω_t = angular velocity threshold, rads/s.

h = distance from driver to freeway edge, ft.

y' = width of exit wedge from freeway edge to ramp edge at which driver is focused when diverge begins, ft.

α = angle of ramp divergence, degrees

Provided in the following is a step-by-step derivation of this equation.

The basic equations used in the derivation of angular velocity were originally defined by Gordon, Cozan, and Michaels (22) who pioneered research on angular velocity determination. The basic terms, convention, and frame of reference used in the determination of angular velocity of a fixed point with respect to a driver is illustrated in Figure B-3. The basic equation which describes the angular velocity of a point, in this case the exit wedge, as the driver approaches is:

$$\omega \approx \frac{V_x y}{x^2+y^2} \tag{B-33}$$

Where,

ω = angular velocity, rads/s.

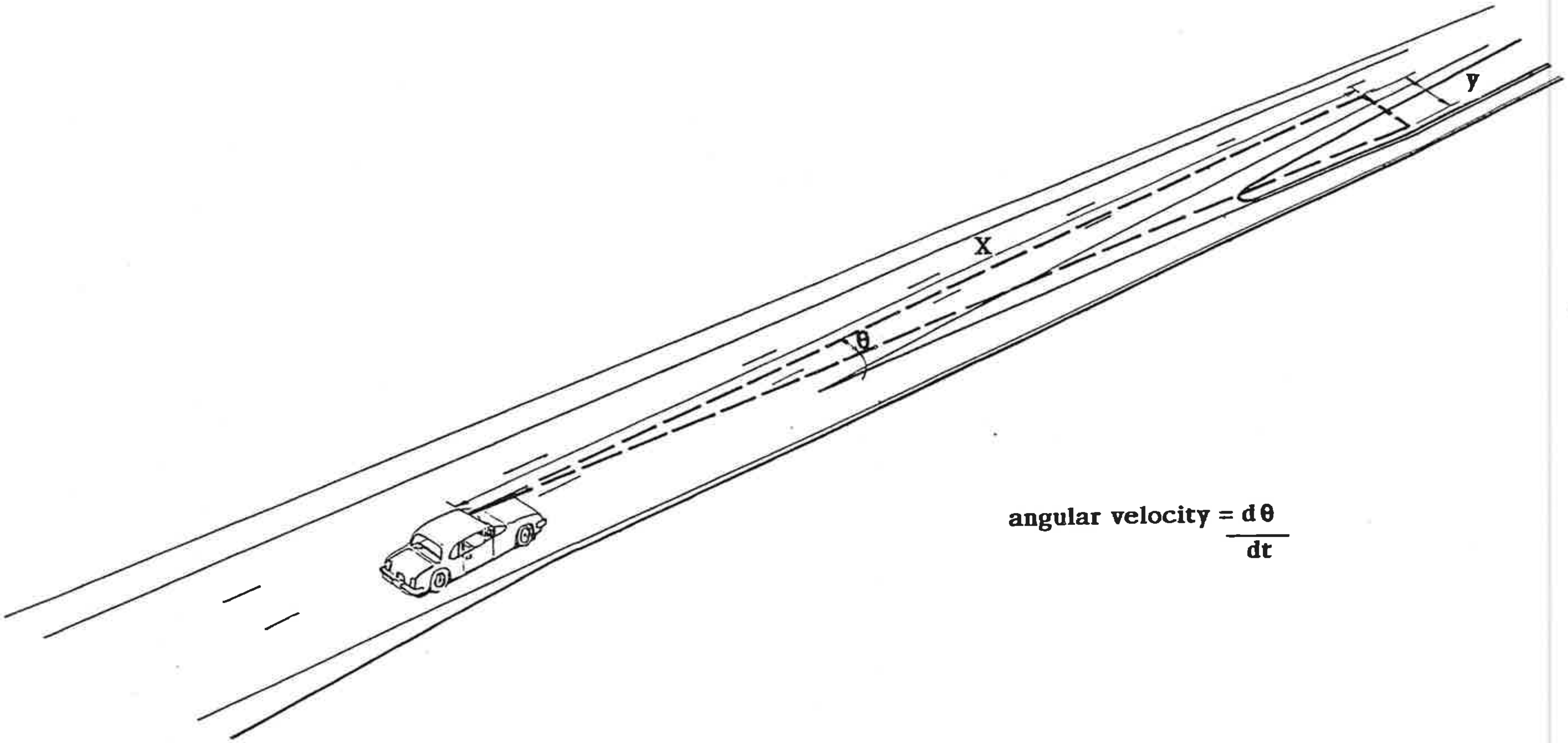
V_x = velocity of a point in the driver's visual field with respect to the driver in the x-direction, f/s.

x = longitudinal distance between the driver and a fixed point, ft.

y = lateral distance between the driver and a fixed point, ft.

Figure B-4 illustrates the basic layout of a vehicle approaching an exit with respect to the driver and a fixed point on the exit wedge. Based on this diagram, the following trigonometric equations can be written:

$$y' = x' \tan \alpha \tag{B-34}$$



$$\text{angular velocity} = \frac{d\theta}{dt}$$

Figure B-3
COMPONENTS OF ANGULAR VELOCITY
IN THE EXIT PROCESS

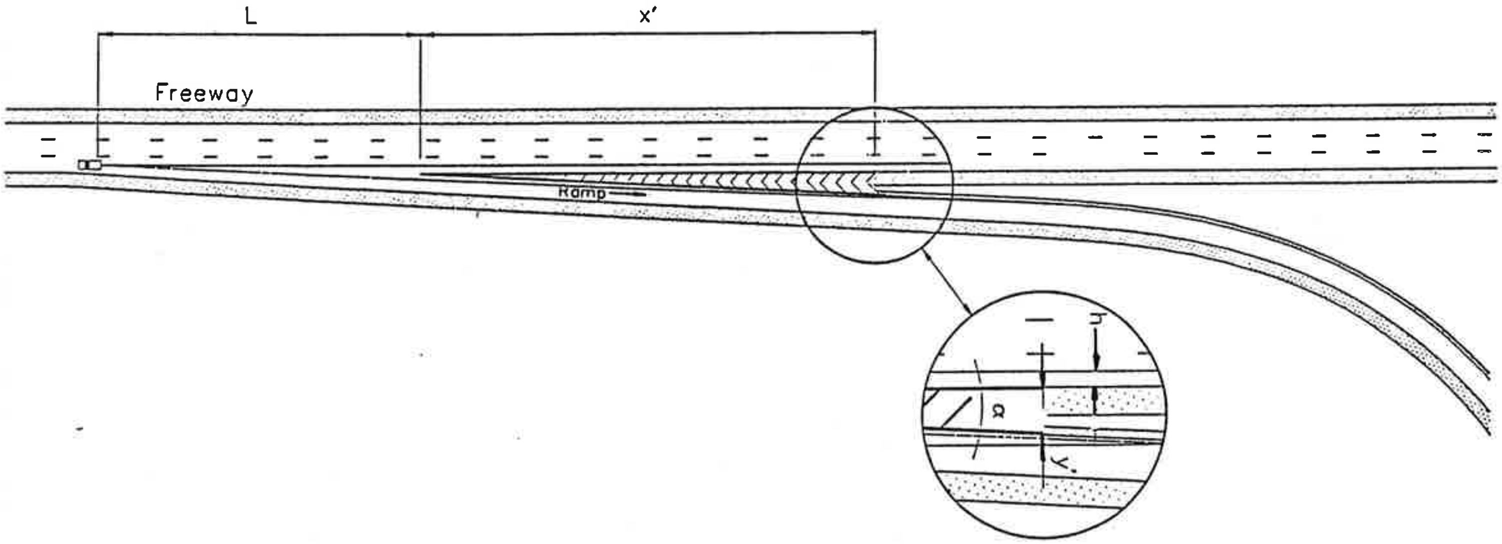


FIGURE B-4

DRIVER PERSPECTIVE—EXIT WEDGE

$$y = h + y' \qquad \text{(B-35)}$$

$$x = x' + L \qquad \text{(B-36)}$$

Where,

y' = width of exit wedge from freeway edge to ramp edge of point on which driver is focused, ft.

x' = distance from beginning of exit wedge to point on which driver is focused, ft.

Substituting these equations into Equation B-33 gives:

$$\omega = V_x \frac{h+y'}{(x'+L)^2 + (h+y')^2} \qquad \text{(B-37)}$$

Solving for L gives:

$$L = \sqrt{\frac{V_x(h+y')}{\omega} - (h+y')^2} - x' \qquad \text{(B-38)}$$

Substituting Equation B-34 into Equation B-38 gives the final form of Equation B-32.

Deceleration In-Gear Zone, DG,

According to the principles of motion, the distance an object moves is a function of time, the initial velocity of the object, and the change in velocity or acceleration rate. Therefore, the distance a decelerating vehicle travels can be described as:

$$L_{DG} = V_d t_g - \frac{1}{2} D_g t_g{}^2 \qquad \text{(B-39)}$$

Where,

L_{DG} = distance travelled in gear, ft.

V_d = velocity at beginning of diverge steering maneuver, f/s.

t_g = time spent in gear, sec.

D_g = deceleration rate while in gear, f/s/s.

According to the same principles, the velocity reached at the end of a deceleration is:

$$V_g = \sqrt{V_d{}^2 - 2L_{DG}D_g} \tag{B-40}$$

Where,

V_g = velocity after travelling a distance in-gear, f/s.

Deceleration While Braking zone, DB,

The distance from a point, either on a curve or at a terminus, at which a driver will begin braking, can be described by Equation B-29, similar to the visual clear distance in the entry model.

$$L_{DB} = \sqrt{\frac{aV_g}{\omega_t} - a^2} \tag{B-41}$$

Where,

L_{DB} = distance from a point at which a driver will begin braking, ft.

a = lateral distance between the driver and a point on a curve or at a ramp terminus, ft.

V_g = velocity at end of deceleration in gear, f/s.

ω_t = angular velocity threshold, rads/s.

Again, applying the principles of motion gives:

$$D_b = \frac{V_g^2 - V_c^2}{2L_{DB}} \qquad \text{(B-42)}$$

Where,

D_b = deceleration rate while braking, f/s/s.

V_c = velocity reached after braking determined by the ramp curvature or condition, f/s.

APPENDIX C

DATA COLLECTION AND REDUCTION APPROACH

One of the key elements of this research study was collection of field data to be used in developing the entrance and exit speed-change lane models. These data included vehicle speeds, acceleration and deceleration rates, steering maneuvers, and any other data necessary to define and model the entering and exiting process. Described below are the data collection plan, data collection methods, and data reduction tasks performed in this study. The actual field data are summarized in Appendix D along with a description of the sites which were selected for data collection.

DATA COLLECTION APPROACH

The primary objective of the data collection was to provide the basic data needed to validate and calibrate the behavioral and operational models developed for the entry and exit processes. The data collection was performed in two phases. A small amount of data were collected at several freeway entrance and exit ramps for use in the initial development of the models. These data provided preliminary indication of the values of certain key variables in each model and identified additional data needs. Based on these needs, a second data collection phase was performed, covering a greater number of sites and reflecting a variety of geometric and operational conditions.

Five types of data were collected at each site:

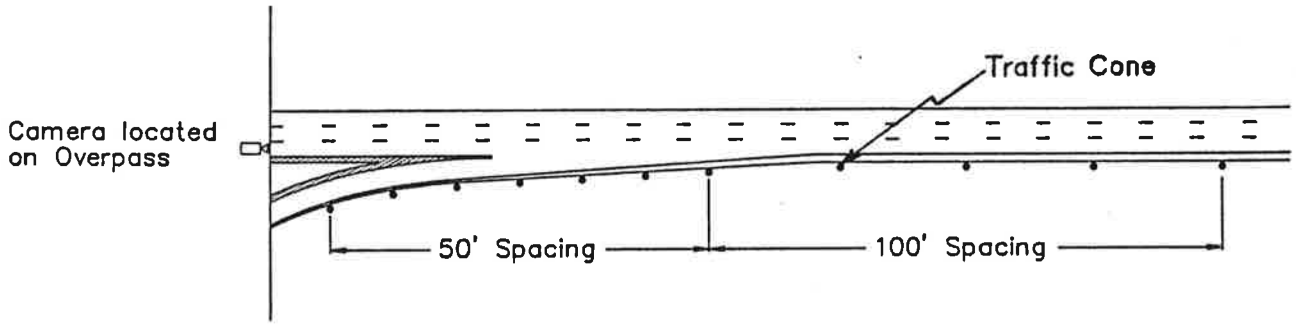
- Speed data
- Traffic volume and composition data
- Geometric data
- Driver behavioral data
- Supplementary data

Videotape was used to collect the data at each site. Much of the geometric data were collected manually. Typical data collection setups are illustrated in Figure C-1. The figure shows the locations of the video cameras and the control points, or cones, used to track each entering or exiting vehicle. Two video cameras were employed at sites which required greater coverage. The specific procedures used to collect each of the data types are discussed below.

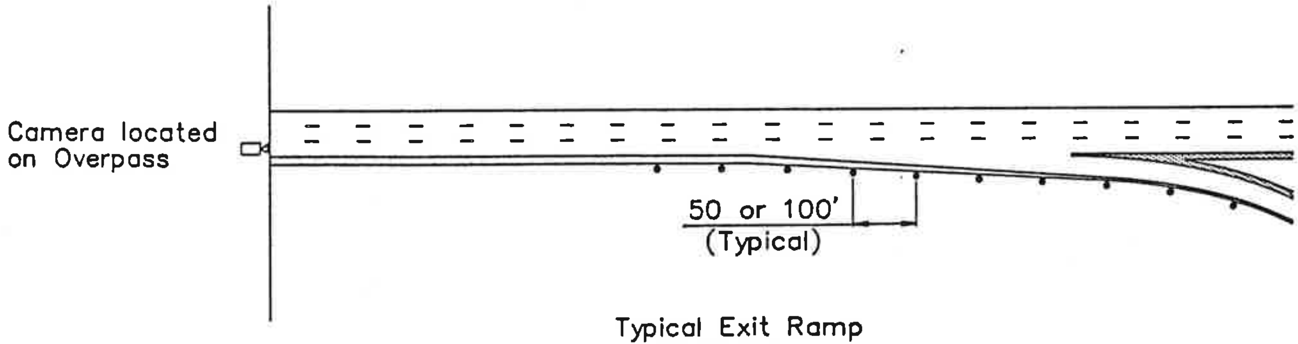
SPEED DATA

The primary data of interest was the speed of vehicles entering or exiting the freeway at different points along the freeway, speed-change lane, and ramp. These speeds provided a profile of vehicle speed change during transition, indicating where and with what magnitude vehicles were accelerating or decelerating, the speeds at which vehicles were entering or exiting the freeway, and the angular velocity threshold of each driver. The speeds of freeway vehicles were also collected in order to determine the speed differentials at which ramp vehicles were entering or exiting the mainline.

In Figure C-1, each set of traffic cones represents a trap. Each trap measured either 50 or 100 feet in length. The length of each trap was determined by location on the speed-change lane, distance from the video camera, and overall speed-change lane length. Fifty-foot spacings were used on sections of the speed-change lane and ramp requiring greater amounts of speed data, such as the initial part of the entrance ramp where vehicles are initially accelerating or prior to the exit wedge where the deceleration in gear is occurring. On the entrance ramps, cones were placed to cover the controlling ramp curve, the tangent ramp section prior to the physical merging and where initial acceleration occurs, and the speed-change lane out to the 6-foot point. If possible, the cones extended past the end of the speed-



Typical Entrance Ramp
Field Set-up



Typical Exit Ramp
Field Set-up

FIGURE C-1

TYPICAL DATA COLLECTION SET-UP

change lane. On diamond type ramps, the cones extended as far upstream on the ramp as possible. Placement of the cones was determined by the characteristics of each site and in some cases, it was not possible to completely cover both the ramp and the speed-change lane due to obstructions. On the exit ramps, cones were placed on the freeway upstream of the beginning of the speed-change lane taper, along the speed-change lane to the exit ramp wedge, and along the ramp up to the controlling curve or as far as possible on diamond-type ramps.

Speeds were calculated for each trap by determining the travel time required by the vehicle to move from one cone to the next. Therefore, the resulting speed was actually an average speed across each trap.

TRAFFIC VOLUME AND COMPOSITION DATA

The traffic volume and composition data were collected for the ramp and the right lane of the freeway. The traffic composition was classified by passenger car, truck, RV, and bus. At several sites, freeway volume data were collected for all lanes. Manual counts of traffic volume and composition were made from the videotapes during the office data reduction. All traffic volume and composition counts were taken by 1-minute periods.

GEOMETRIC DATA

The geometrics of each site were documented during the videotaping. The length of the speed-change lane, from the ramp controlling curve or terminus to the 6-foot point of the speed-change lane taper was measured. Key points along the speed-change lane were identified, including the location of the physical nose of the wedge, the painted or marked nose, and any other physical or geometric elements which could influence the entry or exit process. An estimate was also made of the degree of ramp curvature, degree of angle of divergence, and grade. Where possible, as-built plans were obtained from state transportation departments for use in verifying the geometric conditions at each site. The videotapes taken at each site proved to be a valuable asset when questions arose regarding site characteristics.

DRIVER BEHAVIORAL DATA

In addition to speeds, it was important to identify the behavior of drivers entering and exiting the freeway. This included identifying when vehicles began the steering maneuver to enter or exit the freeway mainline, when entering vehicles forced themselves onto the freeway, when entering vehicles began to slow down in anticipation of the end of the speed-change lane, when exiting vehicles began to brake, and overall driver behavior on the speed-change lane. The locations of these occurrances on the ramp or speed-change lane were denoted by the trap in which they took place. These observations were made through analysis of the videotapes in the office. The beginning of the entry or exit steering maneuver was defined as when the front tire of the entering or exiting vehicle, either left or right, touched the line denoting the right edge of the freeway lane. Completion of the steering maneuver was denoted by the rear wheel of the vehicle, either right or left, crossing the right edge of the freeway lane.

Changes in vehicle speed due to braking were denoted by the observance of brake lights or a rapid decrease in distance relative to a leading or following vehicle. Freeway merges were classified as either free, forced, or aborted. A free merge was defined as the smooth transition of the ramp vehicle creating no sudden disturbances to the freeway traffic. A forced merge was identified by the braking or sudden lane change of a freeway vehicle in response to the merging vehicle. An aborted merge was defined by the slowing of the merging vehicle to a relatively slow speed or stop while still on the speed-change lane.

While videotaping at each site, field observations of unusual driver behavior or other occurrances were noted. These data were useful in explaining unexpected results in the data-reduction phase.

SUPPLEMENTARY DATA

Some supplementary data were collected including:

- Freeway vehicle headways
- Duration of steering maneuvers
- Duration of deceleration in gear
- Location of driver focal point, y', on the exit ramp

The headways of vehicles in Lane 1 of the freeway were noted for each merging vehicle observed in order to determine the gap which was accepted or rejected. In addition, the duration of the entry and exit steering maneuvers, and the time spent decelerating in gear by the exiting vehicles were determined from the videotapes.

In order to determine the point y' in the exiting process, defined as the width of the exit wedge area on which the driver is focused when the steering maneuver is initiated, several vehicle test runs were performed. Five different test drivers made several test runs on various randomly selected exit ramps. As the driver began the exit steering maneuver, the section in the exit wedge area on which the driver was focused was noted. The driver then estimated the width of this section either visually or by actually pacing off the distance. The objective of this limited test study was to derive an approximation of the magnitude of the value of y', which originally had been considered indeterminant with field studies.

DATA REDUCTION APPROACH

A major effort was required to reduce data from the videotapes made in the field. There were three primary activities in the video data reduction. First, a traffic count by 1-minute periods was made by an observer reviewing the videotape. It was felt that 1-minute counts would best reflect the volume on the freeway into which a ramp vehicle was merging. These traffic volumes were broken down by vehicle type (passenger car/truck/RV/bus) and at certain sites by lane. The volume counts were made from normal speed (real time) playback of the videotape.

The second step in the reduction process and the most time consuming was the tracking of individual vehicles entering and exiting the freeway. As each cone was passed, by either the front or rear tires depending upon the camera angle, the video time was recorded. These times were input into a Lotus 123 spreadsheet and the average speeds between each set of cones, or trap, were calculated. Acceleration and deceleration rates were calculated from the speed data. Several other pieces of data were also recorded during the vehicle tracking. On the entrance ramps, these data included:

- The vehicle-type (passenger car, truck, RV, bus).
- The point at which the merge steering maneuver was initiated and completed.
- On curvilinear ramps, the point at which the ramp vehicle completed the steering maneuver to transition from the ramp to the speed-change lane.
- The type of vehicle representing the leading and lagging freeway vehicle.
- The location and speeds of the leading and lagging freeway vehicles when the ramp vehicle began to merge.

- The location and speed of the lagging freeway vehicle at the selected merging end.
- Whether the ramp vehicle accepted or rejected the initial freeway lag.
- Whether the merge was free, forced, or aborted.

On the exit ramps, in addition to the speeds of the exiting vehicle, the following data were also reduced during the tracking process.

- The type of vehicle exiting the freeway.
- The points at which the exit steering maneuver was initiated and completed.
- The point at which braking began. At certain diamond-type ramps, these data were not obtained due to the inability to capture the end of the exit ramp on the videotape.

The vehicle tracking process required that the videotapes be run at slow speed, in some cases, frame-by-frame. This precluded a 100 percent sampling of the entering and exiting vehicles on the videotape. Instead, only those entries or exits which provided the cleanest data and which could be used to calibrate and validate the model were selected. For the entrance ramps, only those merges in which the leading and lagging freeway vehicles were within a reasonable distance of the merging vehicle were considered. A reasonable distance was defined as where the merging vehicle had to consider the freeway vehicle when accepting the available lag or gap. This meant that only periods with moderate to high freeway volumes, in excess of 1,200 pcphpl, were considered. There were no similar criteria set for the exit ramps. Essentially, time considerations for the vehicle tracking phase of the data-reduction process and the need for clean data were the primary criteria set forth in determining the sample size. A more detailed summary of the data collected at each site is discussed in Appendix D.

The third phase of the data-reduction process was to count the free, forced, and aborted merges occurring at each site. In addition, at certain sites, the number of merging vehicles accepting the initial freeway lag were counted.

Quality control was performed throughout the data-reduction process. Several factors created difficulties in reducing the field data, especially in the vehicle tracking process. Parallax caused by the camera angle, glare, shadows on the videotapes, and the visual blocking of vehicles by other vehicles, made the data-reduction process difficult and time consuming. All of the data reduced from the videotapes were checked for questionable results. Such data were rechecked on the videotapes and corrected, if necessary. During the data reduction process, the videotape observers concentrated on obtaining a reasonable amount of accurate, "clean" data rather than large quantities. Data from each site was prioritized as either 1) very useful data, 2) somewhat useful data, or 3) unusable or undesirable data. Except for several unusable sites noted in Table D-1, all sites provided at least some data which were used to validate or calibrate the entrance and exit models. Prioritizing each site was one means of speeding up the data-reduction task and improving the quality of the resulting data set.

APPENDIX D

SUMMARY OF FIELD DATA AND SITE CHARACTERISTICS

SITE CHARACTERISTICS

The sites at which data were collected are presented in Table D-1. Data were collected at 35 sites, located in Illinois, California, and Arizona. All sites were located in an urban/suburban environment. Approximately two-thirds of the sites were entrance ramps. A range of ramp designs, grades, speed-change lane designs, and lengths were covered by the sites selected. All sites were located in urban or suburban areas and all had freeway speed limits of 55 mph. Data were taken only under dry pavement conditions.

AMOUNT OF DATA AVAILABLE

Table D-2 summarizes the amount of data collected and available for analysis. Data were collected at a total of 35 sites, comprising 23 entrance ramps and 12 exit ramps. Data from three sites, AZ04, AZ05, and IL06 were unusable due to unexpected traffic and weather conditions. Data from these sites were not reduced.

The data collected at 19 entrance ramps were used to validate and calibrate the entrance model. Eight sites which provided the highest quality data were used to test the various components of the entry model. These sites were,

Site	Freeway	Location
AZ07	SR 360	Stapley Road
CA03	SR 163	Washington Street
CA04	I-15	Carrol Canyon Road
CA06	I-15	Carmel Mountain Road
CA11	I-5	Genesee Avenue
CA14	I-5	Eastern Avenue
CA16	I-5	Rosecrans Boulevard
IL02	I-94	Lake Avenue

TABLE D-1

SITE CHARACTERISTICS

State	Site #	Route	Location	Ramp Type	Grade	SCL Type	Available L_{EN} (ft)	Mainline Volume (vph)	%HV	Ramp Volume (vph)	%HV
Arizona	AZ01	I-19	NB Irvington Entrance Tucson	Curved	Level	Taper	1500	1650	4	550	2
	AZ02	I-19	SB Irvington Exit Tucson	Diamond	+ 2-3%	Taper	1500	1100	8	400	1
	AZ03	I-19	NB Ajo Way Exit Tucson	Diamond	Level	Taper	300	1700	5	400	1
	AZ04	I-17	NB Grant Entrance Phoenix	Diamond	- 3-4%	Taper	700	Unusable Data			
	AZ05	I-17	SB Van Buren Entrance Phoenix	Diamond	- 3-4%	Taper	700	Unusable Data			
	AZ06	SR-360	EB Rural Rd Exit Phoenix	Diamond	+ 2-3%	Taper	1500	6000	4	500	1
	AZ07	SR-360	EB Stapley Rd Entrance Phoenix	Diamond	- 2-3%	Taper	1500	2000	1	125	6
	AZ08	SR-360	EB Val Vista Rd Exit Phoenix	Diamond	+ 2-3%	Taper	800	2000	3	500	1
	AZ09	SR-360	WB Mill Ave Entrance Phoenix	Diamond	- 2-3%	Taper	1500	6000	4	500	1
	AZ10	SR-360	EB Alma School Rd Exit Phoenix	Diamond	+ 2-3%	Taper	1500	6000	4	500	
California	CA01	SR-163	NB Quince St Exit San Diego	Diamond	+ 2-3%	Taper	400	2500	5	200	1
	CA02	SR-163	SB Robinson St Entrance San Diego	Diamond	- 3-4%	Taper	500	3500	3	250	1
	CA03	SR-163	SB Washington St Entrance San Diego	Diamond	- 3-4%	Taper	300	4000	2	300	2
	CA04	I-15	NB Carrol Canyon Rd Entrance, San Diego	Diamond	- 2-3%	Taper	800	8000	4	500	2
	CA05	I-15	NB Carmel Mountain Rd Entrance, San Diego	Diamond	- 2-3%	Taper	800	3000	10	450	5
	CA06	I-15	SB Carmel Mountain Rd Entrance, San Diego	Curved	- 2-3%	Taper	1000	4500	13	600	3
	CA07	I-15	NB Poway Rd Entrance San Diego	Curved	- 2-3%	Taper	900	3500	12	150	12
	CA08	I-5	NB Genesee Ave Exit San Diego	Diamond	+ 2-3%	Taper	500	4500	2	200	10
	CA09	I-15	SB Poway Rd Entrance San Diego	Curved	- 2-3%	Taper	800	5000	5	500	3

TABLE D-1 (CONTINUED)

SITE CHARACTERISTICS

State	Site #	Route	Location	Ramp Type	Grade	SCL Type	Available L_{EN} (ft)	Mainline Volume (vph)	%HV	Ramp Volume (vph)	%HV
	CA10	I-5	NB La Jolla Village Dr Entrance, San Diego	Curved	- 2-3%	Taper	700	4000	2	200	2
	CA11	I-5	SB Genesee Ave Entrance San Diego	Curved	- 2-3%	Taper	450	3500	4	300	3
	CA12	I-8	EB Hotel Circle Exit San Diego	Curved	Level	Taper	300	7200	2	275	2
	CA13	I-8	WB Hotel Circle Entrance San Diego	Curved	Level	Parallel	1000	Volume Data Not Reduced			
	CA14	I-5	NB Eastern Ave Entrance Los Angeles	Curved	Level	Taper	400	3400	8	200	5
	CA15	I-5	NB Atlantic Blvd Exit Los Angeles	Diamond	+ 2-3%	Taper	250	6000	11	250	24
	CA16	I-5	NB Rosecrans Blvd Entrance, Los Angeles	Diamond	Level	Parallel	600	4000	11	425	12
	CA17	I-5	SB Grande Vista Ave Entrance, Los Angeles	Curved	Level	Parallel	500	Volume Data Not Reduced			
	CA18	I-210	WB Vernon Ave Entrance Los Angeles	Diamond	- 2-3%	Taper	800	Volume Data Not Reduced			
Illinois	IL01	I-94	NB Lake Ave Exit Chicago	Curved	Level	Taper	200	4000	11	300	5
	IL02	I-94	NB Lake Ave Entrance Chicago	Curved	Level	Parallel	500	4500	11	450	5
	IL03	I-290	WB Harlem Ave Exit Chicago	Diamond	Level	Taper	300	3500	14	650	7
	IL04	I-290	WB Harlem Ave Entrance Chicago	Diamond	Level	Taper	600	4000	10	850	5
	IL05	I-94	SB Dundee Rd Entrance Chicago	Curved	Level	Parallel	600	2500	6	800	2
	IL06	RT-41	SB Deerfield Rd Entrance Chicago	Curved	Level	Taper	600	Unusable Data			
	IL07	RT-41	NB Deerfield Rd Exit	Curved	Level	Parallel	300	2500	10	350	4

TABLE D-2

SUMMARY OF FIELD DATA

	Sites	Hours
Total Data Collected	35	61.6
Unusable Sites	3	4.7
Sites Not Sampled	6	8.9

	Sites	Hours	Vehicles Sampled
Entrance Ramps	19	34.9	
Total Data Used For:			
IA Zone	8		348
GSA Zone	8		348
MSC Zone	8		244
VC Zone	8		348
Forced Merge Study	19		7,106
Lag Rejection Study	6		36
Exit Ramps	7	13.1	
Total Data Used For:			
DS Zone	7		440
SC Zone	6		384
DG Zone	5		176
DB Zone	3		97

Since high quality field data were required for the model analyses, only a limited sample size was used to test each model component. These samples were chosen based on the reasonableness of the data. The total number of vehicles used for the various elements of each model are also given in Table D-2.

Exit data were collected at a total of 12 exit ramps. Data from 7 exit ramps was selected for use in testing the various components of the exit model. The sites selected included,

Site	Freeway	Location
AZ03	I-19	Ajo Way
AZ06	SR 360	Rural Road
AZ10	SR 360	Alma School Road
CA01	SR 163	Quince Street
CA12	I-8	Hotel Circle
CA15	I-5	Atlantic Boulevard
IL07	RT-41	Deerfield Road

Data from all seven exit ramps were used to test various assumptions and relationships developed for the DS zone. Six of the sites were used to analyze the SC zone, five were used for the DG zone, and three were used to test the DB zone.

For several reasons only a portion of the data from each selected site was reduced and analyzed. First, in the case of the entrance ramps, only those vehicles merging into relatively small freeway gaps were considered. Ramp vehicles which merged into large freeway gaps did not provide any useful operational or behavioral data for testing of the entrance model. Therefore, only periods of moderate to high traffic volumes on the freeway were considered. Periods of low freeway volumes were reviewed, however, no useful data were obtained. Second, due to the amount of time required to reduce and check individual vehicle data, it was not possible to reduce large quantities of data. Third, due to the type and accuracy of data needed, the videotape observers had to be selective in determining which vehicles would be sampled. Finally, the field data included a high degree of variability due to random errors, parallax caused by less than desirable videotaping angles, geometric and operational characteristics of each site, and probably of greatest impact, the variability in driver behavior.

Entry Data

Table D-3 presents a summary of the total data set used to test the entry model. Average values and standard deviations are provided for each variable. Distributions of various data from the total data set are provided in Table D-4. As noted earlier, the final data set used for calibration and validation of the entry model contained data from eight sites which fit the criteria necessary to provide the required level and quality of data.

The data collected from each of the eight primary sites are summarized in Table D-5. The truck data collected from each entry site are summarized in Table D-6. The results of the forced merge study are presented in Table D-7.

Exit Data

Table D-8 summarizes the total exit data set used to test the exit model. The total data set is summarized further in Table D-9. The total exit data set contains data from seven primary sites. The data from each site are summarized individually in Table D-10. These exit data were used to calibrate and validate the various components of the exit model.

TABLE D-3

SUMMARY OF OVERALL ENTRY DATA

Data Collected	Vehicles Sampled	Average		Standard Deviation
		Unweighted	Weighted by Site	
V'_f, mph	348	49.3	49.3	9.3
v'_o, mph	348	40.4	40.4	11.1
v'_{r1}, mph	348	44.4	44.4	9.4
λ', pcph	348	4,795	4,794	2,075
a_o, f/s/s	348	3.0	3.0	5.7
t_s, sec	244	2.3	2.1	2.1
ω_t, rads/s	214	0.0184	0.0184	0.0196
L_{EN} (measured), ft	342	240	240	140
Headway Accepted, sec	346	2.4	2.5	1.1

TABLE D-4

DISTRIBUTIONS OF ENTRY RAMP DATA

Distribution of Lane 1 Speed, V'_f

V'_f (mph)	Samples	Cumulative Total	Cumulative Percent
35	14	14	4.0
40	36	50	14.4
45	62	112	32.2
50	90	202	58.0
55	64	266	76.4
60	41	307	88.2
65	19	326	93.7
70	12	338	97.1
75	7	345	99.1
80	2	347	99.7
85	1	348	100.0
90	0	348	100.0
> 90	0	348	100.0

Distribution of Accepted Headways

Headway (sec)	Samples	Cumulative Total	Cumulative Percent
0.5	0	0	0.0
1.0	14	14	4.0
1.5	59	73	21.1
2.0	82	155	44.8
2.5	65	220	63.6
3.0	57	277	80.1
3.5	28	305	88.2
4.0	18	323	93.4
4.5	10	333	96.2
5.0	4	337	97.4
5.5	1	338	97.7
6.0	2	340	98.3
> 6.0	6	346	100.0

Distribution of v'_r at Merge

v'_r (mph)	Samples	Cumulative Total	Cumulative Percent
20	0	0	0.0
25	0	0	0.0
30	13	13	3.7
35	48	61	17.5
40	75	136	39.1
45	58	194	55.7
50	54	248	71.3
55	44	292	83.9
60	35	327	94.0
65	18	345	99.1
70	2	347	99.7
75	1	348	100.0
> 75	0	348	100.0

Distribution of ω_t

ω_t (rads/s)	Samples	Cumulative Total	Cumulative Percent
0.001	14	14	6.5
0.002	9	23	10.7
0.003	7	30	14.0
0.004	13	43	20.1
0.005	7	50	23.4
0.006	13	63	29.4
0.007	11	74	34.6
0.008	9	83	38.8
0.009	8	91	42.5
0.010	8	99	46.3
0.011	7	106	49.5
0.012	5	111	51.9
0.013	8	119	55.6
0.014	5	124	57.9
0.015	5	129	60.3
0.016	4	133	62.1
0.017	5	138	64.5
0.018	2	140	65.4
0.019	3	143	66.8
0.020	3	146	68.2
0.021	1	147	68.7
0.022	1	148	69.2
0.023	2	150	70.1
0.024	0	150	70.1
0.025	4	154	72.0
0.026	6	160	74.8
0.027	1	161	75.2
0.028	0	161	75.2
0.029	3	164	76.6
0.030	6	170	79.4
>0.030	44	214	100.0

TABLE D-4 (CONTINUED)

DISTRIBUTIONS OF ENTRY RAMP DATA

Distribution of L_{GSA} (meas)

L_{GSA} (ft)	Samples	Cumulative Total	Cumulative Percent
50	37	37	10.8
100	43	80	23.4
150	68	148	43.3
200	32	180	52.6
250	21	201	58.8
300	56	257	75.1
350	19	276	80.7
400	25	301	88.0
450	13	314	91.8
500	10	324	94.7
550	14	338	98.8
600	4	342	100.0
> 600	0	342	100.0

Distribution of $V'_f - v'_r$ at Merging End

$V'_f - v'_r$ mph	Samples	Cumulative Total	Cumulative Percent
-20.0	2	2	0.6
-15.0	5	7	2.0
-10.0	21	28	8.0
-5.0	44	72	20.7
0.0	57	129	37.1
5.0	72	201	57.8
10.0	44	245	70.4
15.0	38	283	81.3
20.0	20	303	87.1
25.0	21	324	93.1
30.0	8	332	95.4
35.0	9	341	98.0
40.0	3	344	98.9
> 40.0	4	348	100.0

TABLE D-5

SUMMARY OF ENTRY DATA BY SITE

Site: Carmel Mountain, SB
Samples: 49

Data Collected	Average	Standard Deviation
V'_f, mph	49.5	4.7
v'_o, mph	57.5	7.3
v'_{r1}, mph	54.7	6.6
λ ', pcph	4,375	720
a_o, f/s/s	-7.8	4.3
t_s, sec	1.2	0.3
ω_t, rads/s	0.0162	0.0236
L_{EN} (measured), ft	394	115
Headway Accepted, sec	2.2	1.1

Site: Carrol Canyon NB
Samples: 49

Data Collected	Average	Standard Deviation
V'_f, mph	44.0	6.3
v'_o, mph	40.6	3.6
v'_{r1}, mph	49.7	5.6
λ ', pcph	8,222	1,500
a_o, f/s/s	3.6	1.2
t_s, sec	2.3	0.9
ω_t, rads/s	0.0234	0.0229
L_{EN} (measured), ft	420	103
Headway Accepted, sec	1.9	1.4

TABLE D-5 (CONTINUED)

SUMMARY OF ENTRY DATA BY SITE

Site: Eastern Avenue
Samples: 52

Data Collected	Average	Standard Deviation
V'_f, mph	58.8	9.8
v'_o, mph	26.8	2.8
v'_{r1}, mph	34.3	2.9
λ ', pcph	6,900	640
a_o, f/s/s	4.6	2.0
t_s, sec	2.5	0.5
ω_t, rads/s	0.0185	0.0155
L_{EN} (measured), ft	90	34
Headway Accepted, sec	2.3	0.7

Site: Genessee Avenue
Samples: 30

Data Collected	Average	Standard Deviation
V'_f, mph	55.9	7.5
v'_o, mph	49.8	6.1
v'_{r1}, mph	54.1	6.1
λ ', pcph	3.424	595
a_o, f/s/s	9.7	3.7
t_s, sec	1.4	0.3
ω_t, rads/s	0.0176	0.0158
L_{EN} (measured), ft	290	30
Headway Accepted, sec	2.6	1.0

TABLE D-5 (CONTINUED)

SUMMARY OF ENTRY DATA BY SITE

Site: Rosecrans Boulevard
Samples: 9

Data Collected	Average	Standard Deviation
V'_f, mph	52.2	7.1
v'_o, mph	28.7	4.3
v'_{r1}, mph	39.3	3.5
λ', pcph	5,193	625
a_o, f/s/s	11.5	2.9
t_s, sec	1.8	0.5
ω_t, rads/s	0.0067	0.0076
L_{EN} (measured), ft	145	50
Headway Accepted, sec	2.5	0.8

Site: Stapley Road
Samples: 26

Data Collected	Average	Standard Deviation
V'_f, mph	57.8	6.5
v'_o, mph	53.1	7.3
v'_{r1}, mph	52.5	8.3
λ', pcph	2,060	370
a_o, f/s/s	7.6	5.5
t_s, sec	2.2	0.8
ω_t, rads/s	0.0194	0.0251
L_{EN} (measured), ft	260	100
Headway Accepted, sec	3.0	1.8

TABLE D-5 (CONTINUED)

SUMMARY OF ENTRY DATA BY SITE

Site: Washington Street
Samples: 64

Data Collected	Average	Standard Deviation
V'_f, mph	41.6	6.0
v'_o, mph	35.9	3.9
v'_{r1}, mph	40.0	5.5
λ ', pcph	3,695	875
a_o, f/s/s	2.5	1.2
t_s, sec	1.9	0.7
ω_t, rads/s	0.0240	0.0193
L_{EN} (measured), ft	140	54
Headway Accepted, sec	2.1	0.8

Site: Lake Avenue
Samples: 69

Data Collected	Average	Standard Deviation
V'_f, mph	46.6	6.2
v'_o, mph	35.4	3.4
v'_{r1}, mph	38.3	3.6
λ ', pcph	3,670	775
a_o, f/s/s	3.8	1.6
t_s, sec	3.3	1.4
ω_t, rads/s	0.0166	0.0197
L_{EN} (measured), ft	190	75
Headway Accepted, sec	2.8	0.9

TABLE D-6

SUMMARY OF OVERALL ENTRY DATA - TRUCKS

Samples: 17

Data Collected	Average	Standard Deviation
V'_f, mph	47.7	6.9
v'_o, mph	38.1	8.1
v'_{r1}, mph	42.8	7.2
λ', pcph	4,360	2,100
a_o, f/s/s	2.3	3.3
t_s, sec	2.3	1.0
ω_t, rads/s	0.0248	0.0267
L_{EN} (measured), ft	230	165
Headway Accepted, sec	3.6	1.9

TABLE D-7

FORCED MERGE STUDY RESULTS

Site	Location	Merges Observed Free	Merges Observed Forced	Merges Observed Aborted	Total	Available L_{EN} (ft)	Percent Free	Percent Forced	Percent Aborted
CA03	Washington	254	42		296	300	85.8	14.2	0.0
CA14	Eastern	356	66	3	425	400	83.8	15.5	0.7
CA11	Genesee	276	44		320	450	86.3	13.8	0.0
CA02	Robinson	150	95	3	248	500	60.5	38.3	1.2
IL02	Lake Avenue	217	74		291	500	74.6	25.4	0.0
CA16	Rosecrans	507	71		578	600	87.7	12.3	0.0
IL05	Dundee	707	105	1	813	600	87.0	12.9	0.1
IL03	Harlem	367	58		425	600	86.4	13.6	0.0
CA10	La Jolla Village	196	14		210	700	93.3	6.7	0.0
CA09	Poway SB	556	35		591	800	94.1	5.9	0.0
CA05	Carmel Mountain NB	533	13		546	800	97.6	2.4	0.0
CA04	Carrol Canyon	372	24		396	800	93.9	6.1	0.0
CA18	Vernon	176	9		185	800	95.1	4.9	0.0
CA07	Poway NB	131	7		138	900	94.9	5.1	0.0
CA06	Carmel Mountain SB	607	33		640	1,000	94.8	5.2	0.0
CA13	Hotel Circle	135	8		143	1,000	94.4	5.6	0.0
AZ09	Mill Avenue	214	21		235	1,500	91.1	8.9	0.0
AZ01	Irvington	527	15		542	1,500	97.2	2.8	0.0
AZ07	Stapley Avenue	81	3		84	1,500	96.4	3.6	0.0

TABLE D-8

SUMMARY OF OVERALL EXIT DATA

Data Collected	Vehicles Samples	Average Unweighted	Average Weighted by Site	Standard Deviation
V'_f, mph	440	51.7	51.7	10.5
V'_d, mph	441	49.4	49.4	9.2
$V'_f - V_d$, mph	437	3.7	3.7	4.1
V'_g, mph	261	37.6	37.6	15.7
V'_b, mph	114	18.4	18.4	16.1
T_g, sec	176	4.0	5.7	1.5
D_g, f/s/s	176	5.8	9.1	4.5
T_b, sec	97	4.5	6.7	2.1
D_b, f/s/s	97	10.4	16.3	6.0
L_{DS} (measured), ft	300	314	202	82.1
L_{DS} (calculated), ft	300	323	211	43.7
t_{sc}, sec	384	1.6	1.6	0.7
ω_t, rads/s	289	.0082	.0082	.0048

TABLE D-9

DISTRIBUTIONS OF EXIT RAMP DATA

Distribution of V'_b

V'_b (mph)	Samples	Cumulative Total	Cumulative Percent
5	82	82	41.8
10	5	87	44.4
15	29	116	59.2
20	26	142	72.4
25	46	188	95.9
30	7	195	99.5
35	1	196	100.0
40	0	196	100.0
45	0	196	100.0
50	0	196	100.0
55	0	196	100.0
> 55	0	196	100.0

Distribution of T_g

T_g (sec)	Samples	Cumulative Total	Cumulative Percent
1.0	4	4	2.3
1.5	8	12	6.8
2.0	4	16	9.1
2.5	15	31	17.6
3.0	23	54	30.7
3.5	10	64	36.4
4.0	24	88	50.0
4.5	19	107	60.8
5.0	25	132	75.0
5.5	25	157	89.2
6.0	6	163	92.6
> 6.0	13	176	100.0

Distribution of ω_t

ω_t (rads/s)	Samples	Cumulative Total	Cumulative Percent
0.001	0	0	0.0
0.002	0	0	0.0
0.003	0	0	0.0
0.004	3	3	1.0
0.005	52	55	19.0
0.006	80	135	46.7
0.007	73	208	72.0
0.008	11	219	75.8
0.009	3	222	76.8
0.010	9	231	79.9
0.011	0	231	79.9
0.012	0	231	79.9
0.013	2	233	80.6
0.014	3	236	81.7
0.015	4	240	83.0
0.016	3	243	84.1
0.017	9	252	87.2
0.018	10	262	90.7
0.019	18	280	96.9
0.020	8	288	99.7
> 0.020	1	289	100.0

Distribution of T_{sc}

T_{sc} (sec)	Samples	Cumulative Total	Cumulative Percent
0.50	1	1	0.3
0.75	14	15	3.9
1.00	51	66	17.2
1.25	82	148	38.5
1.50	83	231	60.2
1.75	10	241	62.8
2.00	7	248	64.6
2.25	37	285	74.2
2.50	53	338	88.0
3.00	40	378	98.4
3.50	6	384	100.0
> 3.50	0	384	100.0

TABLE D-9 (CONTINUED)

DISTRIBUTIONS OF EXIT RAMP DATA

Distribution of V'_f

V'_f (mph)	Samples	Cumulative Total	Cumulative Percent
30	7	7	1.6
35	15	22	5.0
40	36	58	13.2
45	44	102	23.1
50	93	195	44.2
55	77	272	61.7
60	92	364	82.5
65	45	409	92.7
70	21	430	97.5
75	6	436	98.9
80	2	438	99.3
> 80	3	441	100.0

Distribution of V'_d

V'_d (mph)	Samples	Cumulative Total	Cumulative Percent
30	5	5	1.1
35	26	31	7.0
40	51	82	18.6
45	56	138	31.3
50	81	219	49.7
55	93	312	70.7
60	78	390	88.4
65	33	423	95.9
70	13	436	98.9
75	4	440	99.8
80	1	441	100.0
> 80	0	441	100.0

Distribution of T_b

T_b (sec)	Samples	Cumulative Total	Cumulative Percent
1.0	2	2	2.1
1.5	8	10	10.3
2.0	8	18	18.6
2.5	8	26	26.8
3.0	7	33	34.0
3.5	1	34	35.1
4.0	5	39	40.2
4.5	2	41	42.3
5.0	4	45	46.4
5.5	8	53	54.6
6.0	15	68	70.1
6.5	18	86	88.7
7.0	4	90	92.8
> 7.0	7	97	100.0

Distribution of D_b

D_b (f/s/s)	Samples	Cumulative Total	Cumulative Percent
5.0	2	2	2.1
5.5	7	9	9.3
6.0	9	18	18.6
6.5	10	28	28.9
7.0	9	37	38.1
7.5	10	47	48.5
8.0	4	51	52.6
8.5	4	55	56.7
9.0	4	59	60.8
9.5	1	60	61.9
10.0	6	66	68.0
10.5	1	67	69.1
11.0	2	69	71.1
11.5	1	70	72.2
12.0	2	72	74.2
> 12.0	25	97	100.0

TABLE D-9 (CONTINUED)

DISTRIBUTIONS OF EXIT RAMP DATA

Distribution of $V'_f - V'_d$

$V'_f - V'_d$ (mph)	Samples	Cumulative Total	Cumulative Percent
0	71	71	16.1
2	129	200	45.4
4	93	293	66.4
6	47	340	77.1
8	37	377	85.5
10	29	406	92.1
12	13	419	95.0
14	6	425	96.4
16	8	433	98.2
18	4	437	99.1
20	1	438	99.3
22	1	439	99.5
24	1	440	99.8
> 24	1	441	100.0

Distribution of V'_g

V'_g (mph)	Samples	Cumulative Total	Cumulative Percent
20	46	46	17.6
25	34	80	30.7
30	16	96	36.8
35	12	108	41.4
40	16	124	47.5
45	19	143	54.8
50	46	189	72.4
55	37	226	86.6
60	27	253	96.9
65	8	261	100.0
70	0	261	100.0
75	0	261	100.0
80	0	261	100.0
> 80	0	261	100.0

Distribution of L_{SCL} (calc)

L_{SCL} (calc) (ft)	Samples	Cumulative Total	Cumulative Percent
100	0	0	0.0
125	0	0	0.0
150	0	0	0.0
175	0	0	0.0
200	0	0	0.0
225	1	1	0.3
250	9	10	3.3
275	34	44	14.7
300	44	88	29.3
350	137	225	75.0
400	62	287	95.7
> 400	13	300	100.0

Distribution of L_{SCL} (meas)

L_{SCL} (meas) (ft)	Samples	Cumulative Total	Cumulative Percent
100	4	4	1.3
125	0	4	1.3
150	0	4	1.3
175	0	4	1.3
200	71	75	25.0
225	0	75	25.0
250	0	75	25.0
275	0	75	25.0
300	104	179	59.7
350	0	179	59.7
400	121	300	100.0
> 400	0	300	100.0

TABLE D-9 (CONTINUED)

DISTRIBUTIONS OF EXIT RAMP DATA

Distribution of D_g

D_g (f/s/s)	Samples	Cumulative Total	Cumulative Percent
1.0	25	25	14.2
2.0	14	39	22.2
3.0	10	49	27.8
4.0	6	55	31.3
5.0	12	67	38.1
6.0	9	76	43.2
7.0	13	89	50.6
8.0	16	105	59.7
9.0	16	121	68.8
10.0	18	139	79.0
11.0	17	156	88.6
12.0	9	165	93.8
> 12.0	11	176	100.0

Distribution of L_{SCL} (calc) - L_{SCL} (meas)

L_{SCL} (calc) - L_{SCL} (meas) (ft)	Samples	Cumulative Total	Cumulative Percent
10	32	32	10.7
20	27	59	19.7
30	32	91	30.3
40	28	119	39.7
50	30	149	49.7
60	23	172	57.3
70	26	198	66.0
80	21	219	73.0
90	19	238	79.3
100	12	250	83.3
> 100	50	300	100.0

TABLE D-10

SUMMARY OF EXIT DATA BY SITE

Site: Ajo Way
Samples: 47

Data Collected	Average	Standard Deviation
V'_f, mph	55.0	4.8
V'_d, mph	51.2	6.3
$V'_f - V'_d$, mph	5.8	4.4
V'_g, mph	27.4	11.6
V'_b, mph	--	--
T_g, sec	4.7	1.5
D_g, f/s/s	8.7	2.6
T_b, sec	--	--
D_b, f/s/s	--	--
L_{DS} (measured), ft	300.0	0.0
L_{DS} (calculated), ft	320	29.6
t_{sc}, sec	1.3	0.2
ω_t, rads/s	0.0063	0.0005

TABLE D-10 (CONTINUED)

SUMMARY OF EXIT DATA BY SITE

Site: Atlantic Boulevard
Samples: 30

Data Collected	Average	Standard Deviation
V'_f, mph	40.0	6.3
V'_d, mph	39.5	6.4
$V'_f - V_d$, mph	1.9	1.7
V'_g, mph	29.1	13.7
V'_b, mph	12.9	5.1
T_g, sec	4.0	2.4
D_g, f/s/s	4.5	2.3
T_b, sec	3.5	1.7
D_b, f/s/s	12.1	6.2
L_{DS} (measured), ft	--	--
L_{DS} (calculated), ft	--	--
t_{sc}, sec	1.0	0.3
ω_t, rads/s	--	--

TABLE D-10 (CONTINUED)

SUMMARY OF EXIT DATA BY SITE

Site: Hotel Circle
Samples: 54

Data Collected	Average	Standard Deviation
V'_f, mph	45.4	4.1
V'_d, mph	36.2	3.8
$V'_f - V_d$, mph	9.3	3.4
V'_g, mph	25.1	11.6
V'_b, mph	14.1	1.6
T_g, sec	4.1	1.2
D_g, f/s/s	9.2	3.5
T_b, sec	3.8	2.7
D_b, f/s/s	11.8	7.1
L_{DS} (measured), ft	--	--
L_{DS} (calculated), ft	--	--
t_{sc}, sec	1.1	0.2
ω_t, rads/s	0.0176	0.0016

TABLE D-10 (CONTINUED)

SUMMARY OF EXIT DATA BY SITE

Site: Quince Street
Samples: 65

Data Collected	Average	Standard Deviation
V'_f, mph	49.7	4.2
V'_d, mph	48.7	4.3
$V'_f - V_d$, mph	1.3	0.9
V'_g, mph	42.6	11.7
V'_b, mph	22.1	2.7
T_g, sec	3.7	1.0
D_g, f/s/s	7.0	3.3
T_b, sec	5.2	1.5
D_b, f/s/s	8.9	4.7
L_{DS} (measured), ft	211	31
L_{DS} (calculated), ft	286	27
t_{sc}, sec	1.1	0.3
ω_t, rads/s	--	--

TABLE D-10 (CONTINUED)

SUMMARY OF EXIT DATA BY SITE

Site: Rural Road
Samples: 65

Data Collected	Average	Standard Deviation
V'_f, mph	54.4	5.1
V'_d, mph	54.0	5.0
V'_f - V_d, mph	0.6	1.4
V'_g, mph	54.3	4.0
V'_b, mph	--	--
T_g, sec	3.1	0.9
D_g, f/s/s	1.6	1.8
T_b, sec	--	--
D_b, f/s/s	--	--
L_{DS} (measured), ft	268	58
L_{DS} (calculated), ft	316	32
t_{sc}, sec	1.7	0.5
ω_t, rads/s	0.0072	0.0020

TABLE D-10 (CONTINUED)

SUMMARY OF EXIT DATA BY SITE

Site: Alma School Road
Samples: 124

Data Collected	Average	Standard Deviation
V'_f, mph	59.7	7.6
V'_d, mph	57.3	6.4
$V'_f - V_d$, mph	2.7	1.8
V'_g, mph	--	--
V'_b, mph	--	--
T_g, sec	--	--
D_g, f/s/s	--	--
T_b, sec	--	--
D_b, f/s/s	--	--
L_{DS} (measured), ft	398	13
L_{DS} (calculated), ft	348	45
t_{sc}, sec	2.4	0.4
ω_t, rads/s	0.0052	0.0007

APPENDIX E

DRIVER BEHAVIOR ENTERING FREEWAYS

The logic for the freeway entering process is straightforward. Any driver wishing to enter a freeway will have to negotiate a simple or compound curve to enter the acceleration lane. This requires the driver to carry out a pursuit tracking task to follow the curvature and transition onto the acceleration lane. When this maneuver is complete, the driver will then initiate acceleration until traffic gaps approaching in the adjacent lane of the freeway become visible. At that point, the driver will determine the availability of an acceptable gap. If, and when an acceptable gap appears, the driver will then initiate a steering maneuver to enter the freeway mainline from the acceleration lane. If, in this search process, no acceptable gap appears, a point is reached where the driver initiates a deceleration to avoid running off the end of the acceleration lane or being forced onto the freeway mainline. This is defined as the abort zone.

It should be clear that each step involves the driver's capacity to both process information from roadway and traffic and translate that information into speed and steering control responses on the vehicle. The fundamental questions are 1) what information does the driver need to accomplish tasks in each of the steps defined; and 2) what are the time and distance magnitudes required for their accomplishment. The remainder of this appendix is concerned with addressing these questions.

The key element of the merging process is gap detection and evaluation for possible acceptance. Once the gap detection element is defined, and the time and distance requirements for this part of the process are determined, the remaining steps in the process can be defined from this reference. The fundamental question for a driver traveling on a path parallel to the adjacent lane of a freeway is what mainline gap is acceptable. In addition, from a design standpoint, any such process should minimize introduction of a speed change into the mainline traffic flow. From a cognitive standpoint there are only two psychophysical dimensions that provide the driver with direct information about gap size. One is simply judgement of absolute distance separating the two vehicles. However, such a distance judgement has three fatal flaws: 1) accuracy varies inversely with absolute distance (Weber's Law); 2) there is no basis for a criterion for the driver to accept or reject a gap, i.e., the driver does not know how much is sufficient; and 3) it does not recognize the fact that both mainline and ramp vehicles are moving relative to one another.

The second possible measure is the judgement of relative velocity. In psychophysical terms this is angular velocity. This concept is diagrammed in Figure E-1. From the driver's standpoint, a vehicle in the adjacent freeway lane will have either of two components of angular velocity. Angular velocity will either be increasing if the lagging vehicle is closing on the gap seeking driver or decreasing if the lagging vehicle is falling behind relative to the gap seeking driver. Only the first case is critical. Indeed, the driver can establish a very simple criterion for accepting or rejecting any detected gap. If the angular velocity is greater than the driver's threshold, the lagging vehicle must be closing and, therefore, the perceived gap is too small to accept. Conversely, if the angular velocity is below threshold (or negative), there is no perceived closure and the gap is sufficient to accept.

It should be noted that using the threshold of angular velocity leads to a simplified accept-reject criterion for the gap seeking driver which is generally a more stable decision basis than some other criteria for human control. However, it

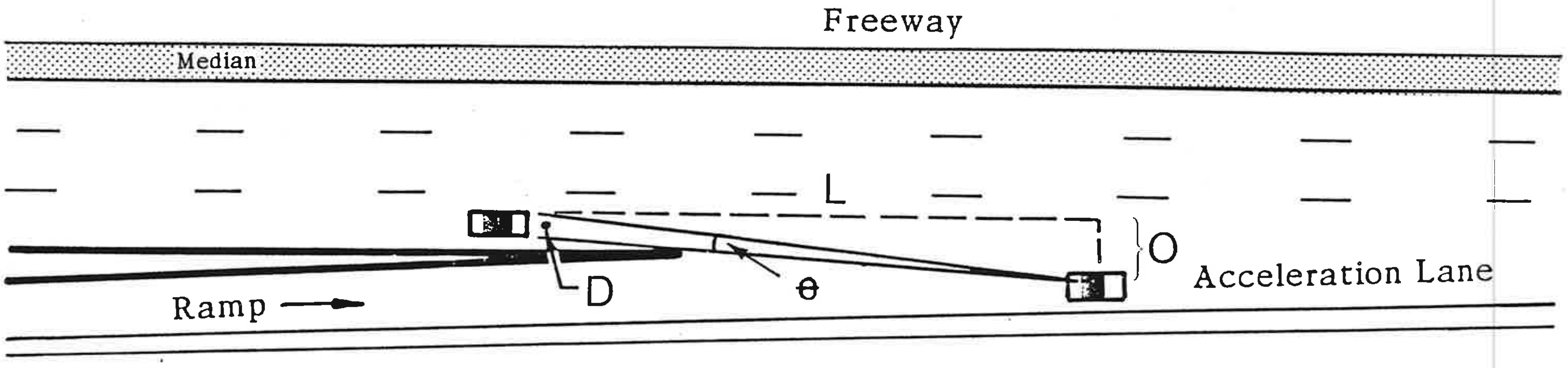


FIGURE E-1

PARADIGM OF GAP SEARCH

is well to point out than in psychophysics the threshold is defined stochastically. It is that stimulus value that is detected with a probability of 0.5. Thus, there will be considerable variability in measured thresholds. However, from previous work noted in the literature survey, it is possible to estimate the threshold of angular velocity in the driving situation, ω_t = .004 rads/s with an expected range of 0.0023 to 0.0069 rads/s.

What this model suggests is that the gap seeking driver will view the oncoming traffic in the adjacent lane of the freeway using the rear view mirror or by turning his head. The approaching freeway vehicle subtends an angle at the eye of the driver on the speed-change lane. It is the rate of change of this angle that is the criterion measure, angular velocity. The simplest expression for this function is:

$$\omega_t = \frac{2D(V_f - V_e)}{L^2} \qquad \text{(E-1)}$$

Where:

ω_t = angular velocity, rads/s.

D = width of the approaching vehicle, ft.

V_f = velocity of freeway vehicle, f/s.

V_e = velocity of merging vehicle, f/s.

L = distance between the two vehicles, ft.

Two observations need to be made concerning Equation E-1. First, D reflects the size of the freeway vehicle. For continuity as well as psychophysical reasons, i.e., the relative insensitivity of the visual system to the vertical dimension, this dimension is taken to be simply the width of the approaching vehicle, or 7 feet for a passenger car. Second, the equation assumes that the angular separation between the two vehicles is small relative to the viewing distance and is thus neglected. What this does is eliminate a rotational angular velocity component. At distances over 100 feet this is small compared to the linear component. At closer distances, or lateral separations greater than 3 to 5 feet, this rotational vector may be expected to increase the perceived angular velocity of the approaching vehicle and hence reduce the likelihood of merging.

A simple and stable model of gap selection has been defined. If the observed gap does not meet the angular velocity criterion, it is hypothesized that the driver will reject the gap and begin to accelerate in order to prepare for the next gap. By accelerating, the gap seeking driver will normally reduce the speed difference between his vehicle and the next lag vehicle on the adjacent freeway lane.

STEERING CONTROL ZONE

It is assumed in this model that when the connecting ramp is a curved section terminating in a tangent section on the acceleration lane, the driver must first control vehicle position by steering from the ramp curvature onto the speed-change lane. In this task, the driver is required to adjust vehicle rotation to equal roadway rotation. This is essentially a tracking task. The section of the acceleration lane in which this occurs is defined as the steering control zone (SC). As the driver approaches a curve at a given speed, a point is reached where the roadway has a component of angular velocity causing the roadway to appear to rotate; to the right for a right hand curve, to the left for a left hand curve. It is this perception that is the basic cue for the driver to initiate a steering control change. The magnitude of steering control required must be sufficient to cause the rotation of the vehicle relative to the driver to equal the perceived rotation of the roadway.

If there is insufficient steering input, the driver will perceive himself drifting left (for a right hand curve) or driving "up" the curve. Conversely, with excess steering input, the driver will perceive himself drifting to the right. Since the angular velocity varies, with the right side of a right hand curve having larger angular velocities than the left (23), the driver will generally tend to understeer rather than oversteer. This, of course, is reinforced in normal design with superelevation as well as normal kinesthetic and vestibular cues. Thus, drivers negotiate curves not only with their eyes and ears but with their acceleration senses as well.

The magnitude of the perceived angular rotation as well as the kinesthetic and vestibular cues depends to a significant degree on the speed at which the driver enters the curve. In effect, drivers can control the angular rotation of the roadway by adjusting their speed which in turn allows the driver to limit the rate of steering input required to track the curve and consequently minimize the centrifugal or centripetal forces that they will experience.

Curve tracking is an obviously complex one for the driver. Most research suggests that the majority of speed control is exercised prior to entry onto the curve. Minimal braking occurs while the steering maneuver is being carried out. Changes of speed will occur, but these are relatively small and done without braking. Hence, in negotiating the ramp connecting the acceleration lane, the driver will be concentrating on steering and the probability is high that the vehicle speed will decrease.

Finally, as the driver approaches the end of the ramp curve, the roadway ceases to rotate. The driver knows that he is approaching a tangent, the acceleration lane. The driver must then reverse his steering input. Because of the steering characteristics of most modern automobiles, the steering correction requires only that the driver release the steering wheel for the vehicle to cease to rotate.

It is this last step in the steering process that is important in terms of acceleration lane length. It is necessary to determine how much distance is required for the driver to complete this transition steering maneuver onto the acceleration lanes. The steering control model developed by McRuer (24) is the logical basis for deriving this length. Unfortunately, this model does not allow for the derivation of a specific value for this situation. However, McRuer (25) does report time requirements for specific classes of steering maneuvers. For a lane change maneuver at 60 mph, it was found that expert drivers could carry out the maneuver in 1 sec. For normal drivers, this time was approximately 3 sec. Therefore, it is possible to estimate a reasonable length required to steer from the ramp curve to the acceleration lane. Assuming a normal driver, tracking the ramp curve at 45 to 50 ft/s, recovery should require approximately one-third to one-half that found by McRuer (24,25). It is estimated that approximately a 1 second steering transition from ramp to acceleration lane would be sufficient. Thus, the length of this transition would be approximately 1 to 1-1/2 times the entry velocity. Assuming an entry speed of 50 ft/s, a maximum of 75 feet should be provided for the entry steering maneuver.

INITIAL ACCELERATION ZONE

It is assumed that at the point where the steering maneuver is complete the driver will be traveling at some speed determined by the design speed of the ramp curve. Further, at the point of entry onto the acceleration lane, the driver's view of approaching traffic on the adjacent freeway lane is constrained either because of an obstructing structure or more simply by the magnitude of the visual angle between the entering driver and approaching traffic. At high merge angles, the component of rotational angular velocity would be high and confuse the driver's judgement of approach angular velocity. In essence, the driver cannot at that point obtain a reliable estimate of that component of angular velocity upon which gap acceptance judgements are made. Consequently, and realistically, one would predict that the driver will accelerate on the acceleration lane until an unobstructed view of traffic in the right hand lane of the freeway is obtained. This should be the case when the acceleration lane is either a curved ramp with a descending ramp connector or a diamond with an upgrade or downgrade connector to the acceleration lane. In the latter case, the vertical component of angular velocity will be added non-linearly to the horizontal component which the driver uses to judge gaps. This would sufficiently reduce the reliability of gap judgement, causing the driver to use such information only for precognitive evaluation. Finally, from simply observing freeway traffic, the driver realizes that there is a significant difference in relative velocity between himself and the traffic stream he seeks to enter. It is reasonable, therefore, to expect the entering drivers to accelerate prior to the beginning of gap search.

The length of this acceleration segment will depend upon the magnitude of acceleration which is acceptable to the driver on the acceleration lane. If the driver accelerates at 4.8 ft/sec for only 2.0 seconds, he will have traveled 110 feet which when added to the steering control distance means that the driver will have a clear view of oncoming traffic for a minimum of 160 to 185 feet. This provides a length sufficient for viewing approaching vehicles and initiating the first gap search trial.

VISUAL CLEAR ZONE

The final component of the acceleration lane is the termination or abort segment. As the driver proceeds down the acceleration lane seeking an acceptable gap, he must be aware that the lane is of finite length. At some point, drivers must respond to the fact that they are running out of acceleration lane. If they do not find a gap beyond a certain point they must then begin to decelerate. Therefore, it is necessary to determine the point at which the driver initiates deceleration to avoid running off the acceleration lane. This visual clear zone (VC) must provide the driver with sufficient distance to implement a forced merge or decelerate to a stop.

From a driver behavior perspective, it has been suggested by Michaels (20, 21) that drivers will adjust speed to maintain the angular velocity of obstructions in their path at threshold. It can be shown that the angular velocity of a discrete or continuous element located laterally relative to the driver's line of reference will increase with lateral distance from that forward reference line. It may also be shown that if a driver's reference point along that line of regard is a distance at which the lateral and vertical angular velocity vectors are at threshold (at speeds of 80 to 90 ft/s), all elements located more than 6 feet to the right will have a detectable component of angular velocity. With a normal location in the acceleration lane, the pavement-shoulder edge will have angular velocity that is approximately at threshold. As the driver approaches the terminus of the acceleration lane, the contrasting pavement-shoulder edge generates a decreasing angular velocity. This provides the driver with an immediate cue to the end of the acceleration lane. If the driver responds to this cue by reducing speed, the forward reference distance is decreased, the angular velocity of the pavement edge at the nearer distance is increased. In essence, there is a simple feedback loop between lateral angular velocity and speed. Operating on this basis, a driver will decelerate smoothly and reach a stop near the end of the acceleration lane. On the basis of this model, if a driver on the acceleration lane is traveling at a speed of 70 to 80 ft/s then as he/she approaches to within 200 to 250 feet of the end of the lane or when the taper produces a lane width of less than 10 feet the driver will begin to decelerate.

In essence, drivers will shift from gap seeking to speed reduction. The beginning of the abort zone is thus defined as that point on the acceleration lane where a driver must shift from gap search to deceleration.

It should be recognized that as drivers enter the abort zone they have two alternatives which are not mutually exclusive. The first is to decelerate to a stop, and the second is to force a merge. That is, the driver will enter the mainline of the freeway even though the gap produces a supra-threshold angular velocity. We would predict that forced merges would increase sharply with distance traveled on the acceleration lane.

One other point to be noted concerns the design of the acceleration lane. It is accepted practice to design the lane as a continuous taper of the order of 50-70:1 depending upon the lane length. This design poses an inherent difficulty for the driver. First, as the driver proceeds, the right edge of the roadway as it enters the locus of the visual reference appears to be moving to the driver's left. This should induce a shift of attention from the gap search task to steering. In essence the taper induces a time sharing between two tasks which reduces the reliability of both. Further, as the road tapers, elements that are off the roadway, e.g. shoulder detail, now enter the action field. The normal perception is that the roadway is ending, leading to the initiation of deceleration discussed above. We would thus predict that forced merges will occur more frequently with a taper acceleration lane design with from a parallel design.

SUMMARY OF THE ENTERING PROCESS

In this analysis, four components have been identified as essential steps by which drivers use the acceleration lane to enter a freeway. Each was treated independently, largely because each element represents a different guidance and control process by the driver. Because of the different requirements, we assume that the driver must time share among them, ordering them in time and space through experience, i.e., learning. Thus the observed continuity of driver behavior on the acceleration lane is actually four separate but overlapping tasks, each with its own performance requirements and each requiring different environmental sources of information upon which drivers must operate. Using this sequential approach it has been possible to derive an estimate of the distance required for each phase. We make the final simplifying assumption that total acceleration lane length required is the sum of these component distances.

APPENDIX F

DRIVER BEHAVIOR EXITING FREEWAYS

In the task analysis of the exiting maneuver, three basic behavioral tasks are required of a driver in exiting a freeway. First is the steering control maneuver to leave the freeway mainline. Second is the deceleration control on the deceleration lane in response to the ramp curvature. Third is the initiation of steering control in order to track the ramp curve. The critical element in this process is the detection and response to the ramp curvature. The exit ramp curve marks the beginning of the deceleration lane at the exit wedge. As the gap search phase was the key element for defining the entering process, detection of the exit ramp curvature appears to be the critical task in defining the exiting maneuver.

THE CRITICAL RAMP JUNCTION

The essential characteristic of a diverging geometry is an opening, a diverging of the roadway. The drivers' task is to locate this opening in sufficient time to leave the freeway mainline without decelerating, but with sufficient time to analyze the ramp so as to track the approaching curve. Hypothetically, then, it is the wedge curvature that is the critical design element in the driver's decision process. The task becomes one of defining the minimum deceleration lane length needed by the driver in order to adjust speed in advance of the controlling curve.

For the ideal situation, it is necessary to determine the distance upstream from the wedge at which the driver begins the exiting maneuver. Hypothetically, the point of initiation of the exiting maneuver should occur when the angular velocity of the controlling curve exceeds the driver's threshold. The driver's perspective of the elements included in the exiting maneuver is displayed in Figure F-1. As the driver approaches, the roadway is diverging at a rate determined

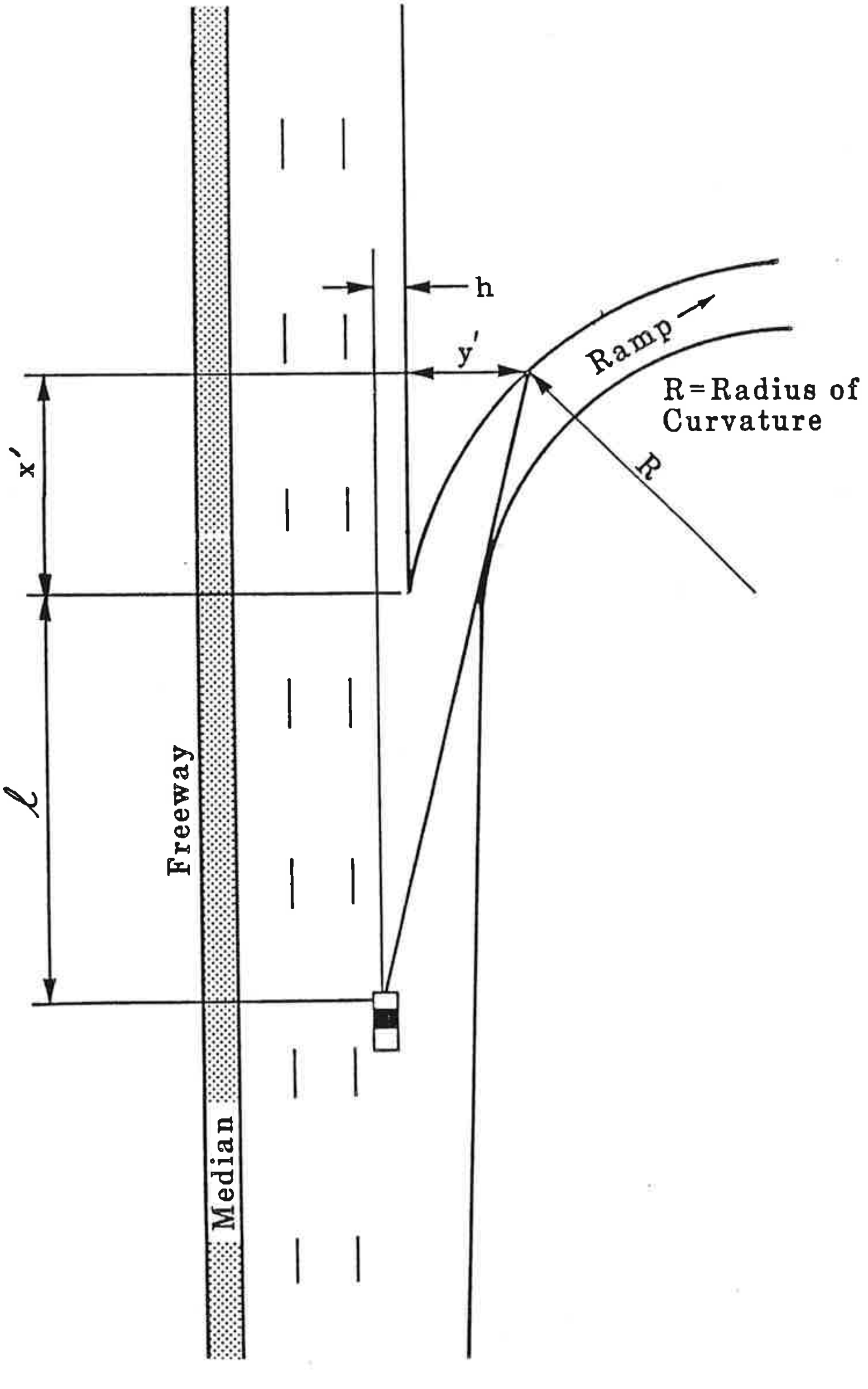


FIGURE F-1

DRIVER PERSPECTIVE—CURVILINEAR OFF-RAMP

by the radius of curvature, as in the case of a clover-leaf type interchange. It is possible to formulate the equation for the perceived angular velocity of any curve of known radius, either simple or compound. Assuming a travel speed of 80 ft/s, a radius of curvature having a supra-threshold angular velocity may be determined using the following equation:

$$\omega_t = \frac{V(h+y')}{(h+y')^2 + (x'+L)^2} \qquad y' = R - \sqrt{R^2 - (x')^2} \qquad \text{(F-1)}$$

Where,

ω_t = angular velocity, rads/s.

V = speed, f/s.

h = distance from driver to freeway lane edge, ft.

R = radius of curvature, ft.

x' = longitudinal distance to point on curve, ft.

L = distance from driver's eye to onset of curve, ft.

y' = distance from freeway edge to ramp edge, ft.

In essence, this equation defines the dynamic characteristics of the driver's visual field. Although a driver may see the ramp curve, especially an ascending curve at a considerable distance ahead, the driver will not respond actively until there is a detectable component of angular velocity.

By scanning the visual field, approach drivers detect the presence of diverging ramp curvature. If the ramp curvature exhibits a detectable angular velocity, i.e., it appears to rotate, the driver has a direct cue and a criterion for beginning the deceleration lane diverge steering maneuver. Ideally, this visual scanning should be at a distance far enough away to provide the driver sufficient time to carry out the steering maneuver. At 80 f/s this distance would be around 250 feet. Upon completion of the steering maneuver the driver should be on the deceleration lane on a course leading into the controlling ramp curvature. The distance from the controlling curve at which the driver initiates the diverge steering maneuver is dependent on the magnitude of the radius of curvature. Shorter distances will occur for larger radii.

Once on the deceleration lane, the angular velocity of the ramp curve increases at an instantaneous rate determined by Equation F-1. The driver will use the deceleration lane length to decelerate so that the pursuit tracking task may be accomplished within the limits of kinesthetic as well as visual control. The length of the actual vehicle deceleration will depend upon the radius of curvature and the distance between the driver's point of completion of the diverge steering maneuver and the beginning of the curve.

It is important to note that this model suggests that the higher the speed at which the controlling ramp curve may be tracked by the driver, the less the deceleration lane length that the driver will use. This leads to a conclusion that, unlike an acceleration lane, there is no single, minimum length for the design of a deceleration lane. Rather, the minimum length of a deceleration lane is a function of ramp curvature.

In the previous discussion, it was assumed that the deceleration lane terminated in a ramp with some radius of curvature, as in the clover-leaf type interchange. For diamond-type interchanges, however, the exiting process is slightly different for the driver. The driver's perspective on a diamond-type interchange is shown in Figure F-2. The controlling curve in this case is simply the angle of divergence from the freeway. The angular velocity in this case may be defined as,

$$\omega_t = \frac{V(h+y')}{(h+y')^2 + (L+x')^2} \qquad y' = x' \tan \alpha \qquad \text{(F-2)}$$

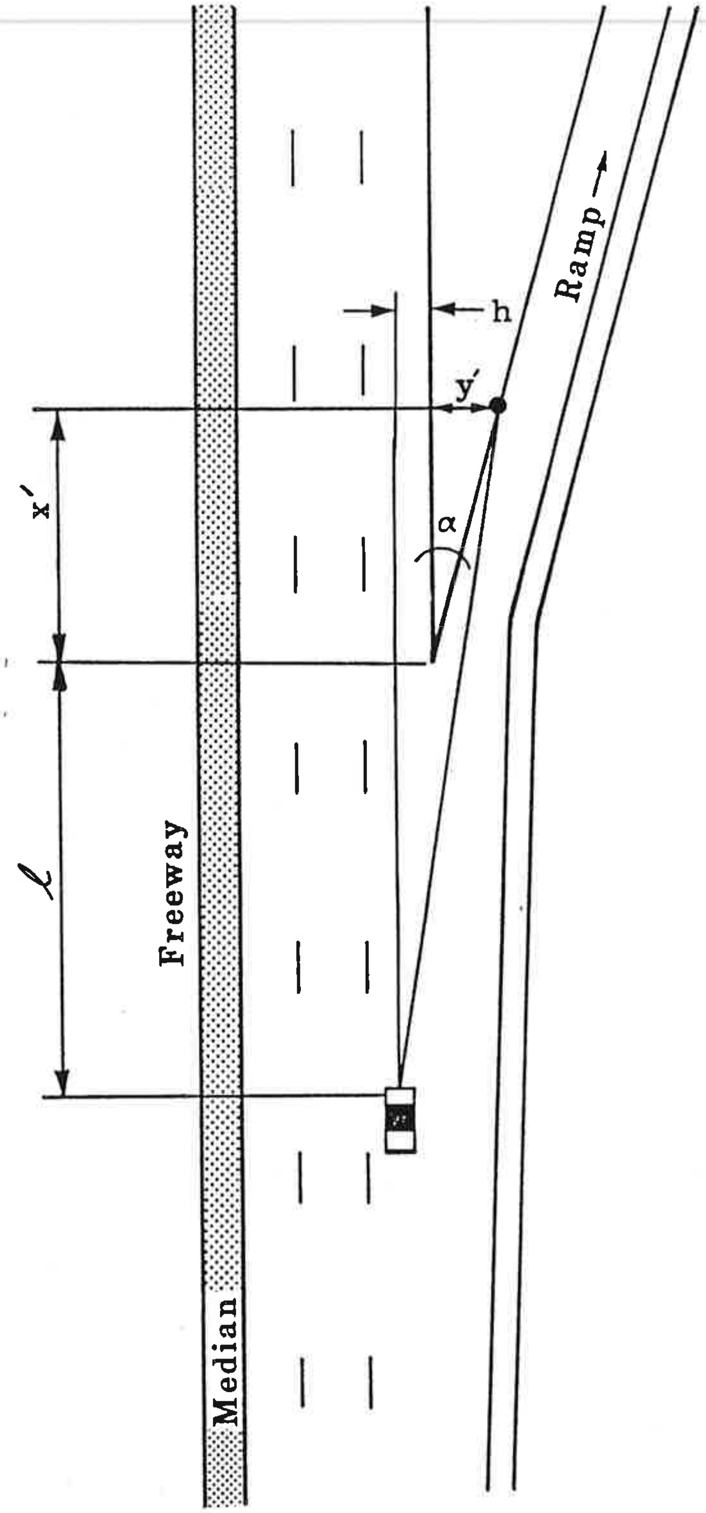


FIGURE F-2

DRIVER PERSPECTIVE—LINEAR OFF-RAMP

Where,

ω_t = angular velocity threshold, rads/s.

V = speed, f/s.

h = distance from driver to freeway lane edge, ft.

x' = longitudinal distance from exit wedge, ft.

α = angle of ramp divergence, rads.

L = distance to wedge from driver's eye, ft.

y' = distance from freeway edge to ramp edge, ft.

It should be noted that a difference between Equations F-1 and F-2 is that the former has a higher order term in the numerator. As far as the driver is concerned, in the curved ramp the perceived angular velocity increases faster with decreasing distance to the beginning of the curve than is the case for the simple angular divergence of the diamond off-ramp. The angular velocity of the ramp may be computed as a function of distance and the angle of diverge.

The distance from the ramp at which a driver will diverge from the freeway will, at a given mainline speed, directly increase with the angle of ramp divergence. We would hypothesize that this diverge steering maneuver would begin when the angular velocity of the ramp reaches threshold. Clearly the deceleration lane length should be sufficient to allow the driver to complete the steering maneuver onto the deceleration lane before requiring the driver to initiate steering to track the angle of ramp divergence. The steering maneuver from the freeway mainline onto the deceleration lane at 80 f/s would require 250 feet. If the design speed for the ramp is 66 f/s, and the comfortable deceleration rate for the driver is 4.8 to 9.7 f/s/s then the driver will require a minimum of 106 feet and a maximum of 212 feet of additional deceleration lane length. Ideally, the maximum length of a deceleration lane terminating in a simple diamond-type off-ramp is 460 feet.

The actual deceleration lane length used by drivers should depend on the degree of curvature for the clover-leaf type interchange and the angle of divergence for the diamond-type interchange. The basic analysis discussed for the two types of interchange designs is predicated on a flat or ascending off-ramp. In addition, it assumes that the length of the ramp is sufficient to allow the driver to carry out any deceleration required by the ramp terminus. In essence, the deceleration lane length is intimately related to the characteristics of the ramp to which it is connected. This is especially significant for a diamond-type interchange in which the terminus is usually an intersection with traffic control. In this case the driver is required to use the ramp to decelerate, to a stop in the worst case, at the junction. The length of the ramp determines the maximum deceleration required of the driver. For a driver approaching the junction, deceleration may be controlled by maintaining the angular velocity of the surrounding elements of the roadway at threshold. It can be shown that deceleration will be continuous, according to the equation below.

$$d = \sqrt{\frac{aV}{\omega_t}} \qquad \text{(F-3)}$$

Where,

d = distance to junction, ft.

ω_t = angular velocity threshold, rads/s.

a = foveal field width, ft.

V = speed, f/s.

Neglecting the vertical component of angular velocity of the intersecting roadway, the angular velocity of elements at the junction, e.g., pavement markings, which fall within a 2.5-degree foveal field (6 feet) will be at threshold at the distances shown in Table F-1 for varying vehicle speeds. If the driver begins to decelerate at these distances, the average deceleration required to reduce the initial vehicle speed to zero at the junction can be calculated. Maximum deceleration will not exceed 11 f/s/s for initial speeds less than 90 f/s.

This analysis assumes that the driver's view from the entry on the ramp to the terminal junction is unobstructed. For an ascending diamond off-ramp with a small angle of departure this condition clearly exists if the junction point is at the crest of the grade. It may or may not exist in the case of a descending ramp. If the driver's view of the junction is obstructed, this reference for deceleration will not be visible. In this case, it is reasonable to hypothesize that the driver will begin decelerating in response to that locus on the ramp which is the limit of the driver's action field. This may cause greater deceleration to occur on the deceleration lane than the analysis described above would predict. This suggests that the deceleration lane for a diamond-type interchange may become an extension of the ramp. Deceleration will occur on the deceleration lane if, and only if, the ramp length is short and/or the driver's field of view of the ramp junction is obstructed. There is, then, a possible trade-off between ramp design and deceleration lane length. The minimum deceleration lane length defined earlier may be increased to compensate for the ramp characteristics and the nature of the ramp terminus. The magnitude of this increase can be determined using the deceleration analysis above. With a single vehicle on the deceleration lane this would pose few problems. However, with high ramp volumes, where two or more vehicles follow one another on the deceleration

TABLE F-1

DECELERATION RESPONSE TO RAMP TERMINUS

Entry Speed (f/s)	Response Distance (ft)	Average Deceleration (f/s/s)
10	122	-0.41
20	173	-1.15
30	212	-2.12
40	245	-3.27
50	274	-4.56
60	300	-6.00
70	324	-7.56
80	346	-9.24
90	367	-11.02
100	387	-12.91
110	406	-14.89

Given: a = 6 ft
ω_t = 0.004 rads/s

lane, deceleration rates of 8 to 10 f/s/s could cause significant queueing instabilities.

In summary, the deceleration lane length is largely determined by the radius of curvature of the connecting ramp in the case of a clover-leaf type of interchange and the angle of divergence of the connecting ramp in the case of a diamond. It is the distance at which these determining elements generate a threshold angular velocity that, for a given mainline speed, define the beginning of the diverge maneuver from the freeway mainline onto the deceleration lane. The radius or divergence angle of the ramp also determines the length of deceleration lane required for the driver to decelerate sufficiently to effectively and comfortably steer through the curve. It follows that the deceleration lane length utilized by the driver will increase as the radius of the ramp curve decreases or the angle of divergence increases. In general, the angular velocity will reach threshold at greater distances for a curved ramp than for a simple diverging one. Consequently, we would predict that drivers will use more deceleration lane length in the clover-leaf type of interchange than for the diamond type.

APPENDIX G

COMPARISON BETWEEN AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE DESIGN VALUES

Several comparisons were made in Chapter 2 between the acceleration and deceleration lane lengths derived from the recommended NCHRP 3-35 models and the design values recommended in the AASHTO Green Book (1984). Direct comparison between the two sets of design values, however, was not readily accomplished due to several significant differences between models. These differences include:

- AASHTO acceleration and deceleration lengths (Tables X-4 and X-6) are based on operating speed below the design speed. The NCHRP 3-35 models assume vehicle operating speed equal to the design speed.
- AASHTO defines the end of the acceleration lane and beginning of the deceleration lane at the 12-foot taper width. The NCHRP 3-35 models uses the 6-foot point.
- The AASHTO acceleration model is based on an initial speed, V'_a (mph), on the entrance curve and a final speed reached, V_a (mph), on the highway. The NCHRP 3-35 entrance model includes an initial speed on the ramp, v'_o, an intermediate speed at the beginning GSA, v'_r, and a final speed reached, V'_f, on the highway.
- The AASHTO acceleration model assumes that ramp vehicles reach a speed 5 mph less than the freeway speed before merging. The NCHRP 3-35 entrance model utilizes an angular velocity threshold criterion which results in varying speed differentials at the beginning of the merge, depending upon other factors.
- The AASHTO acceleration lengths shown in Figure X-68 provide a minimum acceleration length of 690 feet, based on Figure X-68A, although this minimum length is not reflected in the design values provided in Table X-4. The NCHRP 3-35 entrance model does not specify a minimum design length.
- Table G-1 provides a more complete comparison between the AASHTO and NCHRP 3-33 models.

Two separate comparisons between AASHTO and NCHRP 3-35 design values were made. The first comparison was accomplished by estimating with interpolation and extrapolation, the design values provided by AASHTO for the ramp and freeway

TABLE G-1

CHARACTERISTICS OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE MODELS

Item	AASHTO	NCHRP 3-35
Acceleration Lanes		
Physical Definition	Begins at end of ramp controlling curve. Ends at last point where width of the lane is 12 feet. Tapered design: 50:1 to 70:1 taper; width of lane at physical merging end 16 feet. Parallel design: 600 feet min.; 300-foot taper	Begins at end of ramp controlling curve. Ends at the 6-foot width of the tapered section. Tapered design: 50:1 to 70:1 taper; width of lane at physical merging end 16 feet. Parallel design: No minimum length constraint 25:1 to 30:1 terminal taper.
Speed Definition	Running speed based on design speed. Speed reached at end of acceleration lane, V'_a, and initial ramp speed, V'_a, defined by designer.	Operating speed. Freeway operating speed, V'_f, ramp controlling speed, V'_o, and speed of ramp vehicle at begin GSA, V'_r, defined by designer.
Operation	5 mph speed difference between ramp and freeway vehicles at merge.	10 mph speed difference between ramp and freeway vehicles at merge.
Adjustment Factors	Grade; Volume: 1,200 feet minimum length when merge area volume reaches capacity.	Grade; Volume: ramp and freeway; Design vehicle: passenger car or truck on ramp and freeway.
Deceleration Lanes		
Physical Definition	Begins at initial 12-foot width of lane. Ends at controlling ramp curve. Taper Design: angle of divergence, $2^{o} - 5^{o}$. Parallel Design: 800 feet minimum desirable; 15:1 to 25:1 taper.	Begins at 6 -foot width of tapered section. Ends at controlling ramp curve. Taper Design: angle of divergence, $2^{o} - 8^{o}$. Parallel Design: No minimum length constraint. 15:1 to 25:1 taper.
Speed Definition	Running speed based on design speed. Average freeway running speed on freeway, V_a, and average running speed on exit curve, V'_a, defined by designer.	Operating speed. Freeway operating speed, V'_d, and ramp controlling speed, V'_c, defined by designer.
Operation	Speed reduction does not begin until vehicle has entered the deceleration lane.	Speed reduction does not begin until vehicle has entered the deceleration lane.
Adjustment Factors	Grade;	Grade; Angle of Divergence; Design Vehicle: Passenger car or truck.

operating speeds used by the NCHRP 3-35 model. The second comparison was simply the reverse of the first in which acceleration and deceleration lane lengths were generated using the NCHRP 3-35 models based on the ramp and freeway running speeds assumed by AASHTO. Additional adjustments were necessary to account for other model differences. A detailed explanation of each comparison is provided in the following sections.

EXTRAPOLATION OF AASHTO DESIGN VALUES

Comparable AASHTO design values for acceleration and deceleration lengths were estimated graphically. Figures G-1 and G-2 illustrate the methodology used to estimate the comparable AASHTO acceleration lane design values. Figure G-1 provides acceleration lane lengths based on Table X-4 of the AASHTO Green Book. The curves in Figure G-1 were extrapolated past 53 mph, the maximum speed provided in AASHTO. Based on the curves in Figure G-1, a family of curves representing freeway operating speeds of 50, 60, and 70 mph were developed and are provided in Figure G-2. Therefore, from Figure G-2, at a freeway speed of 70 mph and an initial ramp speed of 30 mph, the AASHTO model would provide an acceleration length of approximately 2,450 feet. This length, however, as defined by AASHTO, represents an acceleration lane length which ends at the 12-foot width of the taper and not the 6-foot point as defined by the NCHRP 3-35 entrance model. Therefore, an adjustment of either the AASHTO or NCHRP 3-35 values was necessary for comparative purposes. Based on Figure X-68A in AASHTO, 345 feet was added to the AASHTO acceleration lengths estimated from Figure G-2. The comparable AASHTO acceleration length, then, at a freeway speed of 70 mph and an initial ramp speed of 30 mph would be 2,795 feet (2,450 + 345 feet).

Based on this methodology AASHTO acceleration lengths were estimated for freeway speeds of 50, 60, and 70 mph, and initial ramp speeds of 0, 15, 30, 40, 50, and 60 mph. These lengths are provided in Table G-2. Note in Table G-2 that a minimum acceleration length is provided based on Figure X-68A in AASHTO. This minimum length includes 345 feet for the acceleration lane plus 345 feet to taper from 12 to 6 feet, or 690 feet.

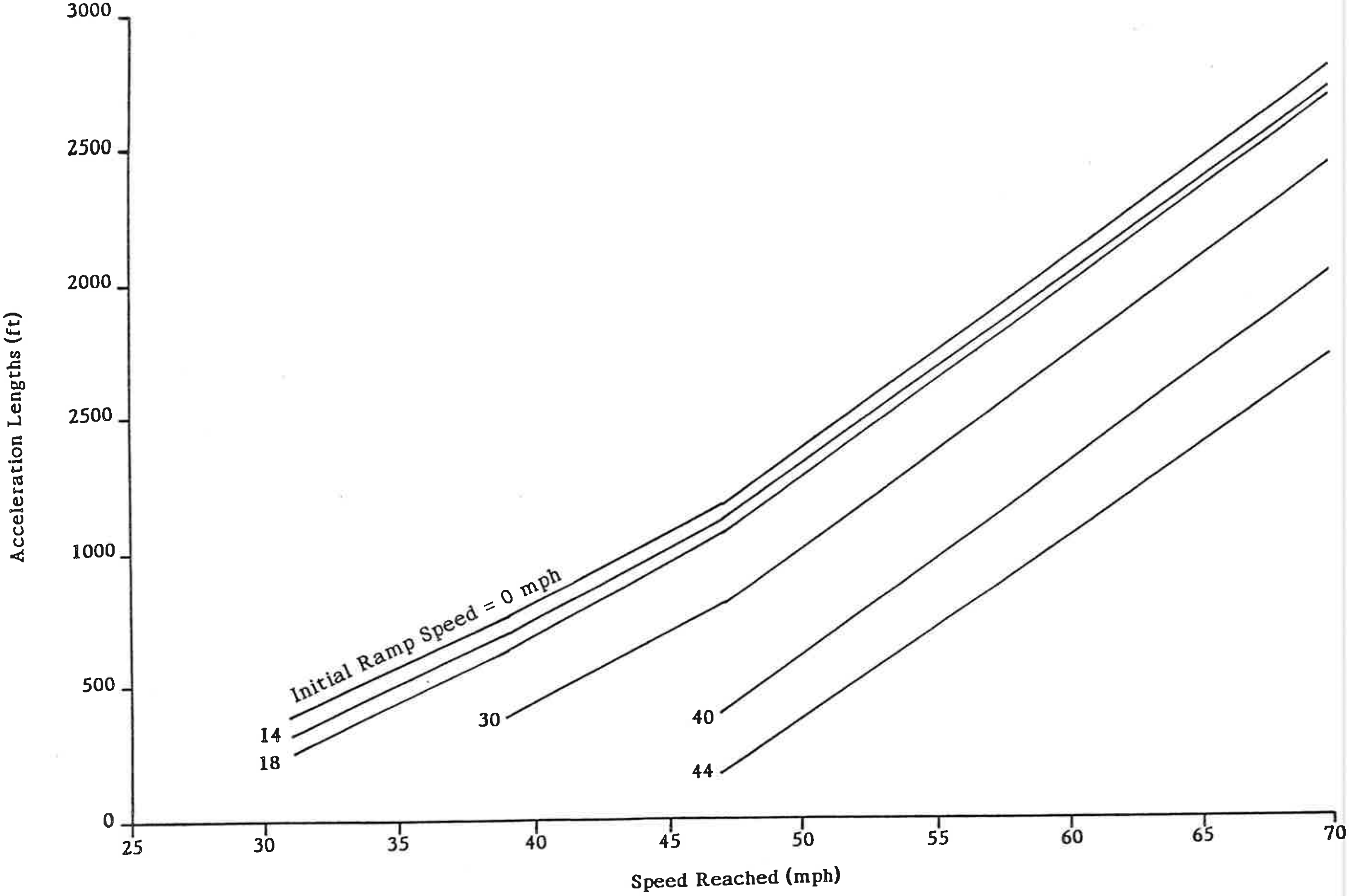


Figure G-1

PLOT OF AASHTO ACCELERATION LENGTHS

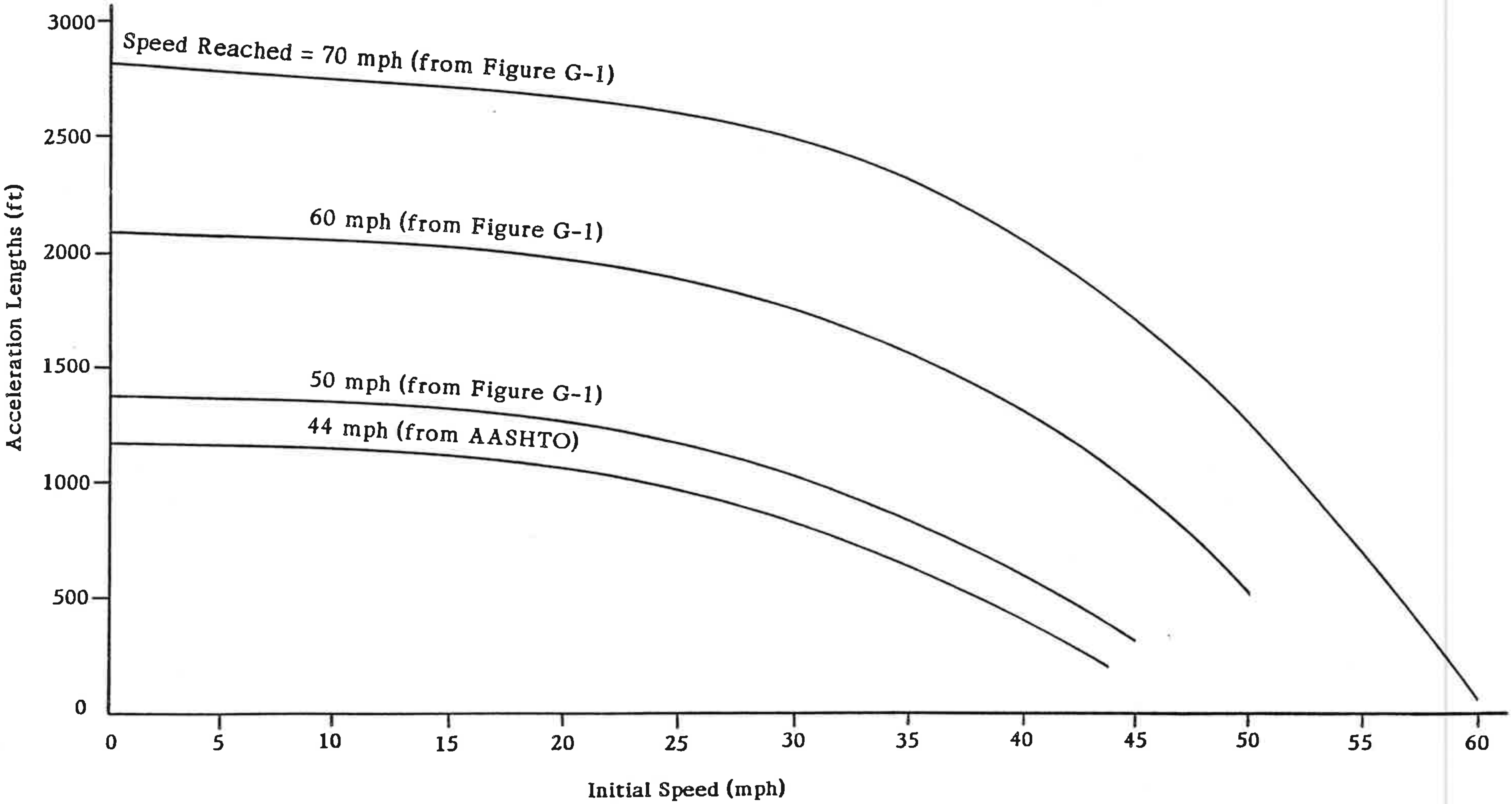


Figure G-2

EXTRAPOLATION OF AASHTO ACCELERATION LENGTHS

TABLE G-2

CURRENT AASHTO SPEED-CHANGE LANE LENGTHS
ENTRANCE RAMPS

Freeway Design Speed (mph)	Current AASHTO Length (ft) Ramp Design Speed (mph)					
	0	15	30	40	50	60
50	1,725	1,645	1,345	945	690*	--
60	2,445	2,345	2,070	1,670	820	690*
70	3,145	3,045	2,795	2,370	1,545	690*

* Minimum acceleration lane length as indicated in the AASHTO "Green Book" (1984), Figure X-68A.

Note: Values estimated from Figure G-2 plus 345 feet to account for additional length from 12-foot point to 6-foot point on the taper section.

Using the same graphical technique, the deceleration lengths provided by AASHTO at 50, 60, and 70 mph were estimated. Figures G-3 and G-4 graphically display the design values provided in Table X-6 of AASHTO and the estimated values. These lengths represent the deceleration length beginning at the 12-foot width of the taper, as defined by AASHTO. Additional length was required in order to provide deceleration lengths comparable with the design values generated by the NCHRP 3-35 model, which defines the 6-foot taper width as the beginning of the deceleration lane. Based on Figure X-69C in AASHTO, 125 feet was added to account for the distance from the 12-foot point to the 6-foot point. For example, with a 70 mph freeway speed and a 30 mph ramp speed, Figure G-4 provides a deceleration length of approximately 720 feet. Adding 125 feet results in a total deceleration lane length of 845 feet. Unlike the acceleration lengths, AASHTO does not provide a minimum deceleration length.

The comparison in Chapter 2, between AASHTO and NCHRP 3-35 design values, is based on the estimated AASHTO values provided in Tables G-2 and G-3. In the comparison between acceleration lengths, however, it is important to understand that the AASHTO model uses two design speeds (speed reached, V_a, and initial speed, V'_a), while the NCHRP 3-35 model uses three design speeds (initial ramp speed, v'_o, speed at begin GSA, v'_r, and freeway speed, V'_f). It is for this reason that the AASHTO values used for comparison in Table 9 and Figures 33 and 34 remain constant for all values of v'_r, defined as the speed at the beginning of the GSA zone.

ALTERNATIVE AASHTO/NCHRP 3-35 MODEL COMPARISON

An alternative method of comparing the AASHTO and NCHRP 3-35 acceleration and deceleration lane lengths was also performed. This comparison involved application of the NCHRP 3-35 models based on the average freeway and ramp running speeds currently used by AASHTO for speed-change lane length determination. The design values which resulted from the NCHRP 3-35 model, in addition to the AASHTO values are provided in Tables G-4 and G-5. Similarly, as in the previous comparison, the AASHTO design values were adjusted for the additional length between the 12-foot and 6-foot taper widths. Therefore, the design values

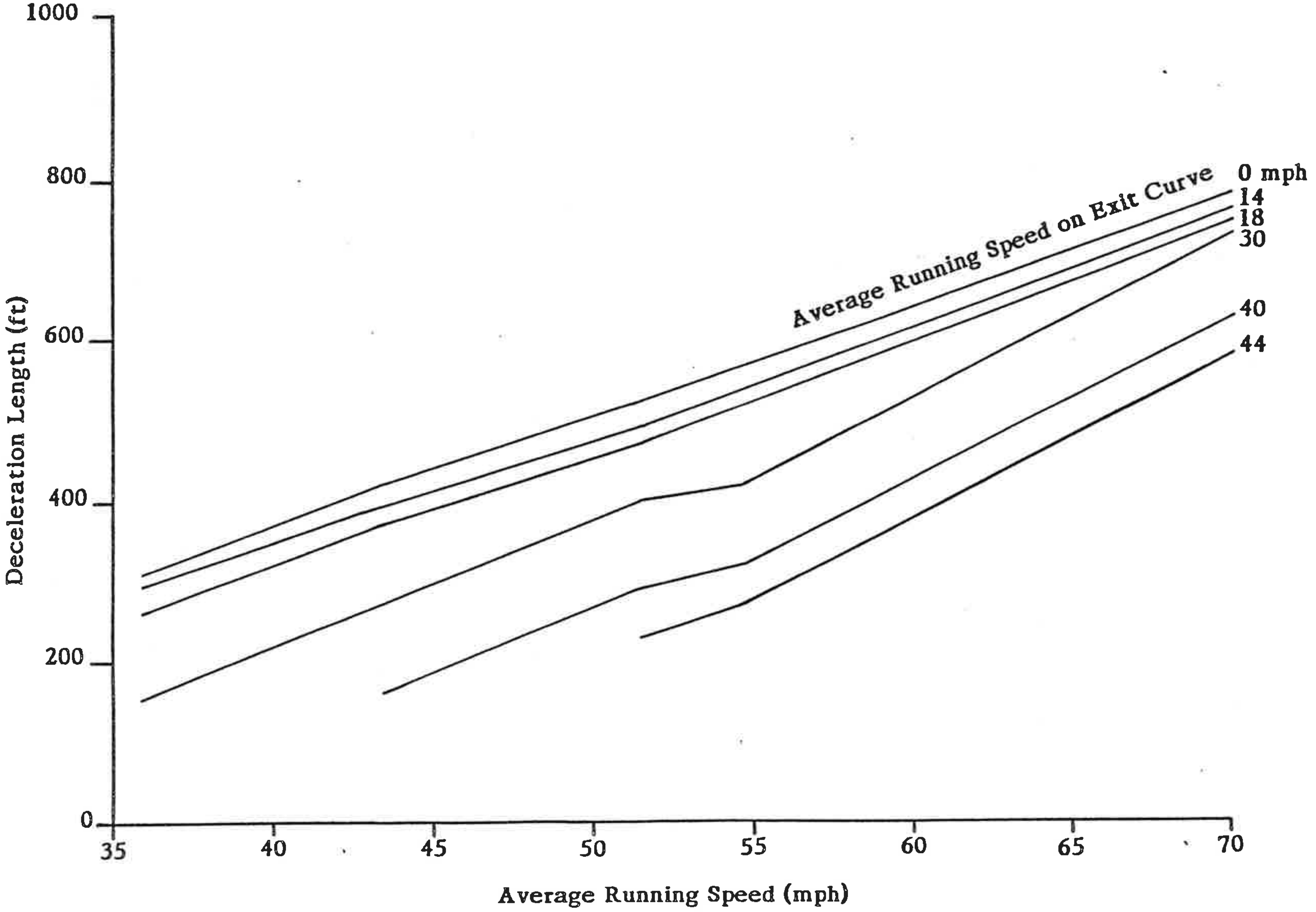


Figure G-3

PLOT OF AASHTO DECELERATION LENGTHS

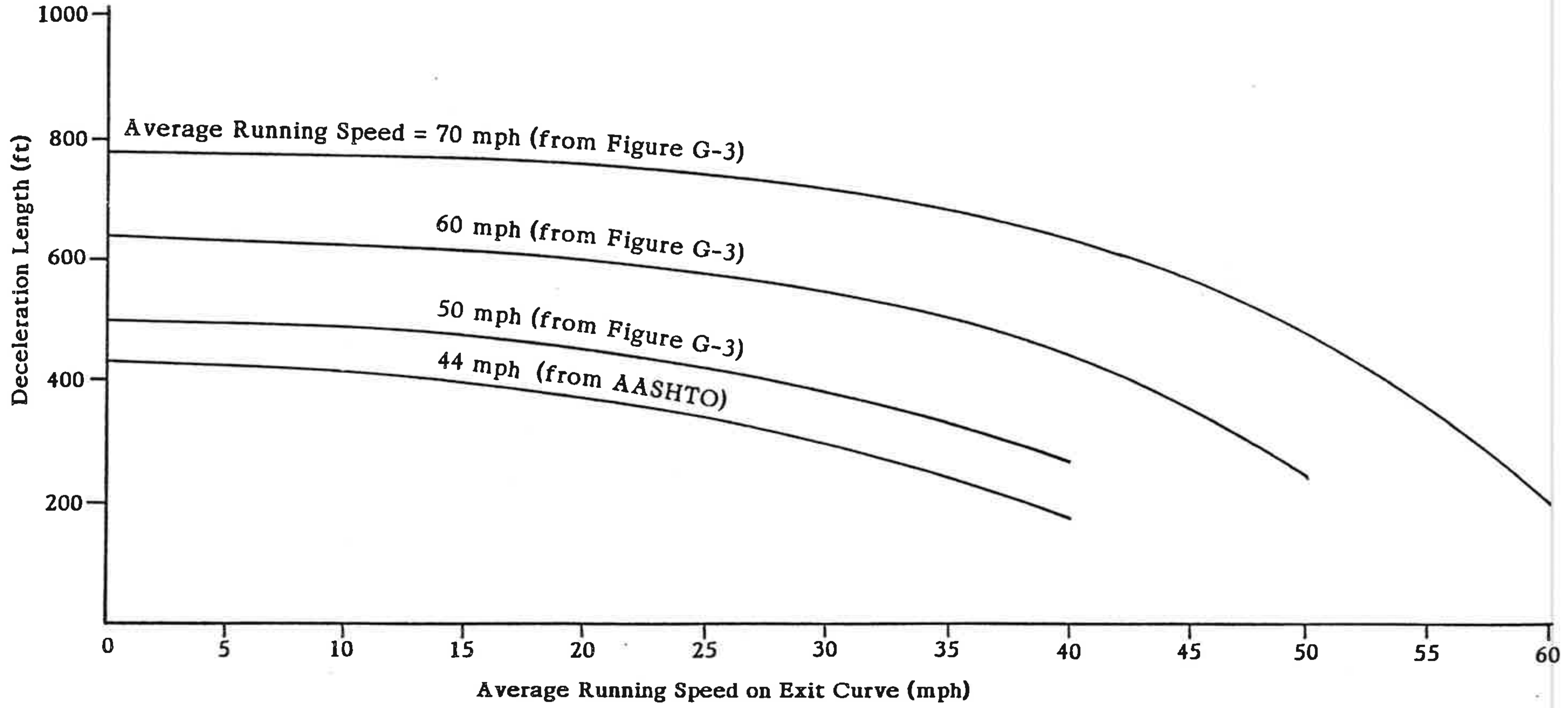


Figure G-4

EXTRAPOLATION OF AASHTO DECELERATION LENGTHS

TABLE G-3

CURRENT AASHTO SPEED-CHANGE LANE LENGTHS
EXIT RAMPS

Freeway Design Speed (mph)	Current AASHTO Length (ft) Ramp Design Speed (mph)								
	0	15	20	25	30	35	40	45	50
50	625	600	575	545	505	455	395	325	--
60	765	735	725	695	675	625	565	505	425
70	915	905	895	875	845	805	745	705	605

Note: Values estimated using Figure G-4 plus 125 feet to account for additional length from 12-foot point to 6-foot point on taper section.

Table G-4

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS ENTRANCE RAMPS

Design Determinants

Freeway Speed, $V_a(V_f)$:	53 mph
Freeway Volume:	1,500 vphpl
Ramp Volume:	500 vph
Design Vehicle:	Passenger Car
Grade Condition:	Level

Initial Ramp Speed $V'_a(v'_o)$ (mph)	Speed-Change Lane Length (ft) AASHTO	NCHRP 3-35 v'_r (mph) 0	15	30	40
0	1,935	2,750	2,305	1,375	1,320
14	1,885	--	2,270	1,340	1,285
22	1,755	--	--	1,300	1,275
30	1,575	--	--	1,210	1,225
40	1,175	--	--	--	1,035

Note: AASHTO values based on Table X-4 plus 345 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-4 (Continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

ENTRANCE RAMPS

Design Determinants

Freeway Speed, $V_a(V_f)$:	53 mph
Freeway Volume:	1,500 vphpl
Ramp Volume:	200 vph
Design Vehicle:	Passenger Car
Grade Condition:	Level

Initial Ramp Speed $V'_a(v'_o)$ (mph)	Speed-Change Lane Length (ft)				
		NCHRP 3-35 v'_r (mph)			
	AASHTO	0	15	30	40
0	1,935	1,890	1,625	1,255	1,235
14	1,885	--	1,590	1,220	1,200
22	1,755	--	--	1,185	1,185
30	1,575	--	--	1,095	1,135
40	1,175	--	--	--	945

Note: AASHTO values based on Table X-4 plus 345 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-4 (Continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

ENTRANCE RAMPS

Design Determinants

Freeway Speed, $V_a(V_f)$:	53 mph
Freeway Volume:	1,500 vphpl
Ramp Volume:	200 vph
Design Vehicle:	Passenger Car
Grade Condition:	Upgrade (3 - 4%)

	Speed-Change Lane Length (ft)				
		NCHRP 3-35 v_r' (mph)			
Initial Ramp Speed $V'_a(v_o')$ (mph)	AASHTO	0	15	30	40
0	2,730	1,890	1,635	1,290	1,290
14	2,655	--	1,590	1,245	1,245
22	2,600	--	--	1,205	1,245
30	2,315	--	--	1,095	1,195
40	1,755	--	--	--	945

Note: AASHTO values based on Table X-4 plus 345 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-4 (Continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

ENTRANCE RAMPS

Design Determinants

Freeway Speed, $V_a(V_f)$:	53 mph
Freeway Volume:	1,500 vphpl
Ramp Volume:	200 vph
Design Vehicle:	Passenger Car
Grade Condition:	Downgrade (3 - 4%)

Initial Ramp Speed $V'_a(v'_o)$ (mph)	Speed-Change Lane Length (ft)				
		NCHRP 3-35 v'_r (mph)			
	AASHTO	0	15	30	40
0	1,300	1,890	1,620	1,235	1,190
14	1,270	--	1,590	1,205	1,160
22	1,190	--	--	1,170	1,145
30	1,085	--	--	1,095	1,095
40	845	--	--	--	945

Note: AASHTO values based on Table X-4 plus 345 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-4 (Continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

ENTRANCE RAMPS

Design Determinants

Freeway Speed, $V_a(V_f)$:	$V_f = 53$ mph
Freeway Volume:	1,500 vphpl
Ramp Volume:	200 vph
Design Vehicle:	Truck
Grade Condition:	Level

Initial Ramp Speed $V'_a(v'_o)$ (mph)	Speed-Change Lane Length (ft)				
		NCHRP 3-35 v'_f (mph)			
	AASHTO	0	15	30	40
0	1,935	1,815	1,825	2,265	3,075
14	1,885	--	1,560	2,005	2,810
22	1,755	--	--	1,950	3,325
30	1,575	--	--	1,055	2,430
40	1,175	--	--	--	925

Note: AASHTO values based on Table X-4 plus 345 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-5

COMPARISON OF AASHTO AND NCHRP 3-35

DECELERATION LANE LENGTHS FOR AASHTO RUNNING SPEEDS EXIT RAMPS

Deceleration Length, L (ft)

Average Running Speed on Exit Curve, V_a (mph)

Average Running Speed, V_a (mph)	0		14		18		22		26	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	615	650	585	650	575	650	545	650	515	650
55	555	680	625	680	615	680	575	680	565	680
58	700	710	675	710	655	710	635	710	595	710

Average Running Speed, V_a (mph)	30		36		40		44	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	495	650	425	630	385	520	325	395
55	515	680	465	680	415	670	365	550
58	575	710	515	710	475	710	425	650

NOTE: AASHTO values based on Table X-6 plus 85 feet to account for additional length from 12-foot point to 6-foot point of the taper section.

Table G-5

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

EXIT RAMPS

Design Determinants

Vehicle Type: Passenger Car
Grade: Level

Speed-Change Lane Length (ft)

Freeway Speed $V_a(V'_d)$ (mph)	Speed on Exit Curve, $V'_a(V'_c)$ (mph)											
	0		14		22		30		40		44	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	645	650	625	650	585	650	535	650	425	520	365	450
55	695	680	665	680	615	680	555	680	455	670	395	550
58	740	710	715	710	675	710	615	710	515	710	465	650

Note: AASHTO values based on Table X-6 plus 125 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-5
continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS FOR AASHTO RUNNING SPEEDS

EXIT RAMPS

Design Determinants

Vehicle Type: Passenger Car
Grade: Upgrade (3 - 4%)

Speed-Change Lane Length (ft)

Freeway Speed $V_a(V'_d)$ (mph)	Speed on Exit Curve, $V'_a(V'_c)$ (mph)											
	0		14		22		30		40		44	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	600	625	575	625	540	600	495	525	395	450	340	450
55	640	660	610	660	565	660	510	610	425	470	380	470
58	680	685	655	685	620	685	565	685	475	550	430	495

Note: AASHTO values based on Table X-6 plus 125 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-5
(continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS

FOR AASHTO RUNNING SPEEDS

EXIT RAMPS

Design Determinants

Vehicle Type: Passenger Car
Grade: Downgrade (3 - 4%)

Speed-Change Lane Length (ft)

Speed on Exit Curve, $V'_a(V'_c)$ (mph)

Freeway Speed $V_a(V'_d)$ (mph)	0		14		22		30		40		44	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	760	660	725	660	680	660	620	660	485	660	415	540
55	810	690	775	690	715	690	640	690	520	690	460	690
58	865	720	835	720	785	720	715	720	595	720	535	720

Note: AASHTO values based on Table X-6 plus 125 feet to account for additional length from 12-foot point to 6-foot point of taper.

Table G-5
(continued)

COMPARISON OF AASHTO AND NCHRP 3-35 SPEED-CHANGE LANE LENGTHS

FOR AASHTO RUNNING SPEEDS

EXIT RAMPS

Design Determinants

Vehicle Type: Truck
Grade: Level

Speed-Change Lane Length (ft)

Freeway Speed $V_a(V'_d)$ (mph)	Speed on Exit Curve, $V'_a(V'_c)$ (mph)											
	0		14		22		30		40		44	
	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35	AASHTO	3-35
52	655	665	625	665	585	665	535	665	425	665	365	665
55	695	695	665	695	615	695	555	695	455	695	395	695
58	740	725	715	725	675	725	615	725	515	725	465	725

Note: AASHTO values based on Table X-6 plus 125 feet to account for additional length from 12-foot point to 6-foot point of taper.

are considered to be comparable. The default values provided in Tables 3 and 13 in the main body of this document were used in the NCHRP 3-35 model in order to generate the design values in Tables G-4 and G-5.

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NCHRP 3-35
SPEED-CHANGE LANES
USER DESIGN GUIDELINES

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

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and
THE TRAFFIC INSTITUTE, NORTHWESTERN UNIVERSITY

December 1989

This document provides guidelines for the design of speed-change lanes (acceleration and deceleration) based on the research performed for NCHRP Project 3-35. It contains brief summaries of the driver processes which occur while entering or exiting a freeway and brief explanations of the entry and exit models developed as part of the research project. This is considered a stand alone document, however, designers requiring additional explanation or information are directed to the Final Report document for NCHRP 3-35 "Speed-Change Lanes," dated December, 1989. The Final Report contains a detailed explanation of the entry and exit processes and the associated models.

DISCLAIMER

This copy is a final corrected version as submitted by the research agency. A decision concerning acceptance by the Transportation Research Board and publication in the regular NCHRP series will not be made until a complete technical review has been made and discussed with the reseachers. The opinions and conclusions expressed or implied in the report are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Research Council, the individual states participating in the National Cooperative Research Program, or the American Association of State Highway and Transportation Officials.

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DESIGN PROCEDURES FOR ACCELERATION LANES

Dynamics of the Entry Process

The process of changing from one facility to another via a ramp involves a series of decisions and control tasks which may tax the ability of the driver to process information and respond appropriately. It is the job of the designer to understand the phenomena which are present in the dynamics of this process and to design ramps so as to facilitate merging.

The movement between highways, along a ramp, involves successive navigational decisions, pursuit tracking, positional control (relative to other vehicles and roadway elements), and gap search and acceptance operations. In some instances, the driver may be doing more than one of these tasks in a time-sharing mode. Each step involves the driver's capacity to process information from roadway and traffic, and to translate that information into speed and steering control responses.

As the vehicle enters a ramp and reaches a speed appropriate for the ramp curvature and superelevation, the driver transitions to a pursuit tracking mode, in which the speed is adjusted to curvature on the basis of both visual and kinesthetic cues. As the acceleration lane is approached, there usually is a transition to a flat curvature, or tangent section, to allow the vehicle to accelerate to near freeway speed. During the acceleration process, the driver also initiates a search for an acceptable lag, or headway, in Lane 1 of the freeway, into which the vehicle must be steered.

The Entry Process

The entry process is considered to begin when the driver is able to initiate final steering control actions to transition to the flatter geometry along which acceleration may be accomplished. The driver must respond to changing curvature and direct the vehicle to a straighter path. The vehicle is then accelerated to a speed approaching the anticipated freeway speed. As the driver approaches the merging end, the traffic in Lane 1 of the freeway becomes visible at an angle and speed differential that allows the driver to begin considering the headway situation and the vehicle's relative position to these headways.

Design Condition

An acceleration lane should, as a minimum requirement, have sufficient length to enable the driver to make the necessary change, between the speed of operation on the turning roadway and the speed on the highway, in a safe and comfortable manner. Moreover, there should be additional length sufficient to permit adjustments in speed, primarily of the entering vehicles, so that the entering vehicle can be positioned opposite a lag, or headway, in the through traffic stream, and maneuver into it before reaching the end of the acceleration lane. During this process, the varying control requirements placed on the driver should not be overlapped, and driver expectancy should not be violated. Furthermore, the entry to the through traffic stream should be accomplished with minimum disruption to through traffic flow.

The design objectives noted above must be met for most drivers. This means that the majority of drivers will be able to complete the entry maneuver in a shorter length and/or easier manner than is designed for. Furthermore, the design case should be one which has the greatest length requirements, even though a great majority of the entering vehicles may require a shorter distance.

A Model of Acceleration Lanes

The length along which the entry process occurs is divided into zones, as described below.

L_{SC} - The steering control zone includes the distance required to steer and position the vehicle as it transitions from the ramp controlling curvature to the flatter geometry of the ramp entrance terminal area.

L_{IA} - The initial acceleration zone is that length along which the driver accelerates to reduce the speed differential between the ramp vehicle and the vehicles expected to be in Lane 1 of the freeway. This is done to reach a speed expected to be acceptable for completing the merge. The speed attained is constrained by the ramp geometry across this zone and the acceleration rate used by the driver of the ramp vehicle.

L_{AP} - The adjust position zone is the length needed for the ramp vehicle to reject the initial lag and align adjacent to the freeway Lane 1 vehicle which has formed the initial rejected lag. The zone begins when the ramp vehicle arrives at the point where the gap search and acceptance process may begin, dictated by the ramp curvature and visibility of Lane 1 of the freeway.

L_{EN} - The final element of the acceleration lane is the minimum length required to complete the freeway entry, L_{EN}. This length includes the distance required to search for and accept a headway. This distance is determined by the distribution of headways in Lane 1 of the freeway, the gap acceptance characteristics of the driver of the ramp vehicle, and the volume on the ramp. Also included in the length, L_{EN}, is a visual clear distance which buffers the ramp driver from the terminus of the acceleration lane so as to avoid potential problems due to timesharing which could occur.

The process outlined above has been translated into a mathematical form. The length of each of the zones may be derived based upon assumptions regarding the values of a set of parameters. The models are presented in Appendix A. Figure 1 illustrates the zones which comprise the acceleration lane length.

Design Determinants

The model for determination of acceleration lane length at an entrance ramp allows for the designer to specify the following design determinants:

1. design vehicle;
2. freeway and ramp running speed;
3. freeway and ramp volume; and
4. grade.

The type of vehicle present in both Lane 1 of the freeway and on the ramp can affect the length required for the acceleration lane. Two design vehicles have been defined - a truck and a passenger car. The characteristics assumed for these vehicles are summarized in Appendix B.

The running speed established along the ramp, or in Lane 1 of the freeway, will be a function of the geometrics, acceleration and deceleration rates used, and the relationship assumed between design speed and running speed. The design speed for a particular section may be identified in the design policy. The acceleration rates are related to the design vehicle, as described in Appendix B. The relationship

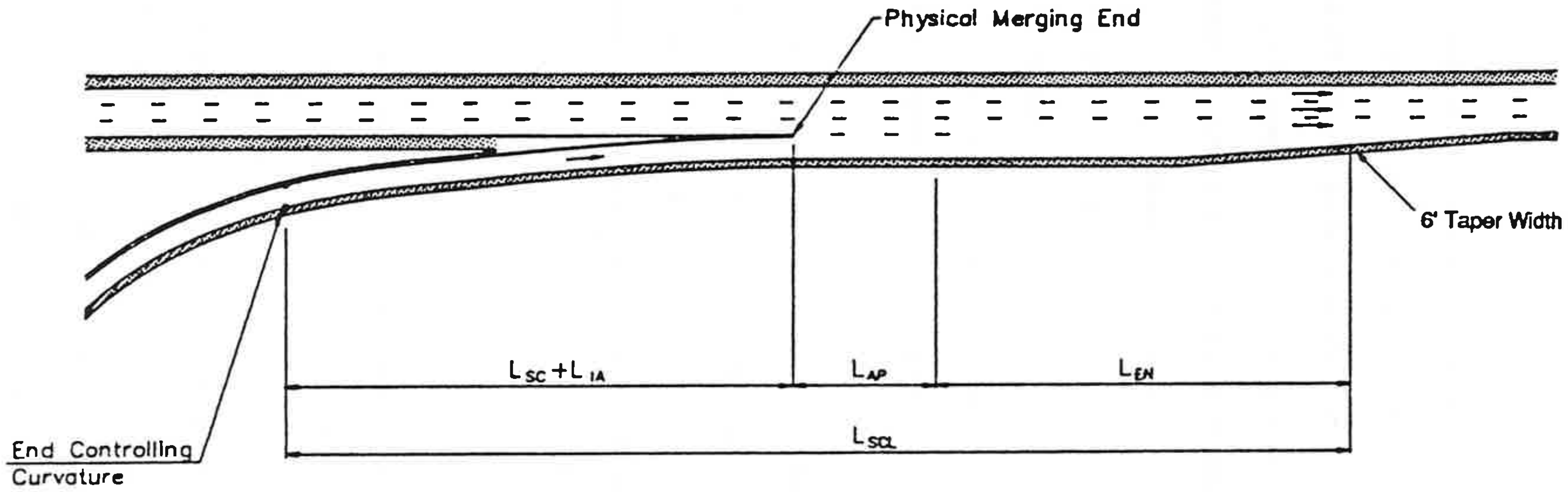

FIGURE 1

DEFINITION OF ACCELERATION LANE COMPONENTS between design speed and running speed is based on low volume conditions for design purposes. As has been done for the determination of stopping distance values, it is recommended that design speed be used in place of running speed. There may be special cases, such as extended up-grades with significant steepness along which the speed of Lane 1 traffic is continuously affected by the presence of large trucks, where running speed, instead of a design speed, may be utilized.

The selection of design volumes for the ramp and freeway would preferably occur at a policy level and be applicable to a range of projects (such as rural areas, or suburban and urban areas). It is also possible that volumes may be specified for a given project. Some guidelines on the selection of design volumes are provided below.

The final design element with which the designer may work is the grade, or profile condition. The effect of grade is primarily reflected through the associated acceleration rates used. These differ for each design vehicle, as shown in Appendix B. Underlying assumptions have been made regarding driver characteristics and are summarized in Appendix B.

Design Guidelines

Acceleration Lane Length

The lengths of the various zones along the acceleration lane have been combined into three major elements as shown in Figure 1. Each element encompasses a unique part of the entry dynamics and each has associated with it appropriate placement criteria. The first element encompasses the steering control and initial acceleration zones ($L_{SC}+L_{IA}$). This length must be provided prior to the beginning of the gap search and acceptance process. Tables 1 and 2 provide values for the lengths required under varying conditions of freeway speed (V'_f), controlling

TABLE 1

ACCELERATION LANE DESIGN VALUES: $L_{SC} + L_{IA}$, (ft)

Passenger Car on Ramp

Near Level Grade

	V'_f = 70 mph							V'_f = 60 mph							V'_f = 50 mph					
	v'_o (mph)							v'_o (mph)							v'_o (mph)					
v'_r (mph)	0	15	30	40	50	60	v'_r (mph)	0	15	30	40	50	60	v'_r (mph)	0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	50	25	-	-	-	-	15	50	25	-	-	-	-	15	50	25	-	-	-	-
30	175	185	50	-	-	-	30	175	175	50	-	-	-	30	175	175	50	-	-	-
40	300	325	250	75	-	-	40	300	325	250	75	-	-	40	300	325	250	75	-	-
50	450	525	475	400	75	-	50	450	525	475	400	75	-	50	450	525	475	400	75	-
60	650	750	775	650	675	100	60	650	750	775	800	675	100	60	-	-	-	-	-	-

Upgrade

	0	15	30	40	50	60		0	15	30	40	50	60		0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	50	25	-	-	-	-	15	50	25	-	-	-	-	15	50	25	-	-	-	-
30	200	225	50	-	-	-	30	200	225	50	-	-	-	30	200	225	50	-	-	-
40	350	400	300	75	-	-	40	350	400	300	75	-	-	40	350	400	300	75	-	-
50	550	650	625	550	75	-	50	550	650	625	550	75	-	50	550	650	625	550	75	-
60	775	950	1025	775	1275	100	60	775	950	1025	1150	1275	100	60	-	-	-	-	-	-

Downgrade

	0	15	30	40	50	60		0	15	30	40	50	60		0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	50	25	-	-	-	-	15	50	25	-	-	-	-	15	50	25	-	-	-	-
30	150	150	50	-	-	-	30	150	150	50	-	-	-	30	150	150	50	-	-	-
40	250	275	200	75	-	-	40	250	275	200	75	-	-	40	250	275	200	75	-	-
50	400	450	400	325	75	-	50	400	450	400	325	75	-	50	400	450	400	325	75	-
60	575	650	650	575	475	100	60	575	650	650	600	475	100	60	-	-	-	-	-	-

TABLE 2

ACCELERATION LANE DESIGN VALUES: $L_{SC} + L_{IA}$, (ft)

Truck on Ramp

Near Level Grade

	V'_f = 70 mph							V'_f = 60 mph							V'_f = 50 mph					
	v'_o (mph)							v'_o (mph)							v'_o (mph)					
v'_r (mph)	0	15	30	40	50	60	v'_r (mph)	0	15	30	40	50	60	v'_r (mph)	0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	325	25	-	-	-	-	15	325	25	-	-	-	-	15	325	25	-	-	-	-
30	1225	1475	50	-	-	-	30	1225	1475	50	-	-	-	30	1225	1475	50	-	-	-
40	*	*	1575	75	-	-	40	2175	*	1575	75	-	-	40	2175	*	1575	75	-	-
50	*	*	*	*	75	-	50	*	*	*	*	75	-	50	*	*	*	*	75	-
60	*	*	*	*	*	100	60	*	*	*	*	*	100	60	-	-	-	-	-	-

Upgrade

	0	15	30	40	50	60		0	15	30	40	50	60		0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	500	25	-	-	-	-	15	500	25	-	-	-	-	15	500	25	-	-	-	-
30	1950	1850	50	-	-	-	30	1950	1850	50	-	-	-	30	1950	1850	50	-	-	-
40	*	*	*	-	-	-	40	*	*	*	-	-	-	40	*	*	*	-	-	-
50	*	*	*	-	-	-	50	*	*	*	-	-	-	50	*	*	*	-	-	-
60	*	*	*	*	-	-	60	*	*	*	-	-	-	60	-	-	-	-	-	-

Downgrade

	0	15	30	40	50	60		0	15	30	40	50	60		0	15	30	40	50	60
0	0	-	-	-	-	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-
15	75	25	-	-	-	-	15	75	25	-	-	-	-	15	75	25	-	-	-	-
30	300	275	50	-	-	-	30	300	275	50	-	-	-	30	300	275	50	-	-	-
40	500	525	425	75	-	-	40	500	550	425	75	-	-	40	500	525	425	75	-	-
50	775	850	925	1050	75	-	50	775	850	925	1050	75	-	50	775	850	925	1050	75	-
60	1125	1250	1500	1125	1575	100	60	1125	1250	1500	2225	1575	100	60	-	-	-	-	-	-

---

*Length greater than 2,500 feet; auxiliary lane should be considered.

ramp speed (v'_o), speed desired at the beginning of the gap search and acceptance zone (v'_r), grade condition on the ramp, and design vehicle on the ramp. Each table represents a different design vehicle on the entrance ramp.

The length required for the adjust position zone (L_{AP}) is given in Table 3 for varying conditions of freeway speed (V'_f), speed desired at the beginning of the gap search and acceptance process (v'_r), grade on the ramp and design vehicle on the ramp. This length must be provided immediately following the initial acceleration zone and placed no further upstream of the merging end than the beginning of the gap search and acceptance zone.

The entry length (L_{EN}) requirement is shown in Tables 4 and 5 for varying conditions of freeway speed (V'_f), initial ramp speed (v'_o), desired ramp speed at the beginning of the gap search and acceptance process (v'_r), grade on the ramp, volume condition, and design vehicles on the ramp and freeway. The level of grade corresponds to the following:

Upgrade	> +2%
Near Level	+2% to -2%
Downgrade	<-2%

Two volume conditions have been selected to represent the variation between urban/suburban and rural locations. These are:

	Freeway Lane 1	Ramp
Urban/Suburban	1,500 pcph	500 pcph
Rural	1,200 pcph	250 pcph

Note that the total urban/suburban volume represents level of service (LOS) E, while the total rural volume represents LOS C.

TABLE 3

ACCELERATION LANE DESIGN VALUES: L_{AP} , (ft)

v'_r mph	Passenger Car on Ramp Upgrade	Passenger Car on Ramp Near Level	Passenger Car on Ramp Downgrade	Truck on Ramp Upgrade	Truck on Ramp Near Level	Truck on Ramp Downgrade
	V'_f = 70 mph					
0	25	25	25	25	25	25
15	50	50	50	75	75	100
30	100	100	100	200	200	200
40	175	175	175	325	325	325
50	275	275	275	600	525	525
60	500	500	500	1,450	775	775
	V'_f = 60 mph					
0	25	25	25	25	25	25
15	50	50	50	75	100	100
30	125	125	125	225	250	250
40	225	225	225	450	450	450
50	425	425	425	1,100	750	750
60	--	--	--	--	--	--
	V'_f = 50 mph					
0	25	25	25	25	25	25
15	50	50	50	100	100	125
30	150	150	150	325	325	375
40	375	375	375	800	800	800
50	--	--	--	--	--	--
60	--	--	--	--	--	--

TABLE 4
ACCELERATION LANE DESIGN VALUES: L_{EN} , (ft)
Passenger Car in Lane 1 of Freeway

Near Level Grade

	Passenger Car on Ramp							Truck on Ramp					
	Rural			Urban/Suburban				Rural			Urban/Suburban		
	V'_f (mph)			V'_f (mph)				V'_f (mph)			V'_f (mph)		
v'_r (mph)	70	60	50	70	60	50	v'_r (mph)	70	60	50	70	60	50
0	1375	1425	1375	*	*	*	0	1400	1450	1450	*	*	*
15	1375	1325	1225	*	*	2275	15	1400	1350	1275	*	*	*
30	1275	1175	925	2325	2050	1175	30	1325	1225	975	*	2325	1300
40	1175	950	800	2050	1200	1000	40	1250	1000	875	2300	1300	1100
50	975	875	-	1225	1075	-	50	1050	975	-	1400	1250	-
60	925	-	-	1150	-	-	60	1025	-	-	1350	-	-

Upgrade

	70	60	50	70	60	50		70	60	50	70	60	50
0	1350	1375	1375	*	*	*	0	1400	1425	1425	*	*	*
15	1325	1275	1225	*	*	*	15	1400	1350	1275	*	*	*
30	1225	1150	925	2325	2050	1175	30	1325	1225	975	*	2325	1300
40	1150	950	800	2050	1200	1000	40	1225	975	875	2250	1300	1100
50	950	850	-	1200	1075	-	50	1000	875	-	1300	1100	-
60	900	-	-	1125	-	-	60	900	-	-	1100	-	-

Downgrade

	70	60	50	70	60	50		70	60	50	70	60	50
0	1425	1425	1375	*	*	*	0	1600	1600	1525	*	*	*
15	1400	1325	1225	*	*	2275	15	1550	1450	1300	*	*	2475
30	1300	1175	925	2325	2050	1175	30	1375	1275	950	*	2300	1250
40	1200	950	800	2050	1200	1000	40	1275	1025	875	2350	1325	1125
50	975	875	-	1250	1075	-	50	1075	975	-	1400	1275	-
60	925	-	-	1150	-	-	60	1050	-	-	1375	-	-

---

*Length greater than 2,500 feet; auxiliary lane should be considered.

TABLE 5

ACCELERATION LANE DESIGN VALUES: L_{EN} , (ft)

Truck in Lane 1 of Freeway

Near Level Grade

	Passenger Car on Ramp							Truck on Ramp					
	Rural			Urban/Suburban				Rural			Urban/Suburban		
	V'_f (mph)			V'_f (mph)				V'_f (mph)			V'_f (mph)		
v'_r (mph)	70	60	50	70	60	50	v'_r (mph)	70	60	50	70	60	50
0	1800	1850	1850	*	*	*	0	1875	1950	2000	*	*	*
15	1750	1700	1575	*	*	*	15	1825	1800	1700	*	*	*
30	1600	1475	1150	*	*	*	30	1675	1550	1225	*	*	1725
40	1475	1150	1100	*	1525	1300	40	1550	1225	1075	*	1675	1424
50	1175	1050	-	1550	1350	-	50	1275	1175	-	1750	1575	-
60	1100	-	-	1425	-	-	60	1250	-	-	1700	-	-

Upgrade

	70	60	50	70	60	50		70	60	50	70	60	50
0	1750	1825	1850	*	*	*	0	1850	1950	1475	*	*	*
15	1700	1675	1575	*	*	*	15	1825	1775	1700	*	*	*
30	1550	1475	1150	*	*	1550	30	1675	1550	1225	*	*	1725
40	1450	1150	1100	*	1525	1300	40	1525	1200	1075	*	1650	1425
50	1150	1050	-	1525	1350	-	50	1200	1050	-	1600	1350	-
60	1075	-	-	1400	-	-	60	1050	-	-	1325	-	-

Downgrade

	70	60	50	70	60	50		70	60	50	70	60	50
0	1825	1850	1850	*	*	*	0	2050	2050	2025	*	*	*
15	1775	1700	1575	*	*	*	15	1950	1850	1700	*	*	*
30	1600	1475	1150	*	*	1550	30	1725	1600	1200	*	*	1625
40	1475	1150	1100	*	*	1300	40	1575	1250	1100	*	1700	1425
50	1175	1050	-	1550	1350	-	50	1300	1200	-	1775	1600	-
60	1100	-	-	1425	-	-	60	1250	-	-	1700	-	-

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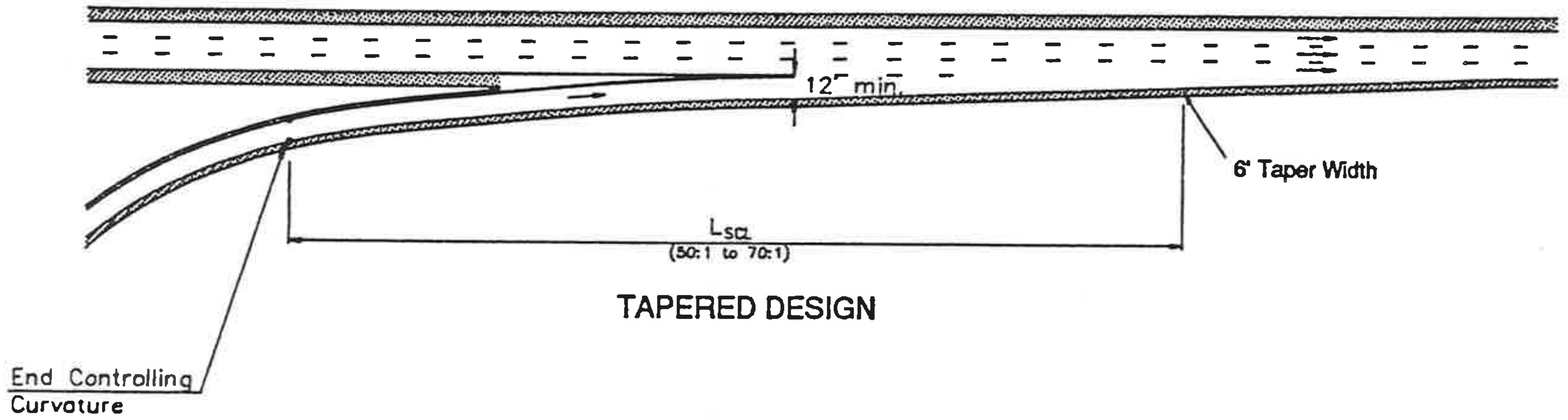
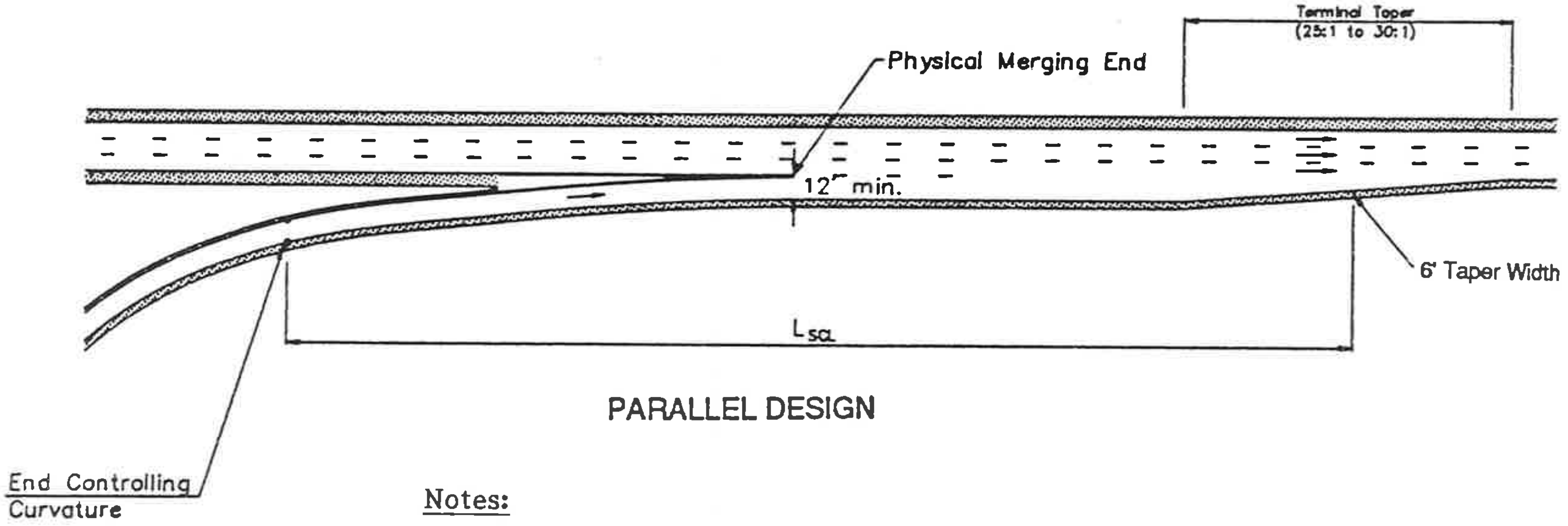
*Length greater than 2,500 feet; auxiliary lane should be considered.

NCHRP Note:

Page 13 was missing from the agency's original, bound report



TAPERED DESIGN



PARALLEL DESIGN

Notes:

1. Curvature of controlling curve should be successively flatter.

2. Curvature should have a radius of at least 1,000 feet within 200 feet upstream of the physical merging end.

FIGURE 2

TYPICAL ACCELERATION LANE CONFIGURATIONS

1. The speed of the ramp vehicle be within 20 mph of vehicles in Lane 1 of the freeway, and
2. The driver of the ramp vehicle be able to clearly view the trailing vehicles in Lane 1, and the reverse.

The latter requirement means that the elevations of the ramp and mainline be within 3 to 5 feet of each other before the gap search and acceptance process may begin. It also means that piers, walls, and other elements of the cross section must not interfere with the sight requirements between the ramp and Lane 1 of the freeway.

It is desirable to avoid vertical and horizontal curvature across the entrance area. Where this is not possible, the curvatures should be as flat as possible. A ramp which descends assists the ramp vehicle acceleration, but in keeping with design principles, the vertical transition to the freeway grade should be accomplished upstream of the merging end, where possible. Typically, if acceleration length (L_{SC} + L_{IA}) or gap search and acceptance length (L_{AP} + L_{EN}) requirements exceed 2,500 feet, an auxiliary lane should be considered.

Design Process

The designer may approach the determination of acceleration lane length in two basic ways:

1. Derive the required lengths for each element of the acceleration lane, given information regarding the design determinants (i.e., speeds, design vehicles, and grade condition); or
2. Test a given design for an acceleration lane by determining if a given layout meets the requirements for the known design determinants.

In either case, since the acceleration lane length, L_{SCL}, is divided into three elements, the designer is allowed a trade-off between the portion of the acceleration lane which is upstream, as compared to downstream, of the merging end. This is accomplished by allowing the designer to establish the speed at the beginning of the L_{AP} zone. The portion of the length of the acceleration lane to be placed on either side of the beginning of the L_{AP} is then determined by reading the appropriate values from the design tables. If, for a controlling ramp speed of 20 mph, a speed at begin L_{AP} is selected as 30 mph, there will be a longer length of the acceleration lane downstream from the begin L_{AP}, and a shorter length upstream, than if a speed at begin L_{AP} of 50 mph were selected.

Thus the designer may assemble the acceleration lane, using the three elements in a manner which best fit the conditions. In doing so, the values selected from the design tables assure that the design objectives will be met.

Where the required lengths are to be derived directly, the designer must have the following information:

1. design vehicles assumed for the ramp and for Lane 1 of the freeway;
2. the value for the controlling speed on the ramp (v'_o) and the location of the last point at which it occurs;
3. the value for the running speeds in Lane 1 of the freeway (V'_f) and at the point where the gap search and acceptance process begins (v'_r);
4. the grade condition on the ramp; and
5. the volume condition.

Tables 1 through 5 are used to select lengths for each of the three elements which comprise the acceleration lane. These are then used to guide the layout of the ramp. Specific constraints on the placement of these elements must be met. That is:

1. the acceleration lane begins at the end of the controlling speed condition on the ramp;
2. the adjust position zone cannot begin upstream of the location at which it is physically possible for the driver of the ramp vehicle to begin the gap search and acceptance process;
3. the beginning of the entrance zone cannot be placed upstream of the physical merging end; and
4. the elements comprising the acceleration lane cannot be overlapped.

When the designer has an existing layout to be tested, the basic information needed includes:

1. design vehicles assumed for the ramp and for Lane 1 of the freeway.
2. the value for the controlling speed on the ramp (v'_o) and the location of the last point at which it occurs;
3. the value for the running speed in Lane 1 of the freeway, (V'_f);
4. the grade condition on the ramp;
5. the volume condition; and
6. the location of:
   a. the physical merging end;
   b. the point where the gap search and acceptance process can begin; and
   c. the end of the acceleration lane.

The designer may then test the design by entering the design tables to determine if the required lengths can be met with the layout under consideration. In order to do this, an assumption is made regarding a desired ramp vehicle speed (v'_r)

to be reached at the beginning of the gap search and acceptance process. The requirements for L_{AP} and L_{EN} are then determined from Tables 3 through 5 as appropriate. These are checked against the available lengths, considering the placement constraints listed above. If the design is found inadequate, several of the elements may be modified to arrive at the desired length.

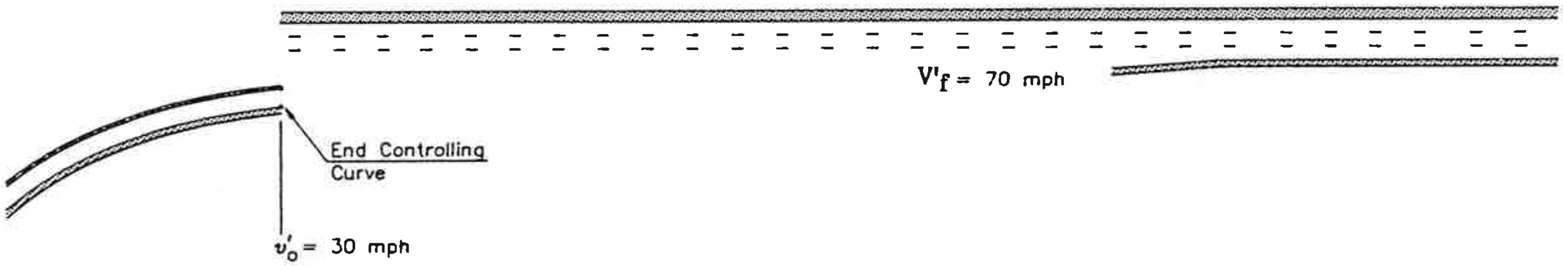
Example Applications

The following pages provide examples of the application of the design procedures for acceleration lanes for a variety of conditions.

Example 1 Determine Acceleration Lane Length Requirements

Design Determinants

Freeway Speed:	V'_f = 70 mph
Initial Ramp Speed:	v'_o = 30 mph
Design Vehicles:	Freeway - Passenger Car Ramp - Passenger Car
Grade Condition:	Freeway - Near Level Ramp - Near Level
Area Type:	Urban
Given Conditions:	



Example 1 Determine Acceleration Lane Length Requirements (Continued)

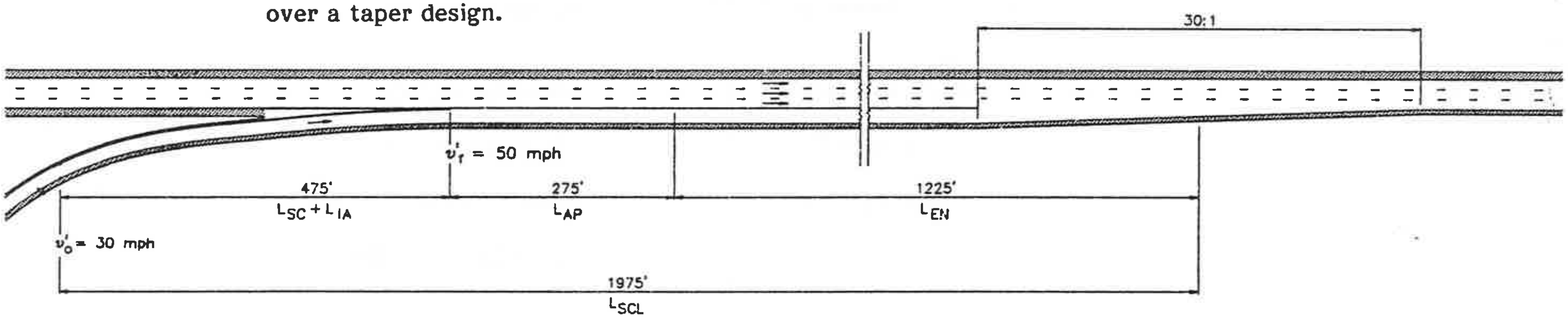
Length Requirements

Since the ramp speed at the begin GSA, v'_r, is unknown, the designer would try several speeds in order to obtain the shortest acceleration lane length. Therefore, for v'_r = 60, 50, 40, and 30 mph;

		v'_r = 60 mph	v'_r = 50 mph	v'_r = 40 mph	v'_r = 30 mph
From Table 1; $L_{SC} + L_{IA}$	=	775 ft	475 ft	250 ft	50 ft
From Table 3; L_{AP}	=	500 ft	275 ft	175 ft	100 ft
From Table 4; L_{EN}	=	1,150 ft	1,225 ft	2,050 ft	2,325 ft
L_{SCL}	=	2,425 ft	1,975 ft	2,475 ft	2,475 ft

Proposed Design

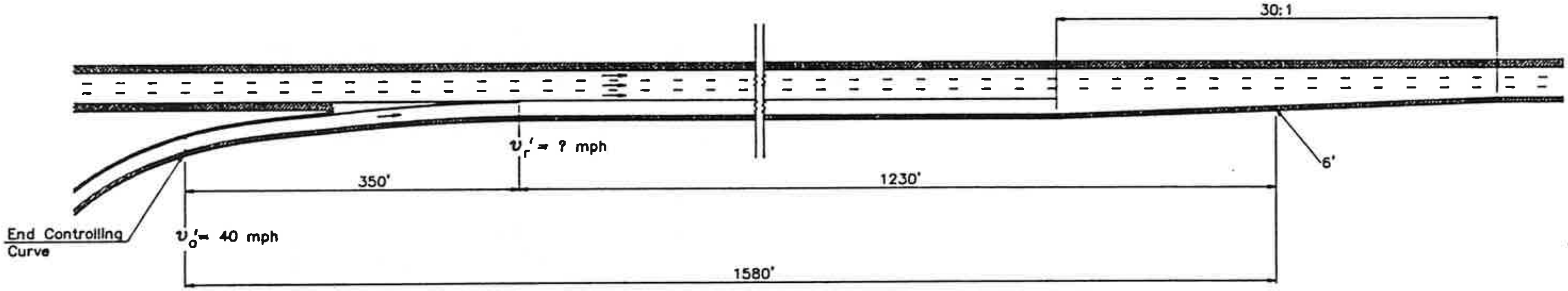
For this design, a v'_r = 50 mph would be selected, resulting in L_{SCL} = 1,975 ft. In order to meet the design constraints for placement of the acceleration lane elements, the following parallel design could be suggested. Based on the length requirement of the acceleration lane, a parallel design is chosen over a taper design.



Example 2 Test An Existing Configuration

Design Determinants

Freeway Speed:	V'_f = 70 mph
Initial Ramp Speed:	v'_o = 40 mph
Design Vehicles:	Freeway - Passenger Car Ramp - Passenger Car
Grade Condition:	Freeway - Near Level Ramp - Near Level
Area Type:	Suburban
Given Conditions:	



Example 2 Test An Existing Configuration (Continued)

Length Requirements

From Table 1, the existing $L_{SC} + L_{IA}$ (350 ft) most closely corresponds to a ramp speed of $v'_r = 50$ mph for the above design conditions. Therefore,

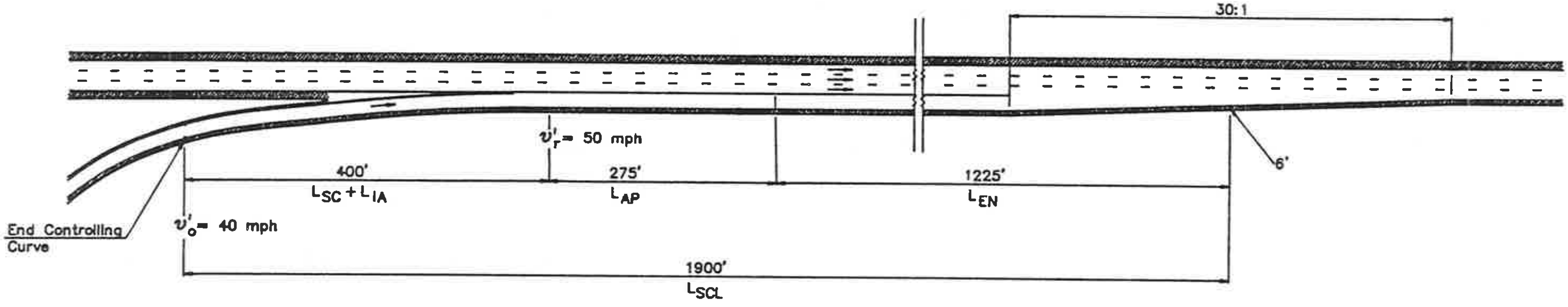
			$v'_r = 50$ mph
From Table 1;	$L_{SC} + L_{IA}$	=	400 ft
From Table 3;	L_{AP}	=	275 ft
From Table 4;	L_{EN}	=	1,225 ft
	L_{SCL}	=	1,900 ft

Comparison with the existing layout shows:

L_{SCL} (1,900 ft) $>$ the existing acceleration lane length (1,580 ft)
L_{EN} (1,225 ft) $\approx$ the existing length (1,230 ft)

Proposed Design

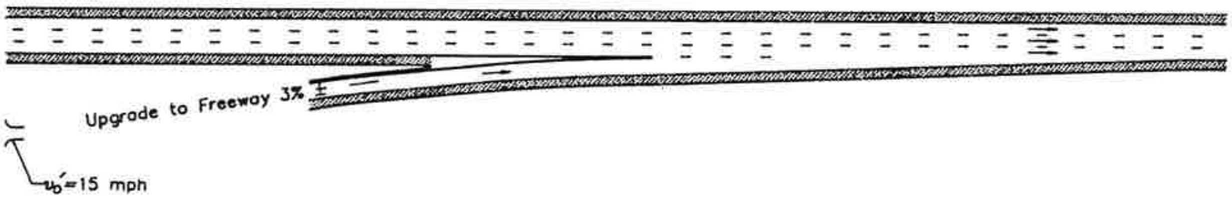
Additional acceleration lane length (1,900-1,580 = 320 ft) is required. Since sufficient length is already provided for L_{EN}, the additional length requirement should be provided for $L_{SC} + L_{IA}$ and L_{AP}.



Example 3 Determine Acceleration Lane Length Requirements

Design Determinants

Freeway Speed:	$V'_f = 70$ mph
Initial Ramp Speed:	$v'_o = 15$ mph
Design Vehicles:	Freeway - Passenger Car Ramp - Truck
Grade Condition:	Freeway - Near Level Ramp - Upgrade (+3%)
Area Type:	Urban
Given Conditions:	



Length Requirements

From Figure X-7, Page 927 in AASHTO, 1,200 to 1,300 feet is required to achieve a 3% grade between beginning of the ramp and the freeway. From Table 2, for the given design conditions, it is clear that a truck would achieve a speed well below 30 mph if it accelerated continuously on the ramp (1,200 to 1,300 feet). This would result in an unacceptable speed differential (> 40 mph) at the begin GSA. Therefore, adequate acceleration length for the design vehicle cannot be provided.

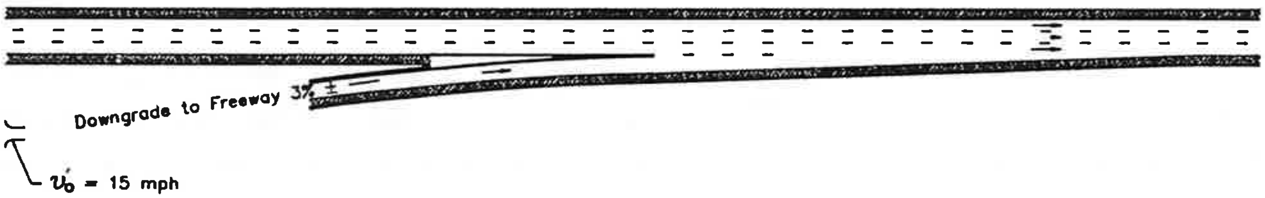
Proposed Design

Due to the high speed differential which will exist at the begin GSA, a normal acceleration lane design is not appropriate. An auxiliary lane (or climbing lane) should be provided in order to allow the design vehicle to reach a speed within 10 mph of the adjacent freeway vehicles. Preferably, this lane would be marked as an auxiliary lane and would terminate at a downstream exit.

Example 4 Determine Acceleration Lane Length Requirements

Design Determinants

Freeway Speed:	$V'_f = 70$ mph
Initial Ramp Speed:	$v'_o = 15$ mph
Design Vehicles:	Freeway - Passenger Car Ramp - Truck
Grade Condition:	Freeway - Near Level Ramp - Downgrade (-3%)
Area Type:	Urban
Given Conditions:	



Length Requirements

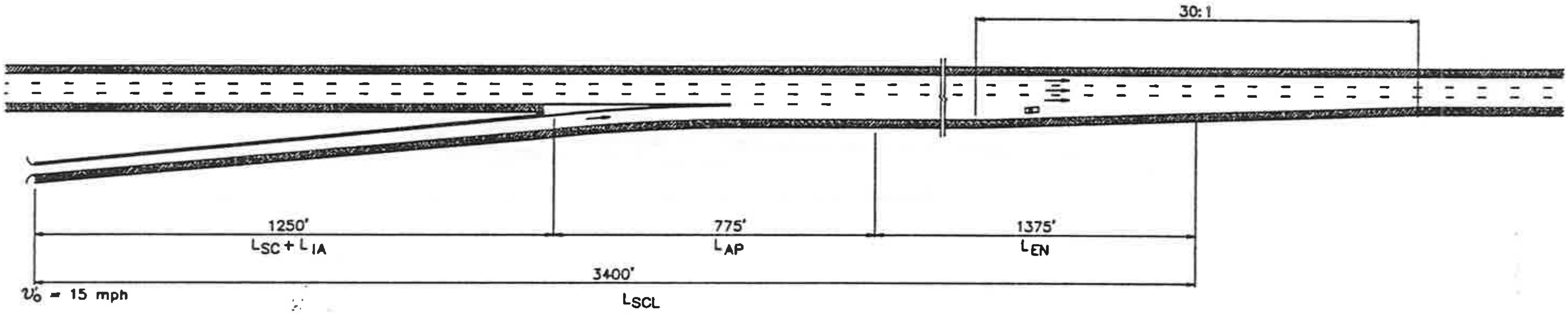
Since the ramp speed at the begin GSA, v'_r, is unknown, the designer would try several speeds in order to obtain the shortest acceleration lane length. Therefore, for v'_r = 60, 50, and 40 mph;

		v'_r = 60 mph	v'_r = 50 mph	v'_r = 40 mph
From Table 2; $L_{SC} + L_{IA}$	=	1,250 ft	850 ft	525 ft
From Table 3; L_{AP}	=	775 ft	525 ft	325 ft
From Table 4; L_{EN}	=	1,375 ft	1,400 ft	2,350 ft
L_{SCL}	=	3,400 ft	2,775 ft	3,200 ft

Example 4 Determine Acceleration Lane Length Requirements (Continued)

Proposed Design

From Figure X-7, Page 927 in AASHTO, 1,200 to 1,300 feet is required to achieve a 3% grade between the beginning of the ramp and the freeway. This distance corresponds to an $L_{SC} + L_{IA}$ = 1,250 feet, at v'_r = 60 mph. Therefore, 2,150 feet are required downstream for L_{AP} and L_{EN}. The total acceleration lane length requirement would be 3,400 feet. A parallel design would be selected.



DESIGN PROCEDURES FOR DECELERATION LANES

Dynamics of the Exit Process

Although less complex than the entry process, transitioning from a freeway lane to an exit ramp involves a series of navigational decisions and control tasks which must be performed by a driver. Within each task, the driver is required to process roadway and traffic information, translating that information into steering and speed control responses.

A driver, having decided to exit, searches for the exit ramp as he travels along the freeway. Once the exit ramp has been located and responding to certain visual and kinesthetic cues, the driver steers from the freeway lane onto the exit or deceleration lane. The driver positions his vehicle in the appropriate trajectory towards the exit ramp. Once on the deceleration lane, the driver must decelerate to some speed governed by the physical geometry or traffic conditions on the ramp.

The Exit Process

Two primary tasks make up the exit process. The first task is the diverge steering maneuver. The exit process essentially begins when the driver initiates a steering control maneuver to move from the freeway lane to the deceleration lane. The driver will initiate this steering maneuver in response to cues in his visual field. These cues are more precisely described as the speed at which certain elements of the exit ramp are departing from the driver's visual field. This speed is defined as the angular velocity.

Once on the deceleration lane, the driver determines his position relative to the exit ramp and, if necessary, adjusts his trajectory to ensure a smooth transition onto the ramp. During these positioning activities, the vehicle is decelerating in-gear at a rate determined by the vehicle type and roadway gradient. Following this position adjustment, the driver must decelerate further, either in-gear, with braking, or both, to reach some ramp-controlling speed.

Design Criteria

When exiting a freeway, a driver does so either individually or as part of a platoon. In the latter case, driver response is controlled more by the lead vehicle than the ramp geometry and exiting essentially becomes a car following process. The former case is considered to have the greatest deceleration length requirement and occurs with sufficient frequency. Therefore, this case should be considered as the design condition.

Similar to the acceleration lane design, the deceleration lane design should, at a minimum, provide sufficient length to allow a driver to exit the freeway lane and decelerate at a comfortable rate. Disruption to the freeway traffic flow should be minimized. This is accomplished by providing the driver sufficient distance upstream from the exit ramp at which to begin steering onto the deceleration lane, thereby reducing any deceleration while still in the freeway lane. To avoid added strain to the driver, it is important that the various tasks which the driver must perform do not overlap.

A Model of Deceleration Lanes

The distance in which the exit process occurs, the deceleration lane, is divided into several zones described below.

L_{DS} - The diverge steering zone represents the distance upstream from the nose of the exit gore or wedge at which the driver desires to begin diverging from the freeway lane onto the deceleration lane.

L_{SC} - The steering control zone represents the distance traveled while steering from the freeway lane onto the deceleration lane. This distance must be no greater than the length of the diverge steering zone (L_{DS}).

L_{DG} - The deceleration in-gear zone includes that length in which the driver is decelerating in-gear. It is assumed that in order to allow for the positioning activities which occur once the driver has transitioned onto the deceleration lane, deceleration in-gear will last for a minimum of 3.0 seconds. Also, since one objective of the deceleration lane design is to minimize speed reduction in the freeway lane, it is assumed that no deceleration occurs in the steering control zone (L_{SC}).

L_{DB} - The deceleration while braking zone includes the length in which brakes must be applied in order to reach the controlling ramp speed. As the driver travels along the deceleration lane, decelerating in-gear, a point is reached at which the driver realizes that his speed is too great for an approaching ramp condition and he/she must brake. Until this braking point has been reached, the driver will continue to decelerate in gear.

L_{SCL}- The total deceleration lane length, L_{SCL} is equal to

$$L_{SC} + L_{DG} + L_{DB}.$$

Mathematical relationships have been developed for the exit process and are provided in Appendix A. Figure 3 illustrates the zones which comprise the deceleration lane length.

Design Determinants

In order to determine the deceleration lane length requirements using the exit model, the following design determinants must be specified by the designer.

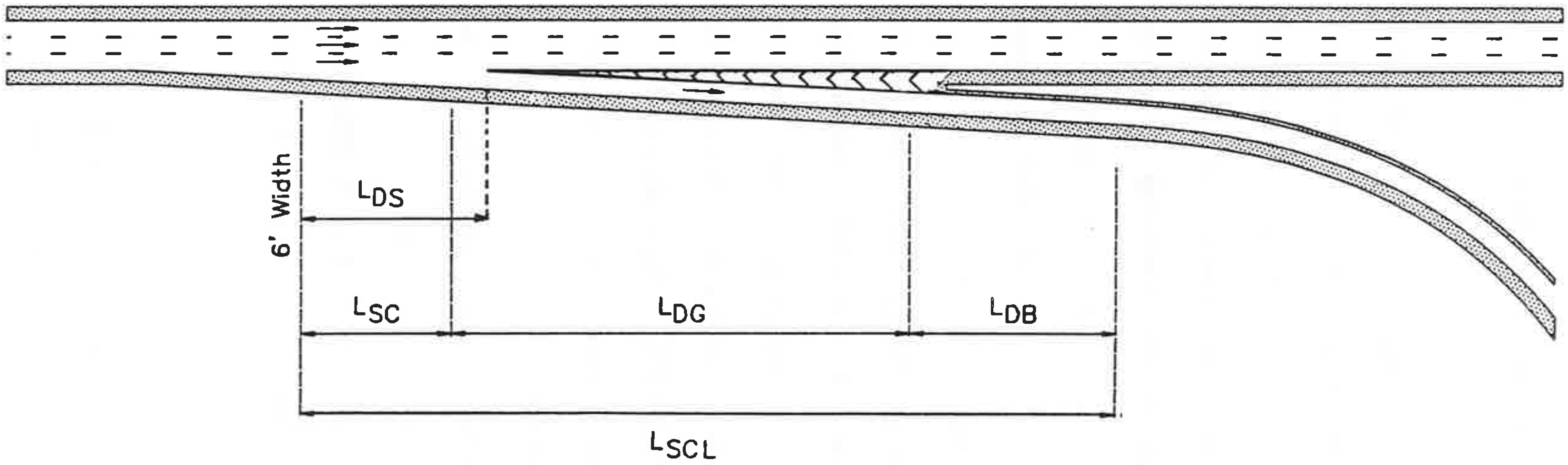


FIGURE 3

DEFINITION OF DECELERATION LANE COMPONENTS

1. design vehicle;
2. freeway running speed; V'_d
3. controlling ramp speed; V'_c
4. grade; and
5. angle of divergence.

The selection of design vehicle, either passenger car or truck, primarily affects the deceleration rates used. The deceleration rates representative of each design vehicle are provided in Appendix B. These deceleration rates also reflect the ramp grade condition.

It is recommended that freeway design speed be used for running speed. Controlling ramp speed will be a function of ramp geometrics. Ramp design speed should also be used in place of running speed, unless local conditions indicate that a slower speed should be used for the design condition.

The angle at which the exit ramp diverges from the freeway mainline affects the placement of the beginning of the deceleration lane. For tangent ramp designs, this angle typically varies from 2 to 6 degrees. The larger the angle, the greater the distance upstream of the exit ramp the deceleration lane must begin. The angle of divergence associated with curvilinear ramp designs are typically greater, up to 18 degrees for a tight loop ramp with a 150-foot radius. Unlike the entry model, neither freeway or ramp volume are design determinants in the exit model.

Design Guidelines

Deceleration Lane Length

The lengths of the four zones in the exit process have been combined into two design elements. The first element is the total length required to complete the exit process or the deceleration lane length, L_{SCL}. This length is the sum of the steering control zone, the deceleration in-gear zone, and the deceleration while braking zone ($L_{SC} + L_{DG} + L_{DB}$). The second element, L_{DS}, defines the distance upstream from the nose of the exit wedge at which the beginning of the deceleration lane must be placed. Tables 6 through 9 provide values for each design element for various freeway speeds V'_d, controlling ramp speeds V'_c,, levels of grade, vehicle type, and angle of divergence.

The levels of grade correspond to the following:

Upgrade: $> +2\%$
Near Level: +2% to -2%
Downgrade: $< -2\%$

Deceleration Lane Configuration

Figure 4 illustrates typical layouts for parallel and tapered deceleration lane designs. In both designs, the deceleration lane begins at the 6-foot wide point of the tapered section. The tapered section of the parallel design typically ranges between 15:1 to 25:1. Neither design is considered superior to the other, however, when a taper rate flatter than 70:1 is required in order to accommodate the deceleration lane length, a parallel design should be used.

The nose of the exit wedge is usually 2-feet wide and is the point where the painted or marked edge lines meet. The driver of the exiting vehicle must be able to clearly view the exit area prior to the beginning of the deceleration lane. Therefore, it is desirable to minimize horizontal and vertical curvature within the exit area in order to maximize sight distance.

TABLE 6

DECELERATION LANE DESIGN VALUES, L_{SCL} , (ft)

Near Level Grade

	Passenger Car on Ramp										Truck on Ramp									
	V'_d = 70 mph										V'_d = 70 mph									
	Angle of Divergence (degrees)										Angle of Divergence (degrees)									
V'_c (mph)	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1725	1725	1725	1725	1725	1725	1725	1725	1725	1725
15	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1525	1525	1525	1525	1525	1525	1525	1525	1525	1525
30	825	825	825	825	825	825	825	825	850	850	900	900	900	900	900	900	900	900	900	900
40	825	825	825	825	825	825	825	825	850	850	850	850	850	850	850	850	850	850	850	850
50	825	825	825	825	825	825	825	825	850	850	850	850	850	850	850	850	850	850	850	850
60	625	625	625	625	700	750	800	825	850	850	850	850	850	850	850	850	850	850	850	850
	V'_d = 60 mph										V'_d = 60 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	725	725	725	725	725	725	725	750	775	800	750	750	750	750	750	750	750	750	775	800
15	725	725	725	725	725	725	725	750	775	800	750	750	750	750	750	750	750	750	775	800
30	725	725	725	725	725	725	725	750	775	800	750	750	750	750	750	750	750	750	775	800
40	725	725	725	725	725	725	725	750	775	800	750	750	750	750	750	750	750	750	775	800
50	550	550	575	575	625	700	725	750	775	800	750	750	750	750	750	750	750	750	775	880
60	400	400	500	575	625	700	725	750	775	800	400	400	500	600	625	700	725	750	775	800
	V'_d = 50 mph										V'_d = 50 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	625	625	625	625	625	625	625	675	700	725	650	650	650	650	650	650	650	675	700	725
15	625	625	625	625	625	625	625	675	700	725	650	650	650	650	650	650	650	675	700	725
30	625	625	625	625	625	625	625	675	700	725	650	650	650	650	650	650	650	675	700	725
40	450	450	450	500	550	600	625	675	700	725	650	650	650	650	650	650	650	675	700	725
50	325	325	450	500	550	600	625	675	700	725	325	325	450	500	550	625	650	675	700	725
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 7

DECELERATION LANE DESIGN VALUES: L_{SCL}, (ft)

Upgrade

V'_c (mph)	Passenger Car on Ramp										Truck on Ramp									
	V'_d = 70 mph										V'_d = 70 mph									
	Angle of Divergence (degrees)										Angle of Divergence (degrees)									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	875	875	875	875	875	875	875	875	875	875	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
15	850	850	850	850	850	850	850	850	850	850	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
30	800	800	800	800	800	800	800	800	850	850	825	825	825	825	825	825	825	825	850	850
40	800	800	800	800	800	800	800	800	850	850	825	825	825	825	825	825	825	825	850	850
50	675	675	675	675	700	750	800	800	850	850	825	825	825	825	825	825	825	825	850	850
60	450	450	575	650	700	750	800	800	850	850	625	625	625	625	700	750	800	825	850	850
	V'_d = 60 mph										V'_d = 60 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	700	700	700	700	700	700	725	725	775	800	725	725	725	725	725	725	725	750	775	800
15	700	700	700	700	700	700	725	725	775	800	725	725	725	725	725	725	725	750	775	800
30	700	700	700	700	700	700	725	725	775	800	725	725	725	725	725	725	725	750	775	800
40	575	575	575	575	625	700	725	725	775	800	725	725	725	725	725	725	725	750	775	800
50	375	400	500	575	625	700	725	725	775	800	550	550	575	575	625	700	725	750	775	800
60	375	400	500	575	625	700	725	725	775	800	400	400	500	575	625	700	725	750	775	800
	V'_d = 50 mph										V'_d = 50 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	600	600	600	600	600	600	650	650	700	725	625	625	625	625	625	625	650	675	700	725
15	600	600	600	600	600	600	650	650	700	725	625	625	625	625	625	625	650	675	700	725
30	450	450	450	500	550	600	650	650	700	725	625	625	625	625	625	625	650	675	700	725
40	300	325	450	500	550	600	650	650	700	725	450	450	450	500	550	600	650	675	700	725
50	300	325	450	500	550	600	650	650	700	725	325	325	450	500	550	600	650	675	700	725
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 8

DECELERATION LANE DESIGN VALUES: L_{SCL}, (ft)

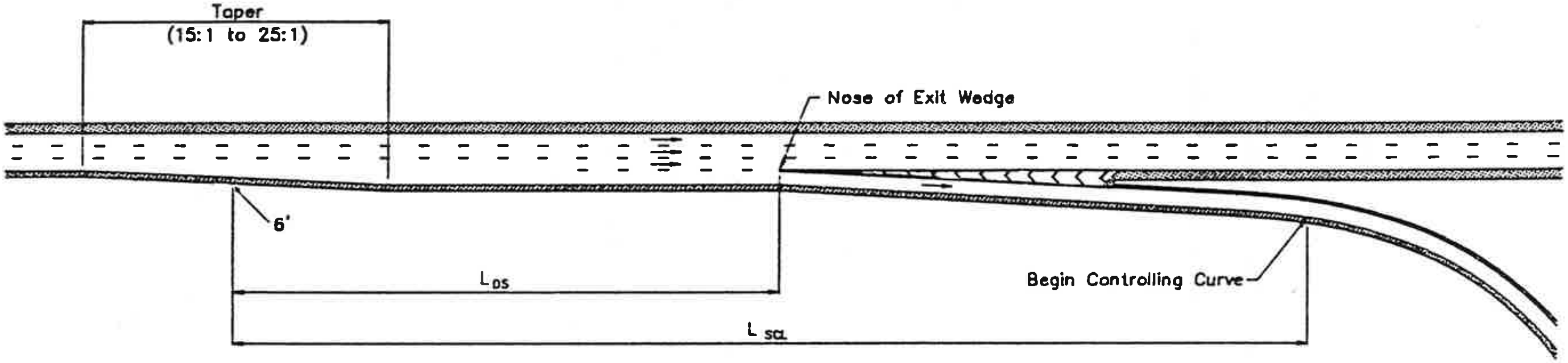
Downgrade

	Passenger Car on Ramp										Truck on Ramp									
	V'_d = 70 mph										V'_d = 70 mph									
	Angle of Divergence (degrees)										Angle of Divergence (degrees)									
V'_c (mph)	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300
15	1275	1275	1275	1275	1275	1275	1275	1275	1275	1275	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
30	850	850	850	850	850	850	850	850	850	850	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
40	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850
50	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850
60	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850	850
	V'_d = 60 mph										V'_d = 60 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	750	750	750	750	750	750	750	750	775	800	875	875	875	875	875	875	875	875	875	875
15	750	750	750	750	750	750	750	750	775	800	750	750	750	750	750	750	750	750	775	800
30	750	750	750	750	750	750	750	750	775	800	750	750	750	750	750	750	750	750	775	800
40	750	750	750	750	750	750	750	750	775	800	750	750	750	750	750	750	750	750	775	800
50	750	750	750	750	750	750	750	750	775	800	750	750	750	750	750	750	750	750	775	800
60	400	400	500	575	625	700	725	750	775	800	400	400	500	600	625	700	725	750	775	800
	V'_d = 50 mph										V'_d = 50 mph									
	2	3	4	5	6	8	10	12	14	18	2	3	4	5	6	8	10	12	14	18
0	650	650	650	650	650	650	650	675	700	725	650	650	650	650	650	650	650	675	700	725
15	650	650	650	650	650	650	650	675	700	725	650	650	650	650	650	650	650	675	700	725
30	650	650	650	650	650	650	650	675	700	725	650	650	650	650	650	650	650	675	700	725
40	625	625	650	650	650	650	650	675	700	725	650	650	650	650	650	650	650	675	700	725
50	325	325	450	500	550	600	650	675	700	725	325	325	450	500	550	625	650	675	700	725
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

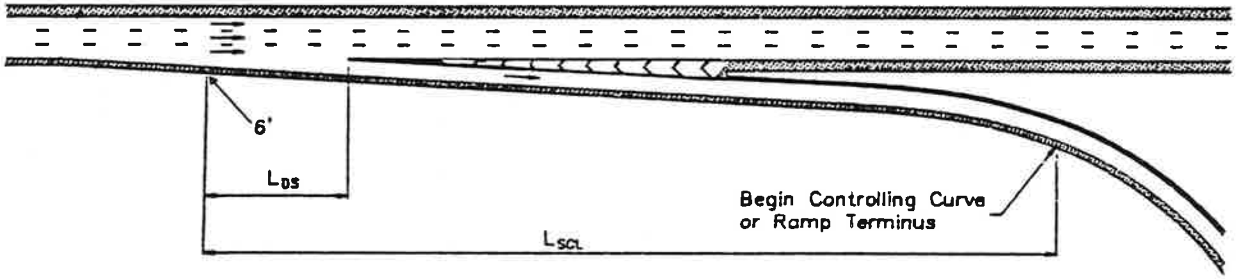
TABLE 9

DECELERATION LANE DESIGN VALUES: L_{DS}, (ft)

Angle of Divergence (degrees)	V'_d (mph) Passenger Cars and Trucks		
	70	60	50
2	225	150	100
3	450	375	325
4	575	500	425
5	650	575	500
6	700	625	550
8	750	700	600
10	800	725	650
12	825	750	675
14	825	750	700
18	850	775	700



TAPERED DESIGN



PARALLEL DESIGN

FIGURE 4

TYPICAL DECELERATION LANE CONFIGURATIONS

Design Process

The design criteria for the deceleration lane can be used to determine the required lengths for a new design, test the appropriateness of an existing design or be used to retrofit older designs which are not used by designers today.

When a designer is preparing a new layout, the following information is required.

1. design vehicle assumed for exiting vehicle;
2. the freeway running speed;
3. the ramp controlling speed;
4. ramp grade; and
5. The angle of divergence of the ramp, approximated if necessary.

Tables 6 through 9 are used to select lengths for the two deceleration lane elements, L_{SCL} and L_{DS}. If the ramp design is to include a tangent section prior to any curvature, the angle of divergence is readily available. If, however, the ramp curvature begins immediately at the diverging end, as in a tight loop, the angle of divergence can be approximated using the equation provided below.

$$\mathrm{COS}\ \alpha = 1 - \frac{25}{R}$$

Where:

α = Angle of Divergence

R = Radius of Curvature (ft)

The lengths which are selected for L_{SCL} and L_{DS} are then used to guide the layout of the deceleration lane and exit ramp. Placement of the deceleration lane is governed by several constraints. These are:

1. the deceleration lane must be placed a distance L_{DS} upstream of the exit wedge (diverging end).
2. the deceleration lane must begin at the 6-foot point of the taper.
3. the deceleration lane must end prior to the controlling point of the ramp curvature or the ramp terminus, depending upon the ramp design.

When an existing design is to be tested, the basic information required includes:

1. the design vehicle assumed for the exiting vehicle;
2. the freeway running speed, V'_d;
3. the ramp controlling speed, V'_c;
4. ramp grade; and
5. the angle of divergence of the ramp, approximated if necessary;
6. the location of:
   a. the merging end;
   b. the beginning (6-foot point) of the deceleration lane;
   c. the end of the deceleration lane.

From Tables 6 through 9, the existing design can be tested to determine if the required lengths are met and correct placement of elements are met.

Example Applications

Several examples of the applications of the procedures in determining deceleration lane design are provided in the following for a variety of traffic and geometric conditions.

Example 5 Determine Deceleration Lane Length Requirements

Design Determinants

Freeway Diverge Speed: $V'_d = 70$ mph

Exit Ramp Design: Curved With Tangent Section

Ramp Controlling Speed: $V'_c = 0$ mph

Angle of Ramp Divergence: 4^o

Design Vehicle: Passenger Car

Grade Condition: Ramp - Near Level

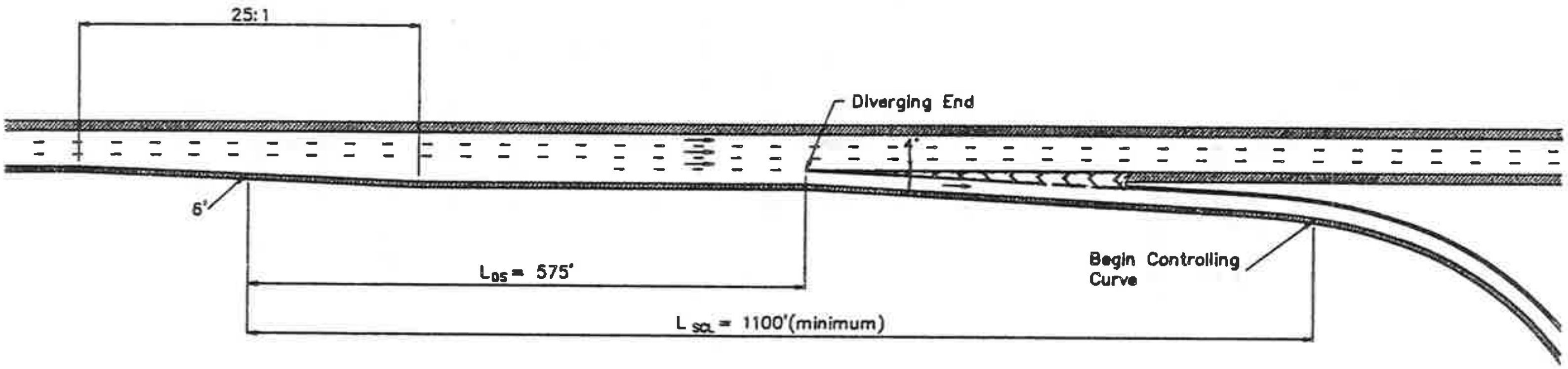
Length Requirements

From Table 6, $L_{SCL} = 1{,}100$ ft (minimum)

From Table 9, $L_{DS} = 575$ ft (minimum)

Proposed Design

Since the required distance, $L_{DS} = 575$ feet, upstream of the diverging end cannot be accommodated with a tapered design, a parallel design should be used.



Example 6 Determine Deceleration Lane Lenth Requirements

Design Determinants

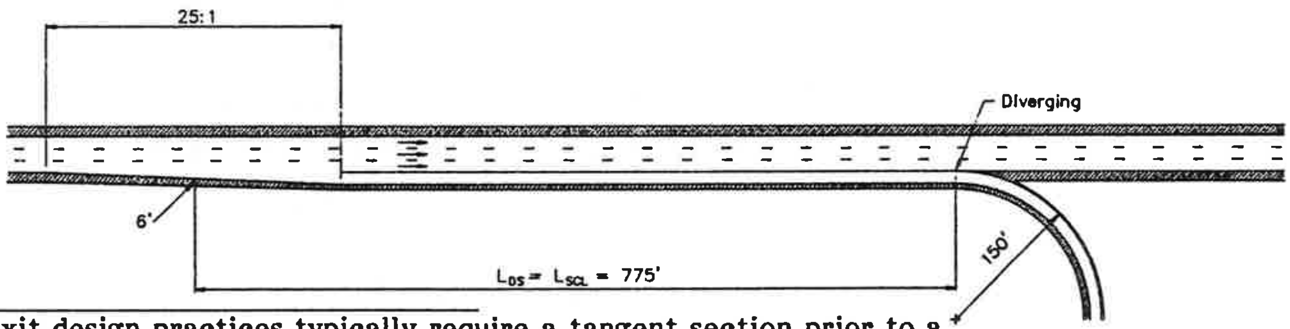
Freeway Diverge Speed:	V'_d = 60 mph
Exit Ramp Design:	Curvilinear with a 150 ft radius*
Ramp Controlling Speed:	V'_c = 15 mph
Angle of Ramp Divergence:	18°; (Estimated based on 150 ft radius of curvature)
Design Vehicle:	Passenger Car
Grade Condition:	Ramp - Near Level

Length Requirements

From Table 6, L_{SCL} = 775 ft (minimum)
From Table 9, L_{DS} = 775 ft (minimum)

Proposed Design

Due to the length requirements, L_{DS} = 775 feet, a parallel design is required. The entire deceleration lane length must be provided upstream of the diverging end.



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*Current exit design practices typically require a tangent section prior to a tight curve. Some older designs, however, do not provide such a tangent section, yet do exist. It is on these older exit designs where a retrofit of a deceleration lane may be required.

Example 7 Determine Deceleration Lane Length Requirements

Design Determinants

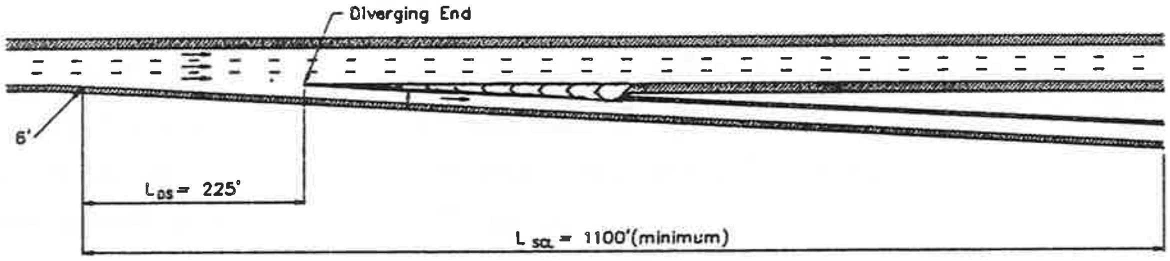
Freeway Diverge Speed: $V'_d = 70$ mph
Exit Ramp Design: Tangent (Diamond)
Ramp Controlling Speed: $V'_c = 0$ mph
Angle of Ramp Divergence: 2^o
Design Vehicle: Passenger Car
Grade Condition: Ramp - Near Level

Length Requirements

From Table 6, $L_{SCL} = 1{,}100$ ft (minimum)
From Table 9, $L_{DS} = 225$ ft (minimum)

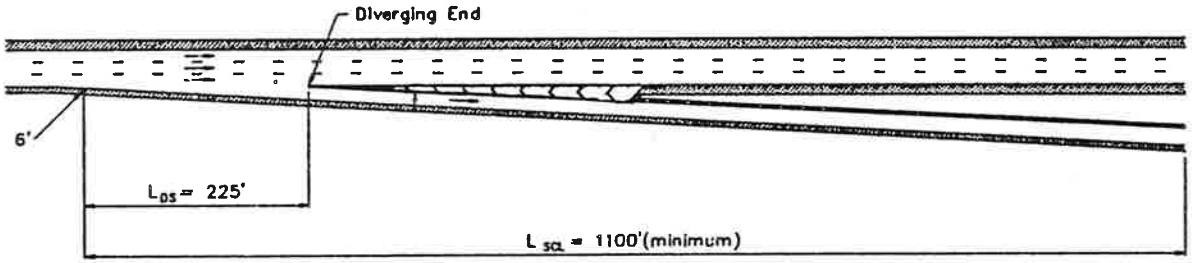
Proposed Design

A tapered design is selected, although a parallel deceleration lane could also be used.



Example 8 Test An Existing Design

Existing Design



Design Determinants

Freeway Speed:	$V'_d = 60$ mph
Existing Design:	Tangent (Diamond)
Ramp Controlling Speed:	$V'_c = 0$ mph
Angle of Ramp Divergence:	4^o
Design Vehicle:	Passenger Car
Grade Condition:	Ramp - Upgrade

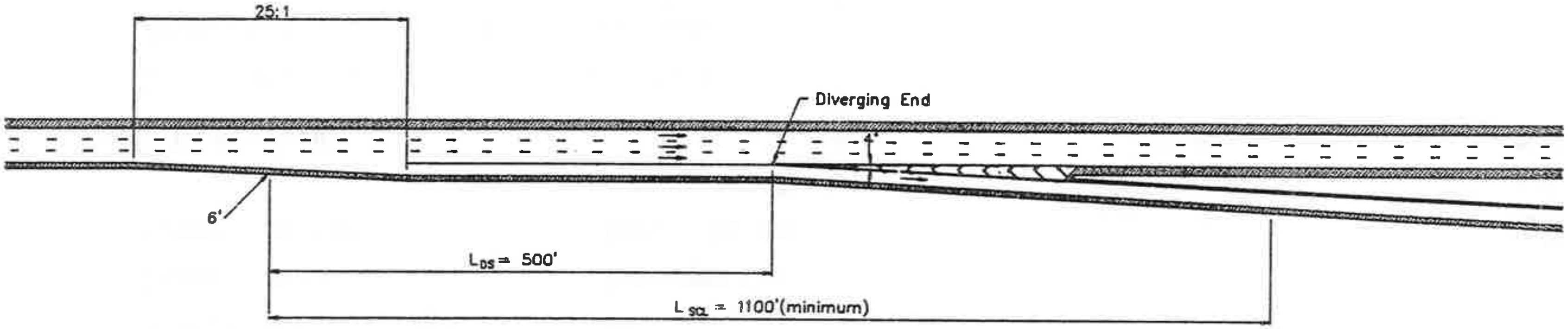
Length Requirements

From Table 7, L_{SCL} = 700 ft (minimum)
From Table 9, L_{DS} = 500 ft (minimum)

Therefore, the total deceleration lane length provided, $L_{SCL} = 1{,}100$ feet, is more than adequate, however, insufficient length, $L_{DS} = 225$ feet, is provided upstream of the merging end.

Proposed Design

Approximately 275 feet (500 feet required less 225 feet existing) of additional length is required upstream of the merging end. A parallel design is proposed.



APPENDIX A

MATHEMATICAL MODELS FOR DETERMINATION OF ACCELERATION AND DECELERATION LANE LENGTHS

TABLE A-1

ENTRY MODEL EQUATIONS

Acceleration Lane Length, L_{SCL}

1. $L_{SCL} = L_{SC} + L_{IA} + L_{AP} + L_{EN}$

Steering Control Zone, L_{SC}

2. $L_{SC} = t_s v_0$

Initial Acceleration Zone, L_{IA}

3. $L_{IA} = \dfrac{v_{r_1}{}^2 - v_o{}^2}{2a_o}$

Adjust Position Zone, L_{AP}

4. $L_{AP} = v_{r_1} t + \dfrac{a_1 t^2}{2}$

5. $t = \dfrac{2\Delta d}{\Delta V + \sqrt{\Delta V^2 + 2\Delta a \Delta d}}$

6. $\Delta V = V_\ell - v_{r_1}$

7. $\Delta a = a_\ell - a_1$

8. $\Delta d = L_o = \alpha V_f + l_r$

9. $v_{r_1} = \sqrt{v_o{}^2 + 2a_o L_{IA}}$

Minimum Entry Length, L_{EN}

10. $L_{EN} = d_{hr} + L_{VC}$

11. $d_h = f_{hr} d_{hr}$

12. $d_h = \dfrac{v_{hr}}{\lambda\beta^2}\left(e^{\lambda\beta T} - \lambda\beta T - 1\right)$

13. $T = \dfrac{L_H}{V_\ell}$

14. $L_H = L_T + F + l_\ell$

15. $L_T = \sqrt{\dfrac{(D+0)(V_\ell - v_{hr})}{\omega_t}}$

16. $\beta = 1 - \left(\dfrac{v_{hr}}{V_\ell}\right)$

17. $F = \alpha V_f$

18. $\lambda = \dfrac{k\lambda'}{3600N}$

19. $v_{hr} = f_h\left(V_f - v_{r_2} + \Delta V_\ell\right) + v_{r_2}$

20. $v_{r_2} = v_{r_1} + a_1 t$

21. $\sigma^2 = \dfrac{1}{\lambda\beta^2}\left(e^{2\lambda\beta T} - 2\lambda\beta T e^{\lambda\beta T} - 1\right)$

22. $\lambda_r = \dfrac{\lambda'_r}{3600}$

Visual Clear Zone, L_{VC}

23. $L_{VC} = \sqrt{\dfrac{D' v_{r_3}}{\omega_t}}$

24. $v_{r_3} = \sqrt{v_{r_2}{}^2 + 2a_h d_{hr}}$

25. $L_{AZ} = \dfrac{v_{r_3}{}^2}{2a_A}$

26. $v_{r_4} = \sqrt{v_{r_3}{}^2 + 2a_h L_{VC}}$

TABLE A-2

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
a_A	Average acceleration (deceleration) rate across the abort zone	f/s/s
a_f	Average acceleration rate of Lane 1 freeway vehicle across AP zone	f/s/s
a_h	Average acceleration across d_{hr}	f/s/s
a_l	Average acceleration rate of ramp vehicle across AP zone	f/s/s
a_o	Average acceleration rate of ramp vehicles in IA zone	f/s/s
D	Width of trailing vehicle in Lane 1 of freeway	ft
D'	Width of pavement at ramp terminus upon which driver will focus as terminus is approached	ft
d	Distance traveled after lag rejection to position vehicle to consider next headway	ft
d_h	Distance required to search for and accept a gap without affect of ramp volume	ft
d_{hr}	Distance required to search for and accept a headway, including delay due to ramp volume	ft
d_s	Added distance required for search and acceptance of a headway, due to affect of ramp volume	ft
F	Minimum car following distance	ft
f_h	Factor to estimate average speed across d_{hr}	ft
f_{hr}	Factor relating d_h and d_{hr}	ft
k	Volume distribution factor	ft
L_{AP}	Length of adjust position zone	ft
L_{AZ}	Length of abort zone	ft

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

TABLE A-2 (CONTINUED)

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
L_{EN}	Length of entry zone	ft
l_f	Length of freeway design vehicle	ft
L_{GSA}	Length of gap search and acceptance zone	ft
L_H	Acceptable distance headway at threshold angular velocity	ft
L_{IA}	Length of initial acceleration zone	ft
L_{MSC}	Length of merge steering control zone	ft
L_o	Initial lag	ft
l_r	Length of ramp design vehicle	ft
L_{SC}	Length of initial steering control zone	ft
L_{SCL}	Length of speed-change lane	ft
L_T	Acceptable distance lag at threshold angular velocity	ft
L_{VC}	Length of visual clear zone	ft
N	Number of lanes in one direction on the freeway	--
O	Offset between ramp and trailing freeway vehicle	ft
T	Acceptable time headway	sec
t	Time to juxtapose ramp vehicle opposite lag vehicle in Lane 1 of the freeway	sec
t_s	Time to complete steering control	sec
V_f	Speed of vehicle in Lane 1 of the freeway	f/s
v_{hr}	Average speed of ramp vehicle across d_{hr}	f/s
v_o	Speed of ramp vehicle at end of controlling condition	f/s

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

TABLE A-2 (CONTINUED)

ENTRY MODEL NOMENCLATURE

Variable	Definition	Unit
v_{r_1}	Speed of ramp vehicle at beginning GSA zone (also v_r)	f/s
v_{r_2}	Speed of ramp vehicle at end of AP zone	f/s
v_{r_3}	Speed of ramp vehicle at end of EN zone	f/s
v_{r_4}	Speed of ramp vehicle at end of VC zone	f/s
ω_t	Threshold angular velocity	rads/s
β	Relative speed factor	--
λ	Freeway Lane 1 volume	pcps
λ'	Total freeway volume	pcph
α	Car following constant	sec
Δa	Difference in acceleration rates of ramp and lag vehicle in Lane 1 of the freeway at end of IA	ft
Δd	Difference between absolute distances traveled by the freeway and ramp vehicles during the vehicle adjustment process	ft
ΔV	Speed differential between freeway Lane 1 vehicle and ramp vehicle at begin GSA	f/s
ΔV_f	Allowable speed differential between ramp vehicle and trailing freeway vehicle after merge	f/s
σ^2	Variance associated with d_h	sec^2
λ_r	Ramp volume	pcps
λ'_r	Ramp volume	pcph

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, v_r = f/s and v'_r = mph.

TABLE A-3

EXIT MODEL EQUATIONS

Deceleration Lane Length, L_{SCL}

$$L_{SCL} = L_{DG} + L_{DB} + L_{SC}, \text{ or } L_{SCL} = L_{DS}, \text{ whichever is greater} \quad (1)$$

Steering Control Zone, L_{SC}

$$L_{SC} = V_d t_S \quad (2)$$

Diverge Steering Zone, L_{DS}

$$L_{DS} = \sqrt{\frac{V_d}{\omega_t}(h+y') - (h+y')^2} - \frac{y'}{\tan\alpha} \quad (3)$$

Deceleration In-Gear Zone, L_{DG}

$$L_{DG} = V_d t_g - \tfrac{1}{2} D_g t_g^{\,2} \quad (4)$$

Deceleration While Braking Zone, L_{DB}

$$L_{DB} = \sqrt{\frac{aV_g}{\omega_t} - a^2} \quad (5)$$

$$V_g = \sqrt{V_d^{\,2} - 2L_{DG}D_g} \quad (6)$$

$$D_b = \frac{V_g^{\,2} - V_c^{\,2}}{2L_{DB}}, \quad D_b \leq \hat{D}_b \quad (7)$$

TABLE A-4

EXIT MODEL NOMENCLATURE

Variable	Definition	Unit
a	Lateral width at braking focal point	ft
D_b	Braking rate	f/s/s
$\hat{D}_b$	Maximum desirable braking rate	f/s/s
D_g	Deceleration rate in gear	f/s/s
h	Lateral distance from driver eye in Lane 1 of freeway to the right edge of pavement	ft
L_{DB}	Distance from ramp controlling point at which braking must begin	ft
L_{DG}	Distance traveled while decelerating in gear	ft
L_{DS}	Distance from nose of exit gore at which driver begins to diverge	ft
L_{SC}	Distance traveled during steering control maneuver to exit freeway	ft
L_{SCL}	Total speed-change lane (deceleration) length	ft
t_g	Time spent decelerating in gear	sec
t_s	Time spent executing steering control maneuver	sec
V_c	Speed at ramp controlling point	f/s
V_d	Speed at the beginning of the diverge maneuver	f/s
V_f	Freeway speed prior to diverge	f/s
V_g	Speed at end of deceleration in gear, when braking begins	f/s
y'	Width of wedge, freeway edge to ramp edge, at a point on which the exiting driver is focused	ft
ω_t	Angular velocity threshold.	rads/s
α	Angle of ramp divergence.	degrees

Note: Speeds in miles per hour (mph) are denoted as the prime of the speed in feet per second (f/s). For example, V_d = f/s and V'_d = mph.

APPENDIX B

DESIGN CONDITIONS

TABLE B-1

DESIGN VEHICLE CHARACTERISTICS

	Passenger Car	Truck
Length (ft)	17.5	85.0
Width (ft)	7.0	8.5
Car Following Factor	1.0	1.5

TABLE B-2

DESIGN DRIVER CHARACTERISTICS

1.	Time for Steering Control	1.5 sec
2.	Angular Velocity Threshold	0.002 rads/s (acceleration lane) 0.004 rads/s (deceleration lane)
3.	Foveal Field Width for Visual Clear Zone	6 feet
4.	Maximum Deceleration Rate	10 f/s/s

TABLE B-3

ACCELERATION RATES (f/s/s)

	Passenger Cars								
Speed (mph)	Downgrade			Near Level			Upgrade		
	a_o	a_l	a_h	a_o	a_l	a_h	a_o	a_l	a_h
0	7	2	4	6	2	3	5	2	2
15	6	2	4	5	2	3	4	2	2
30	5	1	4	4	1	3	3	1	2
40	4	0	4	3	0	3	2	0	2
50	3	-1	3	2	-1	2	1	-1	1
60	3	-2	3	2	-2	2	1	-2	1

	Trucks								
Speed (mph)	Downgrade			Near Level			Upgrade		
	a_o	a_l	a_h	a_o	a_l	a_h	a_o	a_l	a_h
0	3.5	2.0	3.5	0.8	0.6	0.6	0.5	0.5	0.5
15	3.0	2.0	3.0	0.5	0.5	0.5	0.4	0.4	0.4
30	2.0	1.0	2.0	0.5	0.4	0.4	0.3	0.3	0.3
40	1.0	0.0	1.0	0.4	0.0	0.3	0.0	0.0	0.0
50	0.8	-1.0	0.8	0.3	-1.0	0.3	0.0	0.0	0.0
60	0.7	-2.0	0.7	0.3	-2.0	0.3	0.0	0.0	0.0

TABLE B-4

DECELERATION RATES IN-GEAR (f/s/s)

	Passenger Cars			Trucks		
	Downgrade	Near Level	Upgrade	Downgrade	Near Level	Upgrade
All Speeds	2.0	3.0	5.0	1.0	1.5	3.0