Behavioral Model of Freeway Exiting

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A general model of diverging from a freeway to an exiting area was developed on the basis of purely behavioral considerations. The model proposes three sequential response elements that together define speed-change lane length. The first element is a criterion for a driver to diverge from the freeway on the basis of the angular velocity of the exit ramp gore (relative to the driver while approaching the exit in the right lane of the freeway). The second element is the distance required for drivers to complete a steering-control maneuver onto the speed-change lane. The third element is the distance at which drivers begin to brake in order to move from tracking the speed-change lane to tracking the curve of the exit ramp. A mathematical definition of each element was developed. These definitions allowed the prediction of each of the critical distances. The predicted distances were compared to observed exiting behavior on both curved and tangent exit ramps. The diverge, steering-control, and begin-braking distances observed on curved ramps were not statistically different from those predicted by the model. The begin-braking distance estimate for tangent exit ramps was not validated, probably because of instrumental errors in the field data analysis. The results indicate that the model is a reasonable representation of the exiting maneuver and provides a rational means for the design of exit speed-change lanes in terms of its ability to predict how far upstream from the wedge point the speed-change lane should begin, how far from the wedge point the steering-control maneuver ends, and how far from the wedge point the driver will initiate braking for a curved ramp.

To exit a freeway in a safe and efficient manner, the freeway driver must navigate either an off-ramp junction or a weaving area (*1*). Ramp junctions are critical areas on the freeway mainline in terms of highway safety. A basic freeway segment with the same length and volume as a section in a ramp junction will have fewer accidents, on average. This situation suggests that the current design procedure (*2*) used for these junctions does not optimally meet the requirements of drivers. A model based on the process the driver performs to exit the freeway was developed. Such a validated model can provide a more rational means for the design of speed-change lanes (SCLs) in off-ramp junctions.

EXITING PROCESS

To exit the freeway by an off-ramp junction, the driver must perform at least four tasks: (a) detecting the existence of the deceleration lane; (b) diverging from the mainline traffic stream onto the SCL, that is, initiating and performing a steering maneuver; (c) completing the steering maneuver and reorienting to tracking the tangent speed-change lane; and (d) introducing deceleration or steering-control response to the exit ramp's controlling point. The first step involves the sighting of the off-ramp junction from a distance as the driver travels on the freeway. The driver may become cognizant of the exit before it is visible because of informational signs or previous experience. This knowledge should lead the exiting driver to move to the right lane of the freeway. At some point, the exit lane will become visible, and for all practical purposes will be perceived as an expansion of the visual angle subtended by the additional lane. Given normal human visual acuity, this perception should occur long before the physical beginning of the SCL. Both signs and the lane addition may serve as alerting stimuli, but they do not provide a criterion for the initiation of the diverge maneuver.

When the vehicle is in linear motion on the freeway, the driver's field of view is in a continuous state of change. However, certain principles of motion perception are applicable. Roadway elements on which the driver focuses in the far distance appear stationary, whereas points in the near distance and off the line of regard appear to be in motion (*3*). These objects form a continuum, which has a transition distance at which specific points of focus change from their stationary state to a state of motion. This continuum is defined in terms of the angular velocity of elements within the visual field. The points of focus in the transition zone have an angular velocity at or near the driver's angular velocity threshold ω_t. An ω_t value of 0.004 rad/sec is applicable for most drivers (*4*). The distance at which this transition occurs is called the forward reference distance S, which is a function of speed. When elements at the driver's point of focus have an angular velocity ω that is less than the angular velocity threshold, the points appear stationary. However, when $\omega \geq \omega_t$, any point off the line of regard has a detectable component of lateral motion.

Detecting the Movement of the Deceleration Lane

If a driver plans to exit the freeway from a right-hand off-ramp junction, the driver's vehicle is assumed to be in the right-hand freeway lane for some distance before the SCL. As the driver approaches, the exit gore area elements will increase in angular velocity until they reach the driver's angular velocity threshold. Assuming that the driver's point of focus constantly varies, loci at the beginning of the exit ramp will eventually be scanned, especially if the driver plans to exit. At some point, the mouth of the exit ramp will attain a

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suprathreshold angular velocity (i.e., the ramp will be perceived to move laterally relative to the driver). Thus, the ramp appears to change from being a stationary locus to a moving one.

Diverge Criterion

Detection of the angular velocity of the points near the beginning of the exit ramp is hypothesized to be the cue for the exiting driver to diverge. This criterion initiates a steering-control maneuver onto the SCL. The driver is not responding to the magnitude of target size or target angle per se; rather, the driver is responding to the changes in target size and angle (i.e., angular velocity) caused by the forward motion of the car. This proposed diverse criterion will define the distance at which a driver will normally begin a steering change from freeway to SCL. If this hypothesis is valid, then it will define the minimum speed-change lane length (SCLL).

Steering-Control Response

On meeting the diverse criterion, the driver will introduce a steering input to move from the freeway to the SCL. This process requires a distance determined by the acceptable yaw velocity a driver will tolerate. Previous research (*5*) has evaluated this process and defined it explicitly. The chosen distance defines where a driver will be located on the SCL relative to the ramp connector. Obviously, this point should be reached before a driver is required to respond to the ramp geometry.

Brake Deceleration Criterion

Once drivers complete the transition to compensatory tracking of the SCL, they must prepare for a steering or braking response to the exit ramp geometry. For curved exit ramps, braking is hypothesized to be initiated when the inner edge of the controlling curve enters the forward reference distance S, with a braking angular velocity ω_b in the range of 0.1 to 0.3 rad/sec. The value of 0.1 rad/sec is used as the default value for ω_b because that is the value at which changes in angular acceleration approach a minimum (*3*), as shown in Figure 1. This distance (L_{B_c}) would represent the transition from compensatory to pursuit tracking.

For tangent exit ramps (e.g., ramps in diamond interchanges), braking is hypothesized to occur when the points near the ramp terminus reach the driver's angular velocity threshold ω_t at the forward reference distance. Examples of points near a ramp terminus are a traffic signal, a stop sign, or the rear of a vehicle at the end of the queue.

MATHEMATICAL MODEL FOR THE EXIT MANEUVER

On the basis of this description of the diverge process, the SCL was divided into three general longitudinal segments, as shown in Figure 2. The first segment is the steering-control

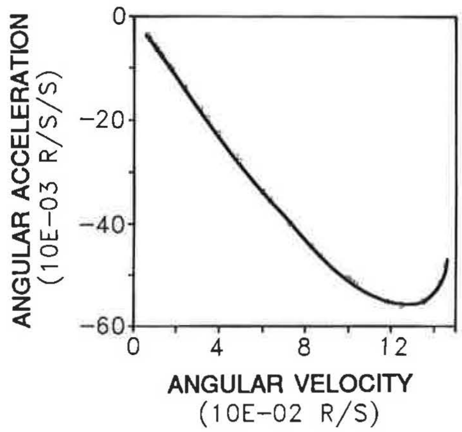

FIGURE 1 Angular acceleration versus angular velocity.

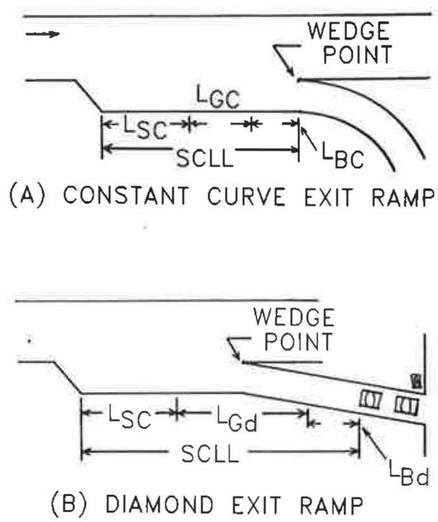

FIGURE 2 Three length components.

length L_{SC}. The second segment is the deceleration-in-gear length L_G, and the third segment is the braking distance L_B. The sum of the lengths of the three segments is equal to the desirable SCLL.

Divergence from Freeway to SCL

As a driver approaches an exit, the individual needs only momentarily view the exit gore, as shown in Figure 3. Point P is the location at which the exit gore will generate an angular velocity greater than the threshold, ω_t. This position is the criterion for the exiting driver to initiate the steering-control maneuver from the right freeway lane onto the SCL. The distance, L_{Det1}, of Point P from the wedge point is defined by the following equation:

$$L_{\text{Det1}} = \left[\frac{V_d}{\omega_t}(h_1 + y') - (h_1 + y')^2\right]^{1/2} - \frac{y'}{\tan\alpha} \qquad (1)$$

The variables in this equation are defined in Table 1. Equation 1 can be applied to off-ramp junctions with curved or

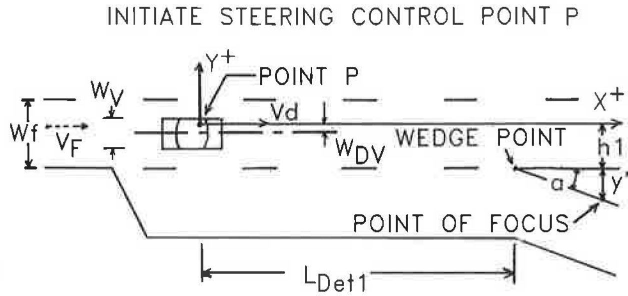

FIGURE 3 Initiate steering-control Point *P*.

diamond-type exit ramps. Distance y' is the area at the beginning of the exit ramp used by the exiting driver as the reference for the initial detection of the exit ramp motion. This distance must be long enough to provide adequate distance for the exiting maneuver to be made smoothly. Depending on ramp design, this reference point may vary considerably. Fortunately, as is obvious from Equation 1, the detection distance is not sensitive to y' over any reasonable range.

Steering-Control Zone Length

Given the point at which steering from the freeway begins, the distance required for the driver to complete the steering maneuver can be estimated. The work of McRuer et al. (5), which provides a completion time for normal drivers, was used. Knowing the freeway speed, the length required for a driver to complete the steering maneuver ending on the SCL can be calculated as

$$L_{SC} = V_d \times SC_t \quad (2)$$

where V_d is the vehicle divergence speed and SC_t is the steering-control maneuver time.

However, when the steering-control maneuver is complete, as shown by Point *T* in Figure 4, the driver approaching the exit ramp will probably require distance to reorient to the

TABLE 1 GLOSSARY

Variable	Definition	Units
a	Lateral distance or effective moving visual width of a vehicle, a≈6.	feet
α	Angle of divergence, for diamond type exit ramps, 2° ≤ α ≤ 5° (2). For curved exit ramps, equivalent divergence angle 2° ≤ α ≤ 3° (2).	degrees
d_{Bd}	Instantaneous braking deceleration for diamond ramp.	ft/s/s
d_G	Coasting deceleration, d_G≈2.	ft/s/s
e+f	Superelevation plus coefficient of friction, e+f≈0.2.	
h_1	Lateral distance from a midpoint between the driver's eyes to a point situated on the right edge of the rightmost freeway lane, $h_1 = (W_f/2) + W_{DV}$.	feet
h_2	Lateral distance from a point on the left edge of the deceleration lane to the midpoint between the driver's eyes in feet, $h_2 = (W_D/2) - W_{DV}$.	feet
L_B	Braking distance.	feet
L_{Bc}	Braking distance for curved off-ramps.	feet
L_{Bd}	Braking distance for diamond off-ramps.	feet
L_{Det1}	Distance from wedge point where driver initiates steering control response.	feet
L_{Det2}	Distance from wedge point where driver begins transition to ramp tracking.	feet
L_G	Deceleration-in-gear distance.	feet
L_{Gc}	Deceleration-in-gear distance for curved off-ramps.	feet
L_{Gd}	Deceleration-in-gear distance for diamond off-ramps.	feet
L_{SC}	Steering control distance, $L_{SC} = V_d * SC_t$.	feet
L_{SCmax}	Maximum steering control distance, $L_{SCmax} = L_{Det1} - L_{Det2}$	feet
R	Minimum radius of curvature, $R = V_c/[15(e+f)]$ (2)	feet

TABLE 1 (*continued on next page*)

TABLE 1 (*continued*)

Variable	Definition	Units
S	Longitudinal sight distance to a point on the inside curve.	feet
SC_t	Steering control maneuver time, SC_t=1.5 (5).	seconds
SCL	Speed change lane.	
SCLL	Speed change lane length.	feet
V_c	Controlling speed on curve.	mph
V_d	Vehicular divergence velocity, $V_d \approx V_f$.	ft/s
V_f	Vehicular freeway velocity.	ft/s
V_G	Vehicular coasting velocity.	ft/s
V_{Gfc}	Velocity of the driver at the end of the deceleration-in-gear phase. For short L_G, $V_{Gfc} \approx V_d$. Exact equation: V_{Gfc}=SQRT(V_d^2 - 2(L_{GC})d_G).	ft/s
V_{Gfd}	Velocity of the driver at the end of the deceleration-in-gear length.	ft/s
ω_b	Braking angular velocity, $\omega_b = V_{Gfc}*y/(S^2+y^2)$.	rads/s
W_D	Width of deceleration lane, W_D=12.	feet
W_{DV}	Lateral distance from the driver's eyes to the longitudinal centerline of the vehicle, $W_{DV} \approx 1.5$	feet
W_f	Width of an Interstate freeway lane, W_f=12.	feet
ω_t	Angular velocity threshold, $\omega_t \approx 0.004$ (4).	rads/s
W_v	Width of a passenger car, W_v=7 (2).	feet
y'	Lateral distance from a point located on the right edge of the rightmost freeway lane to a point on the left edge of the exit ramp in feet, y'≈8.	feet

environment that will now be in rectilinear motion relative to the SCL. Point *T* also represents the location at which the driver may be expected to begin deceleration in gear. The end points of the L_{SC} segment are Points *P* and *T*; these points represent the place the driver initiates the steering-control maneuver and the point at which the maneuver is complete, as shown in Figures 3 and 4.

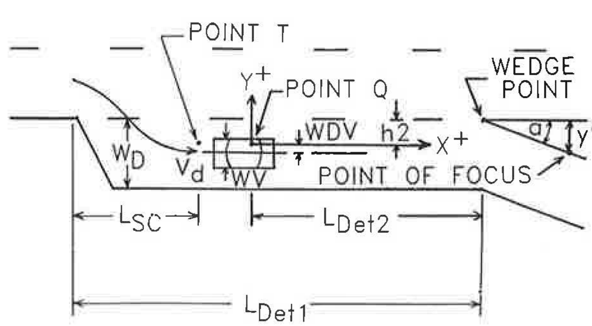

FIGURE 4 Complete steering-control Point *T*.

Confirmation of the Appropriateness of the First Detection Distance and the Steering-Control Length

Point *Q* in Figure 4 is the place at which the driver detects the lateral motion of the point of focus while on the SCL lane (not on the freeway). It is hypothesized that when the point of focus on the left edge of the exit ramp near the wedge point attains an angular velocity approximately equal to 0.004 rad/sec (*4*) and vehicle velocity and lateral position are known, the longitudinal location of Point *Q* can be derived. If coasting distance is provided after Point *Q*, Point *Q* will demarcate that portion of the coasting length after which the driver will anticipate a control response. The longitudinal distance between Point *Q* and the wedge point is labeled L_{Det2}. The second detection distance is derived from the following equation:

$$L_{Det2} = \left[\frac{V_d}{\omega_t}(y' - h_2) - (y' - h_2)^2\right]^{1/2} - \frac{y'}{\tan\alpha} \quad (3)$$

Equation 3 may also be used for off-ramp junctions with either curved or diamond ramp types. The same precautions and considerations taken in the application of Equation 1 are to be used with Equation 3.

Once the positions of Points P and Q are obtained with respect to the wedge point, the maximum length of the steering-control zone is derived by subtracting the longitudinal distance between Point Q and the wedge point L_{Det_2} from the longitudinal distance between Point P and the wedge point L_{Det_1}. This maximum steering-control distance is the distance between the point at which the driver detects the initial motion of the off-ramp from the rightmost freeway lane and the place where the driver detects the initial motion of the off-ramp from the SCL. The equation for the maximum steering-control length is as follows:

$$L_{\mathrm{SCmax}} = L_{\mathrm{Det1}} = L_{\mathrm{Det2}} \tag{4}$$

Equations 3 and 4 are not essential to the model and are presented only to confirm that L_{Det_1} and L_{SC} occur before the point (Point Q) at which the driver detects the initial motion of the off-ramp while on the SCL.

Braking Distance in Response to Ramp Curvature

The longitudinal location of Point R from the controlling point depends on whether the exit ramp is curved (e.g., ramps in cloverleaf interchanges) or straight (e.g., ramps in diamond interchanges), as shown in Figure 5. For the curved exit ramp, Point R represents the beginning of a transitional period in the driver's navigation of the ramp; the driver is switching from compensatory tracking of the SCL to pursuit tracking of the curve. Approaching the curve, the driver initially scans points on the inner edge of the curve at the forward reference distance (S). This sight distance is a function of the driver's speed and lateral distance of the lane edge (*6*). When this focal point on the inner edge of the curve reaches an angular velocity in excess of 0.1 rad/sec, it is hypothesized that the driver will begin braking as part of the transition to pursuit tracking of the ramp curvature. This point, called the driver's braking angular velocity threshold ω_b, occurs at distance L_{B_c} from the wedge point. The equation for deriving L_{B_c} is as follows:

$$L_{B_c} = S - \left\{R^2 - \left[\left(\frac{-V_{Gfc}^2}{4\omega_b^2} - S^2\right)^{1/2} - \frac{V_{Gfc}}{2\omega_b} + R + W_D - h_2\right]\right\}^{1/2} \tag{5}$$

In summary, L_{B_c} is the distance from Point R to the wedge point, as shown in Figure 5. Point R denotes the driver's position when the point of focus on the inner edge of the curved exit ramp at a certain sight distance attains the driver's braking angular velocity threshold; Point R is where the driver will initiate braking with respect to the controlling point, Point S.

Braking in Response to a Ramp Terminus

In the case of diamond exit ramps, the diamond junction control point is usually near the ramp terminus (e.g., traffic

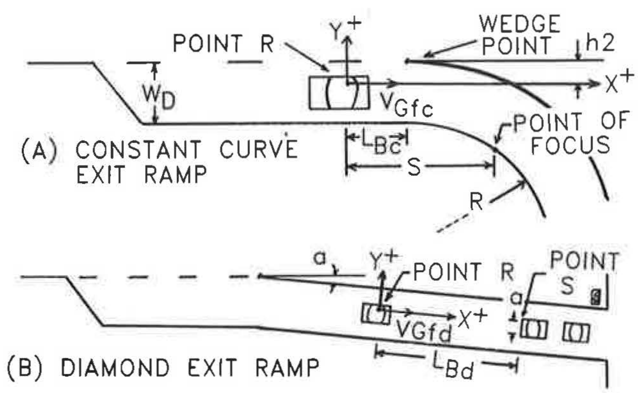

FIGURE 5 Begin-braking deceleration Point *R*.

signal, stop sign, or end of a queue of vehicles). In this case, braking deceleration is hypothesized to begin at Point R when critical elements at the ramp terminus, such as Point S, reach the angular velocity threshold (ω_t) as shown in Figure 5. The distance L_{B_d}, required to stop at the junction point on a diamond ramp can be calculated from the following equation:

$$L_{B_d} = \left(\frac{V_{Gfd}a}{\omega_t} - a^2\right)^{1/2} \tag{6}$$

L_{B_d} is the distance between Points R and S.

It is further hypothesized that the driver will decelerate at a rate sufficient to maintain the angular velocity of the critical elements at threshold. This braking deceleration d_{B_d} is essentially a function of the speed of the driver at the end of the deceleration-in-gear phase V_{Gfd} and length L_{Bd}. The following equation computes the instantaneous braking deceleration required to satisfy this criterion:

$$d_{Bd} = \frac{\omega_t V_{Gfd}}{2a} L_{Bd} \tag{7}$$

Coasting Deceleration Until Ramp Angular Velocity Enters Action Field

Once the appropriate L_{SC} and L_B distances have been determined, the length of the SCL is known, assuming that no coasting length is necessary. The coasting segment is the distance that is not required for steering control and braking; the segment provides time for the driver to reorient to rectilinear motion after completing the steering maneuver and to anticipate the required steering-control and braking response for the exit ramp. For curved and diamond exit ramps, the equation for the distances needed for deceleration in gear, L_{G_c} and L_{G_d}, is as follows:

$$L_{G_c} = L_{G_d} = 50 \text{ to } 100 \text{ ft} \tag{8}$$

Total SCLL

After the three component distances of the SCL have been individually determined for a curved or diamond-type exit ramp, the total length of the SCLL is known. For off-ramp junctions with curved exit ramps,

$$\mathrm{SCLL} = L_{SC} + L_{G_c} + L_{B_c} \quad (9)$$

For ramp junctions with diamond-type exit ramps,

$$\mathrm{SCLL} = L_{SC} + L_{G_d} + L_{B_d} \quad (10)$$

The control point, Point S, is determined by the highway design engineer on the basis of such factors as the amount of right-of-way available, interchange type, radius of curvature, divergence angle, exit ramp volume, and ramp vehicle storage. Curved exit ramps could be designed without a controlling curve, so that the control point becomes the ramp terminus. In such a case, no braking zone would be given near the freeway; drivers would coast most of the way on the ramp and then brake near the terminus. Current practice is to have the driver brake twice, once just before the curve and the second time near the terminus. Diamond-type exit ramps should be designed so that their lengths place the braking that occurs near the terminus far enough away from the freeway.

TEST OF THE EXIT MODEL

Procedure

The driver behavioral model of diverging was evaluated from data collected in an NCHRP study (Reilly et al., unpublished data). The evaluation of the model tests the model's ability to estimate (a) the distance L_{Det_1}, from the wedge point at which the driver initiates a steering-control maneuver; (b) the length L_{SC}, of the steering-control distance; and (c) braking distance L_B. To determine the actual steering-control distances in the field, the divergence speed of the vehicle V_d and the time t_{SC} taken to complete the steering-control maneuver were measured. The braking distance derived from the data was calculated from the average speed during braking V_b and the duration of the braking t_b. Once these three distances were determined, they were compared to the distances produced by the model.

Sites

The seven off-ramp sites used in the confirmation of the model are listed in Table 2. Three sites are in Arizona, three in California, and one in Illinois. Five of the seven sites have diamond-type ramps, and the remaining two have curved exit ramps. Six sites have a taper-type SCL, and one has a parallel-type SCL.

Data Reduction and Analysis

Typically, data were collected at the various sites using one videocamera mounted on an overpass directly overlooking the off-ramp junction. In some rare cases (i.e., unique site characteristics), two video cameras were used, one placed on top of a vehicle to achieve the optimum camera angle. The

TABLE 2 EXIT RAMP SITES

Site	Location[a]	Route[a]	Ramp Type[a]	SCL Type[a]
1.	NB Ajo Way Exit Tucson, Arizona	I-19	Diamond	Taper
2.	NB Atlantic Blvd. Exit Los Angeles, California	I-5	Diamond	Taper
3.	EB Hotel Circle Exit San Diego, California	I-8	Curved	Taper
4.	NB Quince St. Exit San Diego, California	SR-163	Diamond	Taper
5.	EB Rural Rd. Exit Phoenix, Arizona	SR-360	Diamond	Taper
6.	EB Alma School Rd. Exit Phoenix, Arizona	SR-360	Diamond	Taper
7.	NB Deerfield Rd. Exit Chicago, Illinois	RT-41 Edens	Curved	Parallel

[a]Source: Reilly et al., NCHRP 3-35, unpublished data.

right shoulder and the rightmost edge of the exit ramp were delineated by fluorescent orange traffic cones placed at 50- or 100-ft intervals, depending on the length of the site and the angle of divergence or the curvature. The cones extended from a point in front of the beginning of the taper to the point on the exit ramp where the controlling curve could first be seen. For diamond-type off-ramps, the cones were extended down the exit ramp as far as possible given the range of the camera lens.

The data were processed by viewing the videotapes and logging the time displayed on the tape when the front or rear tires, depending on the camera orientation, of selected exiting vehicles reached each cone along the length under observation. Also noted in the processing of the data were the type of vehicle exiting the freeway (i.e., passenger car, truck, bus, or recreational vehicle), the point at which the driver initiated the steering-control maneuver, the point at which the exiting driver completed the steering-control maneuver, and the position of the vehicle at which the driver initiated braking. Braking was observed on nearly all exit ramps; at certain ramps in diamond interchanges, the camera could not track the exiting vehicle to the ramp terminus.

These data were coded into a microcomputer spreadsheet program and analyzed. Because the time at which the vehicle reached a cone and the trap length (distance between two cones) were known, vehicular speed and acceleration profiles along the distance travelled were computed and reproduced graphically.

RESULTS

The driver behavioral model of diverging was validated by examining three different aspects: (a) its estimation of the distance from the wedge point at which exiting drivers initiate a steering-control response, (b) its ability to set the boundaries of the segment where drivers perform their steering-control maneuvers, and (c) its potential for estimating the places where drivers initiate a braking response to safely navigate critical curves for curved exit ramps or stop at ramp termini for diamond exit ramps.

The L_{Det_1} distances from field data and from the model are presented in Table 3. The average difference between model and field ranged from −57 to 86 ft. A hypothesis test using the Student *t*-statistic was performed. At the 5 percent level of significance, the hypothesis that there is no difference between average model L_{Det_1} value and field L_{Det_1} value could not be rejected. A 5 percent level of significance was selected for use throughout this study because of the nature of the traffic data and because the resulting confidence intervals were acceptable.

The estimated and observed steering-control distances were compared. The results are presented in Table 4. A Student *t*-test of the differences between the predicted and observed distances indicated no significant differences at the 5 percent level. Furthermore, the $L_{\mathrm{SC}_{\max}}$ value (for ω_t = 0.004 rad/sec) was greater than the 95 percent confidence interval of measured L_{SC} in all cases. The results confirmed previous research (*5*).

Applying Equation 5 resulted in estimated braking distances before the wedge point for curved exit ramps. Input variables ω_b, S, h_2, and W_D in Equation 5 were assigned their default values. Variable V_{Gfc} was estimated by setting it equal to the average deceleration velocity V_G of Site 3 or by reading it directly from the velocity-distance profile of Site 7. Variable R was approximated by setting it equal to the average braking velocity V_b of Site 3 or by setting it equal to the minimum speed observed on the exit ramp in the velocity-distance profile of Site 7. The results of the comparison between the observed and predicted braking distances from the beginning of the curve are presented in Table 5. The lack of variability in the field data allowed no statistical tests of the significance of the observed differences. However, the predicted values were consistent with the observed values.

Diamond-type exit ramp data were collected at two sites. Use of Equations 6 and 7 produced an approximation of the braking distances required for the driver to stop at the critical point. The critical point was assumed to be the rear end of a passenger car. In Equation 6, the input variables ω_t and a were set at 0.004 rad/sec and 6 ft, respectively. Variable V_{Gfd} was set equal to the average braking speed measured at Sites 2 and 4. After braking distance L_{B_d} was calculated from Equation 6, it was input into Equation 7 to derive d_{B_d}. The model's braking distances and their corresponding field-derived braking distances were compared, and the results are presented in Table 6. The differences between observed and

TABLE 3 BEGIN-STEERING-CONTROL POINT FROM WEDGE POINT VALIDATION

Site	n	Observed (Average)	Predicted	Difference (feet)
1.	47	300	310	10
4.	65	211	297	86
5.	65	268	325	57
6.	124	398	341	-57
7.	11	350	293	-57
			Average difference	= 7 %

TABLE 4 STEERING-CONTROL DISTANCE VALIDATION

Site	n	Observed (Average)	Predicted	Difference (feet)
1.	47	98	113	15
2.	30	58	87	29
3.	54	58	80	22
4.	65	79	107	28
5.	65	135	119	-16
6.	124	202	126	-76
7.	11	175	106	-69
Average difference = -9 %				

TABLE 5 COMPARISON BETWEEN OBSERVED AND PREDICTED BRAKING DISTANCES FOR CURVED RAMPS

Site	n	Observed (Average)	Predicted	Difference (feet)
3	54	100	64	- 7
7	11	25	0	-15

TABLE 6 COMPARISON BETWEEN OBSERVED AND PREDICTED BRAKING DISTANCES FOR DIAMOND RAMPS

Site	n	Observed (Average) (feet)	Predicted (feet) ω_t=0.004 radians/second
2	30	66	253
4	65	169	306

predicted distances were significant at the 5 percent level. Thus, the braking distance model could not be called a correct representation of driver behavior on diamond ramps.

DISCUSSION OF RESULTS

General Remarks and Assumptions

The significant differences between the observed and predicted begin-braking distances for the diamond ramp were surprising. The basic model for this component derives directly from standard car-following theory, which has been extensively validated by empirical methods. The model is a simple closed-loop one based on the principle that the driver maintains the angular velocity of the overtaken vehicle at threshold. The speed profile and, hence, the instantaneous deceleration, can be directly derived by means of Equation 7.

The begin-braking distance had to be derived from the time and distance plots. The speed was calculated by estimating the time spent in each trap. Thus, speed was simply the time spent in a known length of road. Any changes in speed from trap to trap were used to estimate acceleration. With the acceleration and knowing the terminus of the ramp, an estimate of where the deceleration began was derived as a basis of testing the model. However, given that the estimated speed at the beginning of this deceleration period was derived from the average speed from the coasting zone, the estimate is unreliable. Similarly, acceleration derived from video recordings is notoriously unreliable. The empirical data are far too unreliable to be a direct test of the model. A direct test of the model would require simply a measure of the distance at which drivers initiate deceleration. Practically, all that is needed is a measure of the distance from the ramp terminus to the position where brake lights first occur. If the instantaneous deceleration could be measured over this distance, an even more complete test of the model would be possible. Passive measurements of traffic, such as by video recording, make this practically impossible.

With the exception of the braking distance for diamond off-ramps, the proposed model provides a consistent description of the diverge process used by drivers. The validation is reasonable but not robust. One of the problems of testing a rather complex model such as that proposed in a free-field environment is the lack of control over the variables critical to the model. For example, the model is essentially mechanistic and takes no account of higher-order cognitive behavior. In the test sites used, most of the drivers observed were probably regular users. These drivers have learned both the geometric properties of the interchange and the traffic. Thus, they have a set of overlearned response tendencies. This tendency should lead to major modifications in diverging behavior.

Also, neither of the curved ramps had constant radii; they were spirals. In this analysis, an equivalent constant radius was used to approximate the curve. This situation probably explains why the begin-braking actions occurred at angular velocities below 0.1 rad/sec.

In the figures, the model assumed a parallel-type SCL. However, a taper-type SCL can also be assumed, provided that the taper width when the driver is at Point P is 12 ft. Moreover, any deceleration lane length provided before Point P is not necessary. Savings in pavement costs could be obtained if future SCLs do not have pavement before Point P.

An implicit assumption of the model is that the driver carries out one decision-and-control operation at a time throughout the exiting process. This assumption is a fairly standard interpretation of optimum human guidance and control. Highways designed so that the driver can sequence the tasks and thereby minimize control errors are recommended. Rapid alternation among tasks (e.g., braking and steering), not uncommon in highway system operation, may be considered a symptom of poor design.

Another assumption is that the fluorescent cones used in the data collection process did not contaminate driver behavior. The cones were placed as far away from the lane of travel as possible to prevent the drivers from using them as guidance markers. This process was especially needed for the initial detection distance, where the cones were well beyond the decision point and off the far shoulder of the SCL.

Finally, the model assumed that each vehicle measured was independent, and no other vehicles were on the SCL at the same time. In most cases, especially in peak hours, this is rarely the case. When a number of vehicles are on the SCL and exit ramp, the driver must respond to the presence of the vehicles ahead as well as to the geometry. However, in the data used in the analysis, the vehicles were independent.

Given these limitations, the model appears to be a reasonable representation of the diverge and exiting process. The model is most applicable to drivers in unfamiliar environments in low-to-moderate ramp volume situations. In this sense, the model is conservative. The model probably defines the longest SCL requirements for normal passenger car driving. Although the model was developed assuming an SCL and ramp without grade, it can easily be adapted to explain the response to those conditions. In general, the model provides a rational means for the design of freeway exits. A step-by-step procedure of the model's application to geometric exit design is given in the following section.

Coasting Distance

Historically, rates of deceleration have been observed on SCLs, and their coasting phase has been built into SCL design standards (*2*). However, coasting is hypothesized to reflect driver reorientation to compensatory tracking after completion of the steering maneuver and to the angular velocity of the geometric elements of the exit ramp. At the end of the steering-control phase, the angular velocity of the ramp elements have decreased significantly and have changed relative to the driver. The motion detection of the exit ramp for a driver on the SCL may serve as an anticipatory cue for a speed or steering control change for entry onto the exit ramp. One response on the SCL is to coast, that is, to decelerate the vehicle while in gear.

AASHTO policy is to provide a length of ramp for coasting, so that the exiting vehicle can decelerate to exit ramp speed (*2*). The model provides a coasting distance so that the driver has time to recover from the steering maneuver onto the SCL and anticipate an appropriate response to the exit ramp geometry. The underlying issue is really one of the time and distance the driver may require to move from the steering control to compensatory tracking of the SCL, before any control response required by the ramp. Obviously, the length of the SCL must be at least as long as L_{SC}, or the two tasks overlap. In this case, the driver will probably decelerate on the freeway rather than on the SCL. On one curved exit ramp with an SCL shorter than L_{SC}, exiting drivers used the freeway lane to decelerate. In essence, they used sufficient distance to move from compensatory to pursuit tracking of the ramp curve.

The length of the SCL after completion of the steering-control maneuver appears to depend on three factors. One is the variability of the angular velocity threshold and the steering-control length. Angular velocity threshold varies by driver. Moreover, the angular velocity threshold has a log normal distribution with a median value of 0.004 rad/sec (*4*). If $\omega_t < 0.004$ rad/sec, drivers will diverge later than predicted; if $\omega_t > 0.004$ rad/sec, drivers will diverge earlier. Steering-control maneuver time also varies by driver. If $SC_t > 1.5$ sec, L_{SC} will be greater than the model's predicted value; if $SC_t < 1.5$ sec, L_{SC} will be less, assuming constant divergence speed in both cases.

The second factor is the time required by the driver to reorient visually to the critical elements of the ramp diverge area after completing the steering control. The driver must adjust to tracking the SCL and attend to the ramp curvature. This adjustment should not require more than 0.5 to 1.0 sec or, normally, 50 to 100 ft.

The third factor is the ramp curvature, or the effective ramp terminus in the case of the tangent off-ramp. The angular velocity of the curve increases nonlinearly as the distance to the beginning of the curve decreases. This action is a function of speed and radius of curvature. The smaller the radius, the greater will be the distance at which angular velocity will reach the pursuit-tracking magnitude. This distance should determine the begin-braking point. Ideally, the SCLL should be long enough to minimize the deceleration required for the driver to negotiate the curve (i.e., an angular velocity below 0.1 to 0.3 rad/sec). However, if the SCL is long enough to meet the diverge criterion, it will always be long enough to meet the curve-tracking criterion. The model clearly suggests that the distance at which divergence from the freeway begins is the critical determinant of SCLL.

Procedure for Determining SCLL for Curved Off-Ramps

To determine the appropriate length of an SCL that has an exit ramp of constant curvature, the following procedure must be performed:

1. Determine the distance from the wedge point at which the driver, while in the rightmost freeway lane, initiates a steering maneuver onto the SCL (i.e., apply Equation 1).
2. Calculate L_{SC} by using Equation 2.
3. Derive the distance from the wedge point to the place where the driver initiates braking by using Equation 5. To solve Equation 5, perform the following steps:
   —Determine R. If R is not known, assume the controlling speed of the curve, $R = V_c^2/[15 * (e + f)]$.
   —Estimate V_{Gfc} for minimum coasting distance, $V_{Gfc} \approx V_d$.
   —Estimate S using the V_{Gfc} value from previous step, $S = 3.41 * V_{Gfc}$, or consult Figure 6 (*6*).

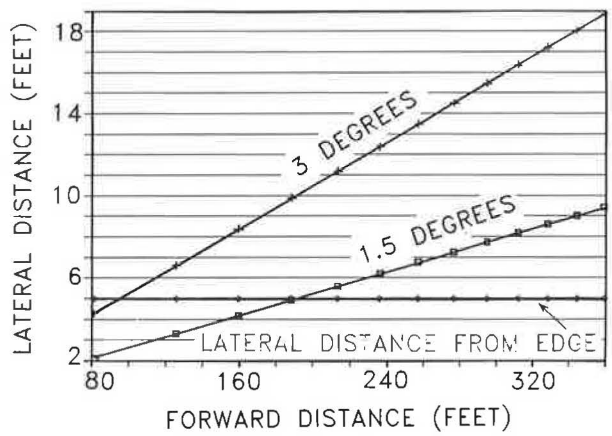

FIGURE 6 RD reference point within visual field.

   —Use Equation 5 to obtain a value for L_{Bc}.
   If $L_{Det2} < L_{Bc}$, a spiral curve, rather than a curve of constant radius, should probably be used. If the exact values for V_{Gfc}, S, and R are known, Table 7 can be used instead of Equation 5.
4. Compute the coasting distance by using Equation 8.
5. Determine the SCLL from Equation 9.

Procedure for Determining SCLL for Tangent Off-Ramps

In order to calculate the SCLL required for diamond-type exit ramps, the following procedure must be completed:

TABLE 7 BRAKING DISTANCES FOR CONSTANT-RADIUS EXIT RAMPS

V_{Gfc} (mph)	S (feet)	15	20	25	30	35	45	V_c (mph)
		75	133	208	300	408	675	R (feet)
30	150	79[a]	45	13	0 [b]	-	-	
35	175	101	63	27	0	0 [b]	-	
40	200	125	82	43	6	0	-	
45	225	[c]	102	60	20	0	0 [b]	
50	250		124	78	35	0	0	
55	275		146	97	51	6	0	
60	300		169	116	67	21	0	
65	325		192	136	85	35	0	
70	350		217	157	103	51	0	

[a]Note: foveal field = 3 degrees
ω_b = 0.1 rad/sec
e + f = 0.2
h_2 = 4.5 feet
W_D = 12 feet

[b]No braking occurs before the wedge point and after Point Q. If braking is initiated, then it must happen on the exit ramp.

[c]$y > R + W_D - h_2$

1. Perform Steps 1 and 2 as described for the curved off-ramp.
2. Calculate the required braking distance using Equation 6. Braking distances are also shown in Table 8, assuming default values.
3. Derive the necessary deceleration-in-gear distance by means of Equation 8 after assuming an average coasting deceleration d_G.
4. Determine the SCLL using Equation 10.

SCLL Needed for Curved Off-Ramps of Various Types

Many curved exit ramps do not have curves of constant radii for long ramps. These curves with varying radii are transitory curves; that is, they begin at the tangent part of the SCL (infinite radius), then change to a spiral curve (varying from infinite radius to the minimum radius), and then to a constant curve at the minimum radius R_{min}, for a short distance as shown in Figure 7. In these curves of varying radii, the coasting length extends past the wedge point and onto the exit ramp. If R_{min} is great enough, the coasting length will end the way it ends at a diamond-type exit ramp, because braking will not be required in advance of R_{min}. If R_{min} is small, the driver will brake before entering the R_{min} arc. This initial braking point puts the driver somewhere past the wedge point and on the spiral curve. In such a case, the driver is no longer in rectilinear motion. When the driver is in curvilinear motion, a different set of equations must be considered in determining at what distance the driver's point of focus reaches the braking angular velocity threshold. Briefly, for the model to handle exit ramps with varying radii, Equation 5 must be modified to reflect the curvilinear motion, and an equation to locate points on the inner edge of the curve in terms of the x,y coordinate system must also be incorporated.

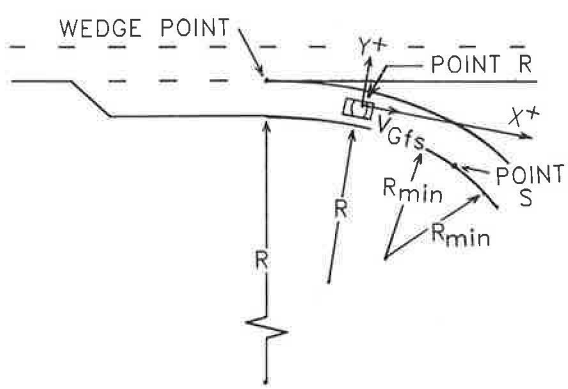

FIGURE 7 Layout of a spiral-curve exit ramp.

The highway design engineer should consider the use of a transition curve only after applying the model for constant curve ramps. If $L_{Det_2} < L_{B_c}$, a transitory curve must be considered, because the SCL is not providing enough length.

SUMMARY AND CONCLUSION

The behavioral model of diverging presents a different way of defining the deceleration length required in the design of freeway SCLs in off-ramp junctions. Such a model offers a rational basis for design rather than the usual empirical means based on vehicle characteristics. The human factors model provides insights into traffic operations in off-ramp junctions beyond those derived from aggregate analysis of vehicle behavior. The results of the model's validation tests using video recordings of traffic on seven off-ramp sites were consistent with the model's estimates of the initial diverge distance L_{Det_1}, the steering-control length L_{SC}, and the braking distance L_{B_c} for curved off-ramps.

Five sites were used in the validation of L_{Det_1}. Seven sites were used to determine the longitudinal distance drivers needed to perform their steering-control maneuver onto the SCL. The comparison between the model's $L_{SC_{max}}$, assuming that ω_t = 0.004 rad/sec, and the measured L_{SC} revealed that $L_{SC_{max}}$ was greater than L_{SC} in all cases. The $L_{SC_{max}}$ value is useful in preventing the overdesigning the SCLL. If L_{SC} is made greater than $L_{SC_{max}}$, drivers will use the extra length for acceleration purposes, that is, use the deceleration lane as a freeway lane.

TABLE 8 BRAKING DECELERATION AND DISTANCE REQUIRED FOR STOPS ON DIAMOND EXIT RAMPS

	Instantaneous measures[a]						Average measures[b]	
	ω_t=0.010		ω_t=0.004		ω_t=0.001			
V_{Gfd} (mph)	d_{Bd} (ft/s/s)	L_{Bd} (ft)	d_{Bd} (ft/s/s)	L_{Bd} (ft)	d_{Bd} (ft/s/s)	L_{Bd} (ft)	Stopping Velocity (mph)	Stopping Deceleration (ft/s/s)
30	6.0	162	3.8	257	1.9	514	15	1.5
40	9.2	188	5.8	297	2.9	593	20	2.4
50	12.8	210	8.1	332	4.1	663	25	3.3
60	16.9	230	10.7	363	5.3	727	30	4.3
70	21.2	248	13.4	392	6.7	785	35	5.4

[a] a = 6 feet.

[b] a = 6 feet, ω_t = 0.004 radians per second.

The validation tests on the braking lengths for curved and diamond-type exit ramps were carried out using data from two curved and two diamond ramps. For the curved ramps, the field data were consistent with the model estimates; the differences were 7 and 15 ft. For the two diamond ramps, observed lengths were significantly different from the model prediction. These differences appeared to be caused by the inability to determine where braking actually began in the field studies.

A topic of further investigation involves diamond off-ramp termini that do not end at intersections; they terminate at merge or weaving sections on frontage roads and streets. In these cases, the exit ramp drivers do not brake to a stop; rather, they brake to match the speed of the vehicle preceding them or traffic on the frontage road or street.

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REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
2. *A Policy on Geometric Design of Highways and Streets 1984.* AASHTO, Washington, D.C., 1984.
3. D. A. Gordon and R. M. Michaels. Static and Dynamic Visual Fields in Vehicular Guidance. In *Highway Research Record 84*, HRB, National Research Council, Washington, D.C., 1965, pp. 1–15.
4. R. M. Michaels and J. Fazio. Driver Behavior Model of Merging. In *Transportation Research Record 1213*, TRB, National Research Council, Washington, D.C., 1989, pp. 4–10.
5. D. T. McRuer and R. H. Klein. *Automobile Controllability—Driver Response for Steering Control*, Reports DOT-HS-801406 and 801407, NHTSA, U.S. Department of Transportation, 1975.
6. R. M. Michaels and L. W. Cozan. Perceptual and Field Factors Causing Lateral Displacement. In *Highway Research Record 25*, HRB, National Research Council, Washington, D.C., 1963, pp. 1–13.

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