

Driver Behavior Model of Merging

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A model of freeway merging is developed based on driver behavior. The model proposes that a ramp driver accepts a gap based on the first order motion vectors of an approaching vehicle, which perceptually is angular velocity. This function simultaneously accounts for relative velocity and distance separation. The total model includes driver behavior on the ramp, steering control onto and on the speed change lane, acceleration, gap search, and an abort zone. The model was tested on 102 merges on both a curved ramp and a tangent connector to the speed change lane. The results indicated that an angular velocity model did explain the merge decision point and that drivers used an angular velocity threshold criterion. Using the model, it was possible to estimate the speed change lane length necessary for the ramp driver to find an acceptable gap 85 percent of the time. This length increased with decreasing ramp design speed, but decreased with increasing volume. In general, a speed change lane length of 800 ft is sufficient to ensure an acceptable gap 85 percent of the time for all freeway volumes over 1,200 passenger cars/lane/hour and ramp design speeds over 30 mph, assuming an acceleration capability of the ramp vehicle of greater than 1.5 ft/sec².

Historically, the design of acceleration lanes on freeways has been based on the acceleration characteristics of vehicles and empirical observations of merging behavior. Most of the evidence suggests that drivers begin to merge when the relative velocity difference between freeway gap vehicles is less than 5 mph. Current design practice is to define a speed change lane length (SCLL) for a given freeway design speed so that vehicles on the speed change lane (SCL) can achieve a speed difference on this order. The length depends on the ramp connector, its radius of curvature, and its grade. AASHTO policy defines SCLL with all these factors considered (1).

A more fundamental approach to defining SCLL is to start with the driving task. Michaels (2) suggested a simple model, which was extended by Drew (3). The question is: On what basis do drivers decide that a gap exists sufficient for them to steer into the freeway lane? If it were possible to define the analytic process used by drivers to reach this decision, it would be possible to define the SCLL. The purpose of this paper is to provide such a model and to test it empirically.

MERGING TASK

The merging process requires the driver to perform a series of tasks. Although they are smoothly integrated by the driver,

the tasks represent discrete steps that must be taken in appropriate order if the merge maneuver is to be successful. These tasks may be defined as follows:

1. Ramp curve tracking,
2. Steering transition from ramp to SCL,
3. Acceleration,
4. Gap search, and
- 5a. Steering transition from SCL to freeway or
- 5b. Abort.

These are shown in Figure 1.

The first two tasks involve a pursuit tracking process (4). It is hypothesized that most drivers will complete these tasks before a gap search phase begins. This is because pursuit tracking requires matching the angular velocity of the curve with the yaw velocity of the vehicle, which is a continuous process. This leaves little opportunity for timesharing with gap search. In addition, the geometrics of most curved ramp connectors give drivers insufficient sight distance to observe approaching vehicles on the adjacent freeway lane. Finally, with a normal downgrade on the ramp connector, the motion vectors of the adjacent roadway and vehicles on it involve second and third order motion. Most evidence in the psychological literature suggests that humans do not scale or use these higher order derivatives of motion (5). Thus, in this phase of the merging task, drivers do not have a stable basis for judging the speed or location of freeway vehicles, absolute or relative.

Once on the speed change lane, however, the driver is following a course parallel to the freeway. Steering control is now a compensatory task (6). Given the handling characteristics of most modern vehicles, the amount of time available for visual search is relatively large. Furthermore, assuming

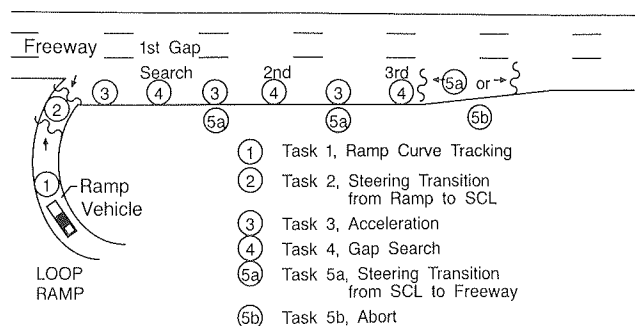


FIGURE 1 Elements of the merge maneuver.

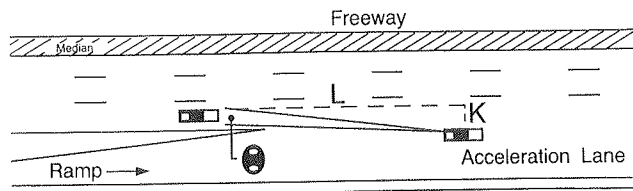


FIGURE 2 Angular velocity.

that the SCL is long relative to the time and space required for the merge, the driver can view the approaching traffic on the freeway lane. Thus, the driver is in the gap search phase.

In this phase, it is possible to define the velocity vectors of approaching vehicles relative to the driver on the SCL. This has been defined by Michaels (2) and Drew (3). The paradigm is shown in Figure 2. Essentially, the driver can evaluate the angular velocity, which is the first order motion vector relative to the ramp driver. This angular velocity is defined quantitatively by a simple first order differential equation:

$$w = k(V_f - V_r)/l^2 \tag{1}$$

where

- w = angular velocity (rad/sec),
- V_f = freeway vehicle speed (ft/sec),
- V_r = ramp vehicle speed (ft/sec),
- l = distance separation (ft), and
- k = lateral offset (ft).

This function is continuous, with w depending jointly on the speed difference and separation. The function varies between plus and minus infinity.

It is hypothesized that drivers operate at some criterion level of w , that is, a threshold that will vary among drivers. If drivers adopt such a criterion as the basis for defining an acceptable gap, then there is a means of predicting the time or distance gap required for a merge maneuver. There is empirical evidence (6,7) that the angular velocity threshold is in the range of 0.01 to 0.001 rad/sec with a nominal value of 0.004 rad/sec.

As drivers observe an approaching vehicle on the freeway lane, the vehicle generates an angular velocity as a function of its speed relative to the ramp driver and its distance from that driver. Depending on the speed and distance relationship, the observed angular velocity will have one of three properties: (a) a positive value, (b) a negative value, or (c) a null value. The first case defines the situation in which the ramp vehicle is traveling at a speed greater than the freeway vehicle, that is, an opening condition. The second case defines the situation in which the ramp vehicle is traveling at a speed less than the freeway vehicle, that is, a closing condition. The third case defines the condition where the relative speed and distance generate an angular velocity below threshold. These conditions are shown in Figure 3. The defining function in Equation 1 is one with two variables determining angular velocity so that the curve shown is selected from the two-dimensional space.

In the first case, the driver is free to merge so long as there is sufficient lead headway. Thus, if the angular velocity of the lead vehicle is at or below threshold, the merging driver may steer onto the freeway lane. For design purposes, the second case is the critical one. If the speed of the ramp vehicle is less

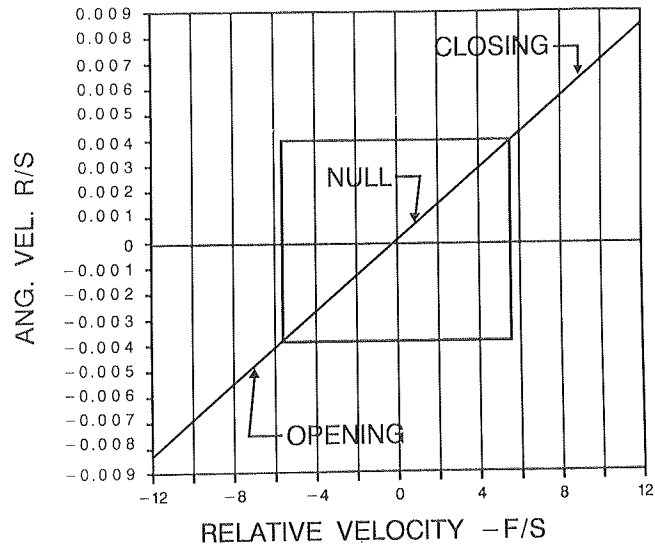


FIGURE 3 The angular velocity function.

than that of the approaching freeway vehicle and that of the lead freeway vehicle, then the decision to merge is determined wholly by the angular velocity of the approaching vehicle. It is hypothesized that in this case the merge will be determined solely by the angular velocity of the following vehicle with the limiting condition that over the length of the SCL the relative positions of the ramp and lead vehicles are such that the ramp vehicle is behind.

Given these conditions, it is possible to define the merge process and to predict where a merge will occur. When the ramp driver steers from the controlling curve and drives parallel to the freeway lane on the SCL, he/she looks down the freeway at approaching vehicles. If the observed gap, lead, and lag generate a less than threshold angular velocity, the driver initiates the steering maneuver required to merge. The sight distance must be sufficient at this initial gap search to estimate the angular velocity of an approaching vehicle. If the lag gap generates a supra-threshold angular velocity, the ramp driver will reject the gap. The control action available to the ramp driver is acceleration. Such acceleration leads to a smaller speed difference between the ramp and freeway vehicles. It is hypothesized that the ramp driver will not initiate a second gap search until the end of the acceleration phase. In other words, the hypothesis is that there is an iterative process: gap search, acceleration, gap search. In theory, this iteration continues until the ramp vehicle speed equals or exceeds freeway speed or the ramp vehicle runs out of SCL.

The best strategy for a ramp driver under congested conditions is to accelerate until the vehicle speed reaches that of the freeway. Unfortunately for ramp drivers, there is no stable criterion for the duration of acceleration required to reach a relative velocity difference of zero or greater. Nor is there a stable criterion for knowing whether the SCL is long enough to reach the relative velocity condition within the acceleration capabilities of a vehicle. A reasonably effective strategy is to use the iterative process described above. Thus, in congested freeway traffic, it is predicted that drivers will demonstrate a speed profile that is a step function as shown in Figure 4.

Merging behavior is constrained by two factors. One is the

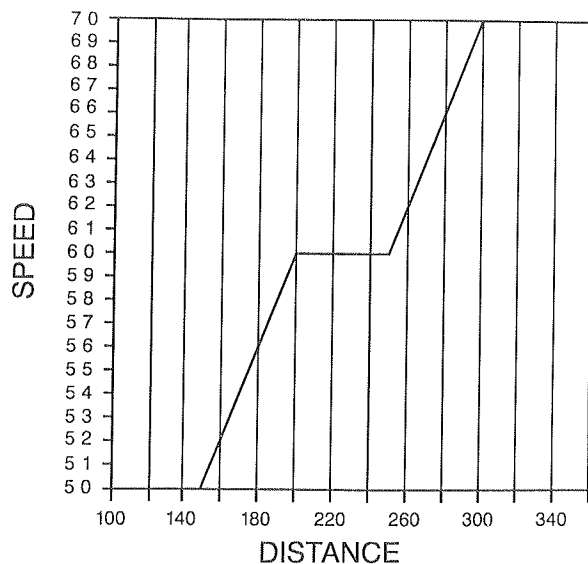


FIGURE 4 Predicted ramp vehicle speed profiles.

controlling ramp curvature, which determines the speed of the ramp vehicle when entering the speed change lane. In loop ramps this is determined by the design speed of the curve. In diamond ramps, this is determined by the grade and angle of convergence.

The second factor is the gap distribution function of the freeway traffic, which is volume dependent. The distribution of gaps can be defined by an Erlang distribution (7) and can be used to estimate the probability of occurrence of a gap meeting the angular velocity criterion for a ramp vehicle arriving at random at any point on the SCL.

Thus, a model of merging can be defined from driver behavior considerations. It is directly possible to validate the proposed model. This test is described in the next section.

MODEL TEST

As described above, the angular velocity model defines the basic information required to test its validity. There are three fundamental questions that must be answered:

1. At the point where steering onto the freeway begins, is there a constant angular velocity between ramp and lag vehicles?
2. Is there an observable and consistent pattern of acceleration on the SCL, and is it related to the angular velocity at merge?
3. Is there an observable and consistent pattern of gap search iterations by ramp drivers?

To answer these questions, it is necessary to measure the behavior of ramp drivers and the properties of the lag gaps into which they enter. This was done by continuous video recording of both ramp and freeway vehicles. Since the primary interest was merging under heavy freeway volume conditions, data were collected during peak periods. Data were collected on both a loop ramp connector and a descending diamond ramp connector.

Measurement was made from a structure overlooking (and at some distance from) the subject SCL. The SCL was marked

at 50-ft intervals for the first 500 ft and at 100-ft intervals thereafter. Both freeway and ramp vehicles were recorded for at least 1 hr during the peak period.

The videotapes were analyzed on a frame-by-frame basis. Therefore, it was possible to track ramp and freeway vehicles in 0.03-sec intervals. Because the distance along the speed change lane was known from the lane markers, it was possible to derive velocity and acceleration for ramp and freeway vehicles. The distance along the SCL where merge began was determined by the point where the left wheel of the ramp vehicle first crossed into the right-hand freeway lane.

To test the angular velocity model, it was essential to measure the location and speed of the freeway vehicle ahead of which the ramp vehicle merged. This was done by starting at the point of merge and determining the location of the lag vehicle on the freeway. It was then possible to rewind the tape and follow the lag vehicle to estimate its speed. It was also possible, using this procedure, to estimate the speed and position of the lead freeway vehicle relative to the ramp vehicle and the beginning of the merge maneuver. The analysis procedure allowed the tracing of the time-distance relations of the ramp vehicle along the SCL as well as these same relations for the freeway vehicles that bounded the accepted gap. Given these data, it was possible not only to obtain a velocity profile for the ramp vehicles but also estimate angular velocity at the beginning of the merge maneuver.

Because this was peak-hour traffic, vehicles entered the test ramp alone and in platoons of two or more vehicles. To account for any interactions, speed, position, and merge measurements were made for each vehicle in a group that was on the SCL simultaneously. Therefore, it was possible to examine the merge process for each vehicle in a queue.

There was a wide variation in the gap distribution on the right-hand freeway lane. Using a criterion of angular velocity threshold, the analysis was restricted to those merges where the lag vehicle was closer than three seconds, that is, to those cases where drivers had a significant merge choice.

RESULTS

Test of the Angular Velocity Model

The angular velocity at the point of merge beginning was computed given the speeds of vehicles on the ramp and the freeway and the separation between vehicles. The angular velocity was computed for both a loop ramp and a diamond ramp. In the case of the loop ramp, the distributions for one-vehicle, two-vehicle, and three-vehicle moving platoons were calculated. The median value was calculated as the best measure of central tendency. A nonparametric test was used to compare the different medians. No significant differences in angular velocity were found for vehicles due to platoon size. Consequently, all the data were pooled and the results are given in Table 1. The median angular velocity was found to be 0.0043 rad/sec. The variance of the distribution was found to be 0.0016 rad/sec. A similar analysis was carried out for a sample of vehicles entering on a diamond interchange. The results are given in Table 2. The median angular velocity at beginning of merge was 0.0034 rad/sec. Thus, the results are consistent and indicate that the decision to merge on the basis of the angular velocity criterion is reasonable.

TABLE 1 ANGULAR VELOCITY DISTRIBUTION FOR LOOP RAMPS

ANGULAR VELOCITY (RADS/SEC)	FREQ. OF OCCURRENCE	CUMULATIVE % FREQ.
-.043 - -.032	1	1.2%
-.031 - -.020	2	3.5%
-.019 - -.008	10	15.1%
-.007 - +.004	28	47.7%
+.005 - +.016	21	72.1%
+.017 - +.028	8	81.4%
+.029 - +.040	4	86.0%
+.041 - +.052	1	87.2%
> +.053	11	100.0%
TOTAL	86	
MEDIAN =	0.0043	

TABLE 2 ANGULAR VELOCITY DISTRIBUTION FOR A DIAMOND RAMP

ANG. VEL.	FREQ.	CUM.%
-.008 - -.004	1	0
-.004 - .000	5	6.25%
.000 - +.004	6	37.50%
+0.004 - +.008	1	75.00%
+0.008 - +.012	1	81.25%
+0.012 - +.016	2	81.25%
N =	16	100.00%
MEDIAN =	.0034 R/S	

Acceleration Patterns of Ramp Drivers

The velocity profiles of the merging vehicles from the loop ramp were plotted as a function of distance along the SCL. The averages are shown in Figure 5 for platoons of one, two, and three vehicles and for all combined. There does seem to be a series of steps. Unlike Figure 4, however, there is a decline in speed between successive accelerations rather than the hypothesized constant speed. This may be accounted for by the fact that drivers in this phase are attending to gap search, not speed control. A decline in speed may be expected for the duration of the gap search.

The number of these "steps" was counted for each ramp vehicle. It was possible to determine the percentage of gap search trials to merge. The data are presented below:

Trial	Distance (ft)	Proportion Merging
1	250	0.20
2	400	0.62
3	500	0.98

As indicated, 20 percent of the merges were made in one trial, 62 percent were made in two trials, and 98 percent were made in three trials. No more than three trials were observed in the data. If the speed of the ramp vehicle is known at the beginning of a gap search and the speed and volume on

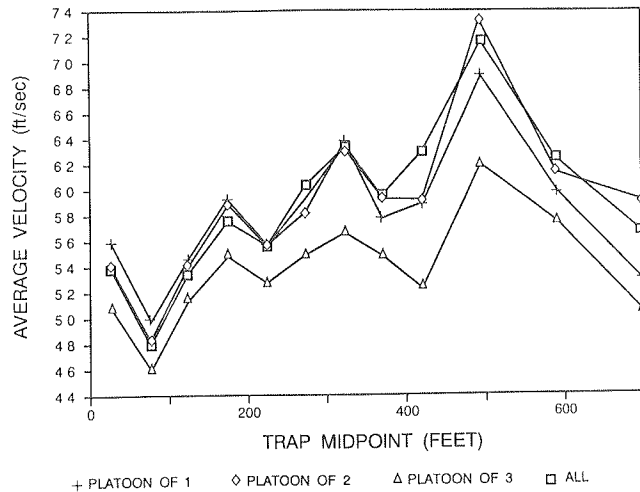


FIGURE 5 Observed velocity profiles: Eastbound Lake Avenue to southbound I-94 (Edens).

the freeway are known, using the Erlang distribution it is possible to calculate the probability that a gap will meet the angular velocity criterion during the first gap search. The probability of an acceptable gap for the subject SCL was 0.18, which is consistent with the observed proportion of 20 percent of first merges.

The data, although quite variable, are consistent with the model predictions. There are steps in acceleration followed by small decelerations that may be interpreted as incidental changes due to the driver attending to gap search. In addition, the probability of merging increases with successive trials. Almost all merges are made with three or fewer trials.

DISCUSSION

The results of the empirical analysis confirm the proposed driver behavior model. The angular velocity of the approaching vehicle is the criterion that drivers use to make a merge decision. The value of 0.004 rad/sec is an acceptable threshold value. Drivers judge gaps in sequence, increasing the probability of finding one acceptable by accelerating between suc-

cessive searches. The number of such searches depends on the speed-volume relations in the mainstream traffic, the acceleration capabilities of the ramp driver-vehicle combination, and the geometrics of the SCL.

In most geometric design situations, the perception of motion is based on relative or absolute angular velocity. Angular velocity determines the control response of the driver; it combines speed and position into a single metric. Furthermore, angular velocity explains traffic behavior under a variety of highway geometrics.

Although the data are consistent with the angular velocity model, the variability in the data is quite high. Measurement error and the enormous variability among drivers in the automobile-highway system account for the variability.

First, measurement error is significant in analyzing the video recordings. Each frame was projected on a video display terminal with a perspective grid overlay. A data analyst recorded when a subject vehicle crossed each of the distance markers, in sequence. Therefore, small time errors lead to large errors in calculating speed and acceleration. The farther down the ramp the vehicle proceeded, given perspective distortion, the greater the errors were likely to be. Not only were there individual errors in time-location, these errors propagated in estimating speed and acceleration. The longer a vehicle was on the SCL, the greater the errors were likely to be. These measurement errors add to the variability of calculated values such as angular velocity.

Second, the relative and absolute sources of speed and position information in the driving environment are very large. Although drivers use little second and third order information, these cues may reinforce expectations and responses. Moreover, angular velocity as the human measure of motion perception is on a continuum, that is, it is scaled according to the normal power law. Drivers need not operate on a conventional threshold criterion, but may scale the closure rate and select a gap acceptance criterion on an angular velocity well above the detection threshold. Furthermore, the system allows drivers to adopt other and mixed merge strategies. At one extreme, drivers learn that maximum acceleration on a SCL of reasonable length will always bring them to a relative velocity that will insure an acceptable gap. Drivers adopting such a strategy should have a speed profile that is continuous rather than discrete as the model suggests. Examination of individual speed traces shows such behavior. In the proposed model, it is hypothesized that the lag vehicle in a pair determines the merge decision. It is also possible to consider the lead vehicle. If a driver enters the SCL at a speed lower than the mainstream, the driver can track the angular velocity of the lead vehicle, accelerating to drive its angular velocity to threshold. At that point, regardless of separation, it would be safe to merge. Evaluating the lead vehicle angular velocities in the data suggests that some drivers operate in this fashion. None of the alternatives discussed is mutually exclusive and drivers are free to use any one or a combination.

Finally, the behavior of mainstream drivers is not passive. Drivers on the right lane of a freeway can detect and evaluate vehicles on the SCL. They can estimate their gap and determine whether it is sufficient for the merging driver to enter. They can then respond by slowing down to allow the merge or speeding up to prevent the merge. They can, given the uncertainty of ramp driver behavior, choose to change lanes to reduce the ambiguity. Such behaviors were observed.

Although there is a tendency to treat traffic flow mechanically, merging appears to be a highly dynamic human decision process and one that is often interactive.

All of these factors add to the variability in observed merge behavior. Although the variability is obvious, it is also clear that there is a consistent analytic process used by drivers in making a gap selection decision. This is the perceived angular velocity of the lag vehicle.

SPEED CHANGE LANE LENGTH REQUIREMENTS

Given the behavioral model, it is possible to develop an SCLL estimating procedure. As a starting point, one can begin with the following assumptions:

1. A modern vehicle with acceleration capabilities in the range of 0.1 to 0.2 *g*,
2. No environmental restrictions on driver visibility,
3. Freeway volumes in the range of 1,200 to 2,000 passenger cars/lane/hour (pcplph),
4. Speed of entry onto the SCL determined by the ramp connector design speed, and
5. The SCL as a parallel lane tangent to the freeway without grade or curvature.

As previously discussed, the merge process is composed of four sequential decision components, to which a fifth component is added:

1. An initial steering control component,
2. An acceleration component,
3. A gap search component,
4. A merge steering component, and
5. An abort component.

Associated with each of these components is a length. The sum of these lengths is the total speed change lane length.

The initial steering control component may be derived from empirical work on steering (4). This is a constant time, which for normal drivers is 1 sec. Given the control ramp design speed, the required length of this segment can be calculated.

The initial acceleration component is defined as a time period of 2 sec in which the driver accelerates at a maximum rate of 0.15 *g*. This time period is derived simply by examining the sight distance available to the driver once on the SCL. Given a structure upstream from the SCL, a minimum distance is required before the ramp driver can see approaching vehicles in the freeway lane. Given a normal range of ramp design speeds, 2 sec of acceleration will provide the merging driver an unobstructed view of oncoming freeway traffic.

Gap search is the third component. Drivers need to view oncoming freeway traffic for 0.25–0.5 sec to detect angular velocity of a lag vehicle. Given the relative velocity at the end of the acceleration component, the probability that a gap will produce an angular velocity less than threshold, 0.004 rad/sec, may be estimated using the Erlang distribution. If the closing angular velocity of the lag vehicle is greater than .004 rad/sec, the ramp driver would reject the gap, accelerate, and then evaluate the new gap. It is suggested that the driver uses such an iterative process. However, there is no way to

estimate the probabilities of each successive gap meeting the threshold criterion distribution using the Erlang.

Merge steering distance, the fourth component of the model, can also be computed. One way to approximate the total distance required for a ramp vehicle to accelerate to a speed such that the probability of finding an acceptable gap is 0.85 or greater is to rewrite Equation 1:

$$V_r = V_f \times (1 - [(w_r/k) \times V_f t_g^2]) \quad (2)$$

The term t_g is the 85th percentile gap length in time drawn from the Erlang for any given right-lane freeway volume, which, in turn, defines V_r as the average speed of the freeway traffic. Given V_r and knowing the ramp design speed, it is possible to calculate the distance required for the ramp vehicle to reach that speed assuming an acceleration of 0.15 g or 4.5 ft/sec². This length may be considered the gap search length.

Finally, the fifth length component is the abort distance. This is the length required for a driver who does not find a gap to decelerate and, if necessary, stop before running out of SCL. In essence, there is a length from the end of the SCL at which the terminus generates an angular velocity greater than 0.004 rad/sec. When a driver reaches this distance, he or she must either decelerate or make a forced merge. In any event, this length requires the driver to shift from gap search to an avoidance response. Equation 1 can also be used to estimate this length component. The ramp terminus is assumed to be a taper section. Hence the angular velocity of the taper diagonal is the cue for the driver. It is assumed in Equation 1 that the offset distance, k , is 4 ft. With the speeds derived from the above discussion and using $w_r = 0.004$ rad/sec, Equation 1 can readily be solved for the length, l . In essence, a simple additive model has been defined to derive a SCLL that will allow drivers to find an acceptable gap 85 percent of the time for any freeway volume. The actual value is conditional on the gap distribution on the freeway, the acceleration acceptable to drivers of the ramp vehicles, and the angular velocity criterion used by drivers to define an acceptable gap.

Using the model, the SCLL was calculated for design speeds of controlling curves of 30 to 45 mph and freeway volumes ranging from 1200 to 2000 pcplph. The results are shown in Figure 6. These lengths are those such that the probability of an acceptable gap is greater than 0.85.

As may be seen, the SCLL decreases with increasing ramp design speed. What is most noteworthy is that SCLL decreases with freeway volume. The reason for this is simply that the freeway speed declines with volume. The mean speeds used in this analysis were taken from the *Highway Capacity Manual* (8). This explains the very short SCLL needed as freeway volume approaches practical capacity. The total SCLL derived from the model varied little over the range of freeway volumes from 1200 to 1800 pcplph and ramp design speeds from 30 to 45 mph. At a freeway volume of 1200, a 50 percent increase in ramp design speed leads to only a 20 percent reduction in required SCLL. For design purposes, if one used the length defined by the 1200 pcplph curve, the SCLL needed for most currently used ramp design speeds is between 650 and 800 ft. It is interesting to note that accident rates on acceleration lanes tend to reach a minimum at a length of 700 ft (9).

These lengths are conservative. They assume far more mechanistic behavior on the part of drivers than is actually observed. If a driver carries out the gap search process on

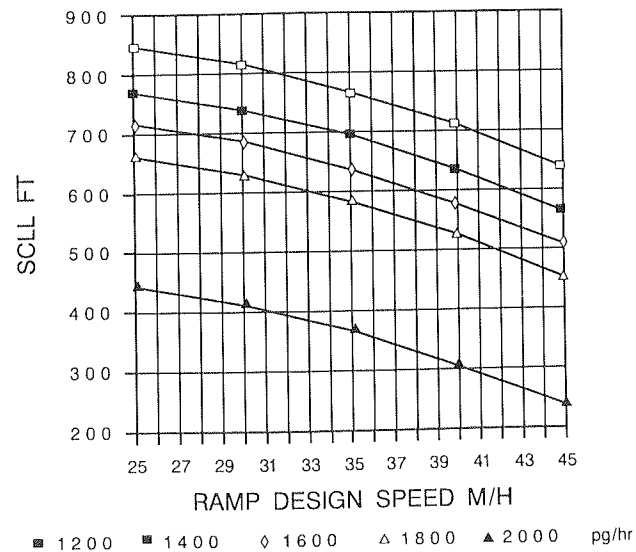


FIGURE 6 Speed change lane lengths by ramp design speed for 85th percentile gap acceptance.

each succeeding iteration, the relation between ramp driver and freeway gap is changed. More importantly, drivers can adjust speed and location relative to any gap and position themselves dynamically.

If the ramp connector is a tangent rather than a curve, the computation of the SCLL is simplified. If the angle of convergence between the ramp and SCL is small, that is, less than 3°, the steering control response required for transition is small and largely compensatory. It may be neglected in the model. In this case, the ramp becomes an acceleration component of the SCL. If drivers accelerate on the ramp at 0.1 to 0.2 g, their speed will be significantly higher at the point where they have a clear view of the freeway traffic than if on the loop connector, which precludes acceleration until physically steering onto the SCL. Therefore, the effective speed of the ramp vehicle at the time of first gap search is significantly higher in the diamond interchange case. Knowing the length of the connector and the normal acceleration used by drivers, it is possible to estimate the speed at the first gap search. The probability of finding an acceptable gap can then be calculated using the procedure discussed above.

The assumptions made in the above analysis are based on a descending ramp connecting with a flat tangent SCL. The analysis does not reflect the range of possible design situations, for example, an ascending ramp connector or an SCL with vertical curvature. What these design variations mainly influence is sight distance and vehicle acceleration. In the case of diamond type connectors, for example, descending ramps lead to higher speeds on entry to the SCL while ascending ramps lead to lower speeds. Adjusting the SCLL is straightforward if the grade and acceleration capabilities of the vehicles are known or are able to be estimated.

SUMMARY AND CONCLUSIONS

The present study attempted to place the freeway merging process in a driver behavior framework. It used an angular

velocity criterion for a driver's decision to merge. By defining the complete merge process as a five-step sequential task, the length of a parallel acceleration lane required for merging can be predicted.

The model was tested using two different types of ramp connectors, a curve and a tangent. Individual vehicles were tracked in time and distance from the end of the controlling curve to merge using high resolution video recording. This allowed the estimation of distance, speed, and acceleration of the ramp vehicle. It was possible to determine the angular velocity at the beginning of the merge maneuver by calculating the speed of the ramp vehicle at merge and that of a lagging freeway vehicle. Analysis of 102 vehicles in the two different design cases demonstrated a constant angular velocity at merge. This threshold value was consistent with previous research. Hence, the results of the research confirm that drivers do use angular velocity as a perceptual basis for the merge decision.

A procedure for estimating speed change lane length to insure acceptable gaps was developed using the model derived in this research. The procedure was applied under ideal design conditions using the worst case of a curved ramp connector to the SCL. The required SCLL was found to be independent of freeway volume over a range of 1200 to 2000 pcplph. The nominal SCLL to insure 85 percent or more merge opportunities for ramp drivers was no more than 800 ft.

The model also indicates clearly that a tangent ramp connector with a small angle of convergence leads to a more effective merge process. This is because the ramp becomes a part of the SCL on which drivers may accelerate prior to the gap search phase. The probability of an acceptable gap will be significantly higher than if the driver must steer from the ramp onto the SCL prior to acceleration, as is the case with a curved ramp connector.

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