COMPARISON STUDY BY COMPUTER SIMULATION OF THE DRIVER'S VISUAL PART-TASK DURING LEFT AND RIGHT FREEWAY MERGING MANEUVERS

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The purpose of this study was to determine whether there is a quantifiable difference in the mechanical elements of the driver's visual part-tasks associated with left on-ramp merges as compared with mirror-image right on-ramp merges. The visual part-task is hindered by the physical limitations of gross movements of the head due to the muscular structure of the human body. Gross horizontal eye movement, or the angular movement of the visual centerline of regard, is consequently constrained. Horizontal and vertical vision is further restricted because of freeway and ramp geometry and obstructions resulting from the physical dimensions of vehicle. A general computer model was developed to simulate dynamically the visual part-task associated with the merging maneuvers. For both left and right merging, there were 6 geometric configurations considered. The results as obtained from the simulation runs clearly showed that there is a significant difference in the ramp driver's ability to see the vehicles traveling on the freeway when he is merging from the left and when he is merging from the right. In addition, the closer a driver is to the ramp nose in the dilemma zone before he is allowed to see the freeway, the less will be the chance that he can see the critical freeway vehicle before he merges. The model can be used not only to test alternative ramp designs but also to analyze individual on-ramps for visual quality.

•THE NORMAL design convention in this country is to have ramp traffic merge with freeway traffic from the right. Sometimes, however, highway engineers are forced to design left entrances because of right-of-way restrictions and the desire for interchange compactness in horizontal and vertical interchanges. Whatever the reasons, safety must be a consideration when the various determinants of interchange design are weighed. The driver's vision and ability to merge safely may be adversely affected by this type of freeway geometry.

This study describes the development and results of a computer simulation model that examines and compares quality of vision from automobiles that are traveling on left ramps and right ramps to determine whether left on-ramps do, in fact, present problems to drivers while merging.

BASIC CONSIDERATIONS

Mechanical functions associated with visual dynamics are referred to as the driver's visual part-task. The simulation model developed in the present study investigates the visual part-task of a ramp driver as he attempts to merge into the adjacent freeway lane. The part-task is at the core of the entire process of control of an automobile; indeed its activation forms the basis for all subsequent decisions that are made instinc-

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tively or deliberately to control the automobile and avoid vehicular physical contact. A ramp driver perceives the freeway automobile traffic movement through the visual stimulus of the independent movement of a particular freeway vehicle. That is a complex phenomenon in that it not only includes the relative movement of the freeway vehicles with respect to the driver himself but also involves a basic assessment of the velocities of those freeway vehicles with respect to the lane in which they are moving. However, because a driver must divide his visual attention among a number of driving tasks while he is merging, he relies heavily on his ability to estimate the relative velocities of the vehicles ahead of and behind which he will merge by turning his head and glancing at the freeway vehicles rather than by fixing his gaze on them.

Michaels (1) has observed that the detection of relative velocity depends on the rate of change of angular motion of an image across the retina of the eye. Therefore, there is a threshold for awareness of relative velocity. That threshold value was found to be 6×10^{-4} rad/sec. Only when the rate of change has reached this magnitude is relative velocity perceived. When the angular rate of change is less than this value, as is the case when a ramp driver actually accomplishes his merge, angular velocity cannot be detected. Because of that condition it was assumed that a driver will begin glancing at the freeway as soon as he feels he can see elements of the freeway vehicles so that he can begin setting up his merge maneuver at the earliest possible opportunity.

As a driver proceeds along an entrance ramp to a freeway, he ceases mentally to drive on only one roadway. Physically he is driving on the ramp roadway all the while he is upstream from the ramp nose. Downstream from that point the ramp roadway and the adjacent freeway lane become a single, variable-width lane until the end of the ramp taper is reached. The merging maneuver is assumed to be completed at or upstream from the termination of the taper.

As the driver completes his merge alignment maneuver, the side projection value (2) of the vehicles immediately ahead and behind approaches zero. Therefore, once the ramp driver decides to accept a gap between the first vehicle behind and the first vehicle ahead on the freeway lane, he becomes, for all practical purposes, a car in the freeway stream. Consequently, it was assumed that the ramp nose represents the psychological termination of the decision process and the commitment to action. Therefore, in the present study, the ramp nose was referred to as the termination of the high-speed merge dilemma zone. The length of the dilemma zone was assumed to be 300 ft. The justification of this assumption and the discussion of detailed derivations of the model operation are presented in another publication (8).

COMPONENTS OF THE MODEL

The proposed merge-vision simulation model integrates 4 groups of parametric data in an effort to quantify the visual kinesthetic responses to external stimuli required of a ramp driver as he attempts to merge with the freeway traffic stream moving in the adjacent freeway lane. The 4 groups of data that were used as input to the model are freeway and ramp geometric configuration, ramp and freeway vehicle characteristics, driver's physical measurements, and traffic characteristics.

Freeway and Ramp Geometric Configuration

The horizontal and vertical elements of the merging zones that were considered in this study are shown schematically in Figure 1. Although any quantifiable ramp terminal configuration could be handled, it was decided to include only the following 3 types of system geometrics in this study because they are the most common types in use. They are show in Figure 2.

1. Opposing sense freeway and ramp curvature—This ramp terminal could be characterized by 2 circles that meet tangentially at only 1 point and whose centers of curvature lie outside one another. The traffic on the ramp approaches the tangent point on the curvature that is of the opposite sense of that approaching the freeway. For the purpose of this study, a 3-deg curve was chosen for the ramp and a 2-deg curve was chosen for the freeway. This approximates the extreme condition allowed for a ramp entrance terminal under AASHO specifications (3).

Figure 1. Horizontal and vertical elements of merging zones.

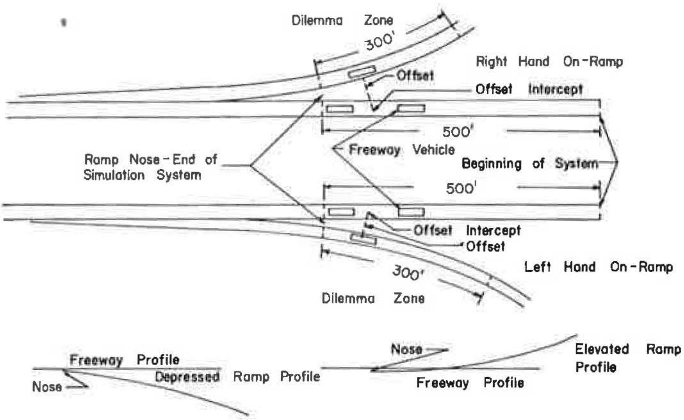

Figure 2. Types of system geometrics considered for the model.

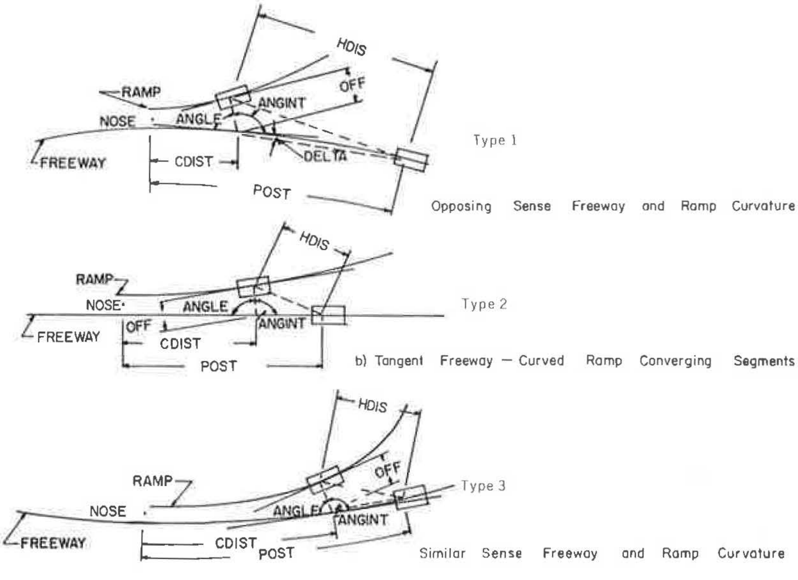

Table 1. Freeway-ramp geometric input data.

Geometric Type and Merge	Ramp Control Point	Offset Distance (ft)	Distance Upstream From Ramp Nose to Offset Intercept Point on Freeway (ft)	Acute Intersection Angle of Offset Line (deg)	Relative Pavement Elevation Difference (ft)	Geometric Type and Merge	Ramp Control Point	Offset Distance (ft)	Distance Upstream From Ramp Nose to Offset Intercept Point on Freeway (ft)	Acute Intersection Angle of Offset Line (deg)	Relative Pavement Elevation Difference (ft)
1, above	1	143.52	331.80	63.083	3.26	1, below	1	143.52	331.80	63.083	2.07
	2	118.01	272.55	65.895	1.63		2	118.01	272.55	65.89	1.92
	3	95.89	215.27	68.673	0.33		3	95.89	215.27	68.673	1.80
	4	76.90	159.64	70.403	-0.64		4	76.90	159.64	70.403	1.71
	5	60.82	105.37	74.117	-1.27		5	60.82	105.37	74.117	1.64
	Nose	47.47	52.234	76.800	-1.57		Nose	47.47	52.23	76.800	1.61
2, above	1	102.04	317.71	73.271	3.26	2, below	1	102.04	317.71	73.271	2.07
	2	87.02	263.10	74.792	1.63		2	87.02	263.10	74.792	1.92
	3	73.58	209.26	76.312	0.33		3	73.58	209.26	76.312	1.80
	4	61.70	156.12	77.833	-0.64		4	61.70	156.12	79.355	1.71
	5	51.31	103.59	79.355	-1.27		5	51.31	103.59	79.355	1.64
	Nose	42.38	51.57	80.875	-1.57		Nose	42.38	51.57	80.875	1.61
3, above	1	60.35	308.37	83.655	3.26	3, below	1	60.35	308.37	83.655	2.07
	2	54.82	256.56	84.110	1.63		2	54.82	256.56	84.110	1.92
	3	49.73	204.94	84.577	0.33		3	49.73	204.94	84.577	1.80
	4	45.08	153.49	85.049	-0.64		4	45.08	153.49	85.049	1.71
	5	40.86	102.20	85.522	-1.27		5	45.86	102.20	85.572	1.64
	Nose	37.08	51.04	85.920	-1.57		Nose	37.08	51.04	85.920	1.61

2. Tangent freeway-curved ramp converging segments—In this geometric type, the curved ramp meets tangentially with the straight line representing the alignment of the freeway. Ramp curvature remains the same as in the previous case.

3. Similar sense freeway and ramp curvature—This terminal condition is exemplified by 2 circles that meet tangentially at only 1 point and whose centers of curvature lie inside one another. The traffic on the ramp approaches the tangent point on the curvature that is of the same sense as that of the freeway. The magnitude of the arc defining degrees of curvature for both roadways was taken to be the same as that given above for opposing sense.

The geometric input data for the model were generated by use of the COGO program (4) loaded on an IBM 360/MP65 digital computer. Those data consist of distances between the assigned locus of points of the driver's vision and the path of the leading edge of the freeway vehicle. In addition, the information includes the angle of intersection of the offset line with the tangent to the freeway vehicle's path at the point of intersection. The offset line is measured at right angles to the ramp vehicle's trajectory at predesignated control points along the ramp. The digital description that was prepared for geometric input to the model is given in Table 1. The input data may be applied to both left and right on-ramps with similar entrance terminal design characteristics.

Vehicle Characteristics

Several parameters involving the vehicles on the freeway and the ramp need to be considered in the formulation of the model. It was assumed that vehicle parameters are normally distributed with a given mean and variance. Accordingly, the required vehicular characteristics were randomly assigned to individual vehicles through a Gaussian random number generator. The characteristics that were considered are discussed in the following paragraphs.

Freeway Vehicle Parameters—Only 2 structural parameters of the freeway vehicles were included: the freeway vehicular clearance over the highway pavement and the overall vehicular height. When a ramp driver approaches the freeway from below, the leading edge of the freeway vehicle first visible would be the front bumper. The bumper height can be taken as the vehicle clearance. Similarly, the vehicle's overall height defines the distance from the freeway pavement to the top edge of the windshield cowling, or the leading edge of the freeway vehicle first visible to the ramp driver approaching from above.

Ramp Vehicle Parameters—To examine microscopically the driver within the automobile capsule, one must adequately describe the cockpit as it relates to the driver. Those elements that will have a direct effect either on the driver's position or on his field of vision were determined, and the necessary data pertaining to those elements were collected. Those parameters that were judged to have an influence on the driver's position or vision within the automobile (5) are shown schematically in Figure 3. The values of the vehicle parameters are given in Table 2.

Driver's Physical Measurements

Two sets of physical measurements of major significance to the visual part-task were considered in this study. They are the driver's eye height and the gross horizontal angle through which a driver may turn his visual centerline of regard. Because most human factors are normally distributed, these 2 parameters were also assumed to follow a normal distribution. Accordingly, an attempt was made to obtain the values for the means and variances of the 2 parameters; the values are given in Table 3.

Driver's Eye Height—The dimensions of the segments of the Alderson 50th percentile male anthropometric dummy (6) were used as the basis for the measurement of the driver's eye height (EYEHT). As shown in Figure 4, vertical plane, this dimension was found to be 34.89 in. measured from the H-point to what has been considered as the geometric center of vision within the driver's head. An effort was made to secure other percentile measurements as well as information for male and female drivers

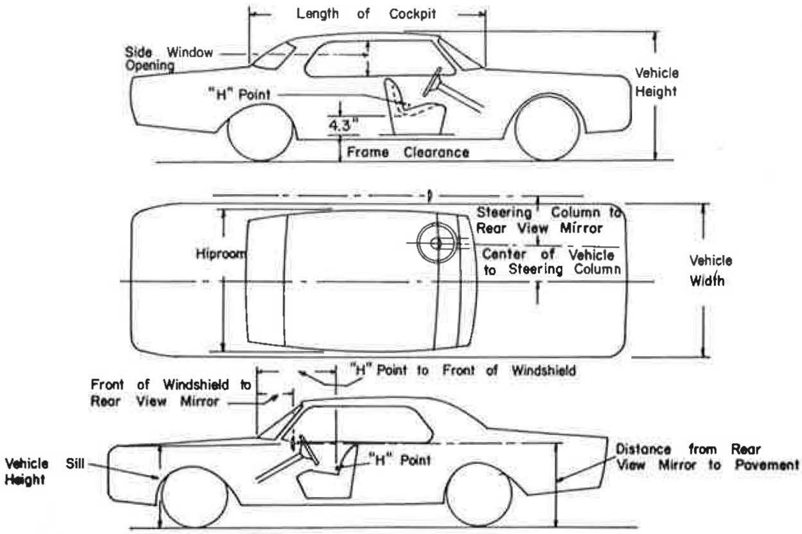

Figure 3. Vehicle input parameters.

Figure 4. Orientation of driver in vehicle.

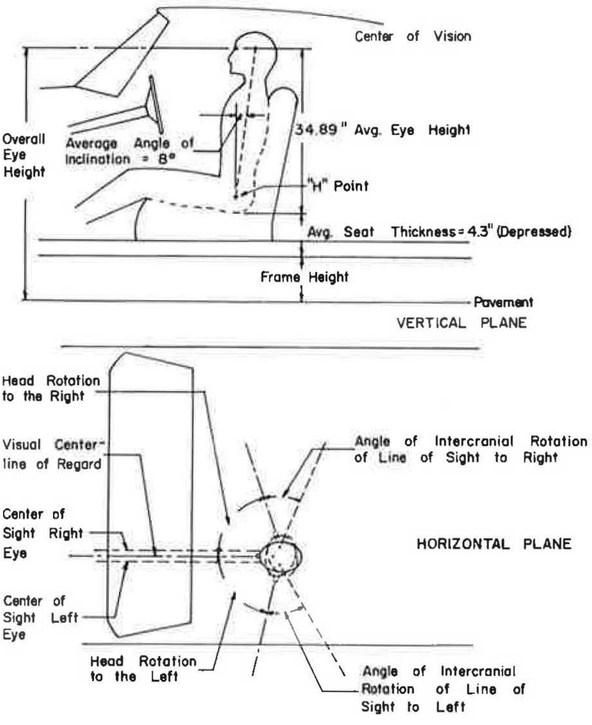

Table 2. Parameters relating to vehicle characteristics.

Parameter Dimension (in.)	Mean (in.)	Standard Deviation (in.)
Vehicle sill height[a]	37.6	1.1
Side window opening[a]	11.8	0.8
Frame to ground clearance[a]	6.3	0.4
Length of cockpit[a]	102.7	6.6
H-point to front of windshield[a]	30.9	1.7
Distance from steering centerline to vehicle centerline[a]	14.4	0.7
Vehicle hip room[a]	58.8	1.5
Vehicle overall width[a]	71.8	3.8
Vehicle overall height[a]	54.3	1.5
Distance from face of outside rearview mirror to front of windshield[b]	18.6	4.9
Distance from centerline of steering column and centerline of regard of rearview mirror[b]	19.5	2.0
Distance from pavement to centerline of regard of rearview mirror[b]	39.2	1.3

[a]Based on sample of 12 vehicle models (1969 AMA specifications).
[b]Based on field measurements of 20 vehicles ranging in age from 1 to 9 years.

Table 3. Parameters relating to driver physiology.

Parameter	Mean	Standard Deviation
Eye height[a], in.	34.9	3.5
Head rotation angle[b], deg		
Left	67.8	7.96
Right	63.9	7.77

[a]Based on 50th percentile of anthropometric dummy.
[b]Based on 40 male drivers, 120 measurements.

separately. However, because of lack of readily available information, it was assumed that the driver's eye-height measurements would fall within a range of ±20 percent of the 50th percentile value, with a 95 percent level of confidence. The standard deviation of the driver's eye-height measurement was, therefore, taken to be 3.56 in.

Gross Horizontal Visual Scan to Left and Right—The angular components of horizontal vision are shown in Figure 4, horizontal plane. To obtain the values of the parameters relative to the gross horizontal visual scan required that tests be conducted on a group of representative drivers to obtain an adequate range of angles through which these drivers could rotate their heads in the horizontal plane both to the right (DHROTR) and to the left (DHROTL). Forty randomly selected male drivers ranging in age from 22 through 53 years were tested in a Cervigon apparatus designed to measure this angle. This apparatus, manufactured by the Kitt Company of Raleigh, N. C., consisted of a large protractor etched on a shoulder rest on which was mounted a rotating chin rest and pointer.

Traffic Characteristics

The traffic flow on the freeway lane adjacent to the ramp was simulated by a shifted exponential distribution of intervehicular headways. The initial preloading of the freeway lane was accomplished by the use of a Poisson distribution of distance spacings. The speeds for the vehicles on the freeway lane were randomly assigned on the basis of a normally distributed speed model. The parameters of the freeway lane speed model were developed on the basis of the information given in the 1965 Highway Capacity Manual (7). The ramp vehicles were also assigned with randomly generated operating speeds according to a normal distribution.

MODEL OPERATION

The simulation logic was divided into 2 parts to simplify the programming of the visual kinematics. Separate programs were prepared for right and left merge situations. The simulator follows an event scan procedure; the system is evaluated only when the ramp vehicle reaches one of the predetermined control points along the ramp dilemma zone.

As a ramp vehicle is introduced into the system at the upstream end of the ramp, relative positions of the ramp vehicle and the closest freeway vehicle behind it are computed, and control is passed to the subroutines containing the logic to test the ramp driver's physical ability to perceive the freeway vehicle. All possible modes of vertical and horizontal vision are checked at each ramp station to determine whether the ramp driver can or cannot see the freeway vehicle from his vehicle while he is traveling in a given terminal geometry. When all prescribed tests have been conducted on the ramp driver, the ramp vehicle is moved forward to the next control point. After the specified number of ramp vehicles are processed through all the control points up to the ramp nose, a printout is obtained of the stored characteristics that describe the visual effects that the type of geometry being investigated has on ramp drivers attempting to make the merge.

The procedure is repeated for each of the 12 ramp geometric configurations (6 left and 6 mirror-image right ramps). The logic associated with the examination of the visual quality related to the 4 major types of ramps is discussed in the following paragraphs.

Left On-Ramp to Freeway From Below

For this merge, right-side and rearward visual scans are of the greatest importance. For a left merge from below, vision in the vertical plane may be precluded by the top of the vehicle door. In order for the ramp driver actually to be able to see the freeway vehicle in the vertical plane, he must be able to see its leading edge beneath the top of the vehicle door. In other words, the vertical angle between the driver's horizon and the leading edge of the freeway vehicle must be less than or equal to the vertical angle between the driver's horizon and the top of the door frame. The situations are shown in Figure 5. Similarly, the ramp driver's horizontal view of the freeway vehicle may be impaired by the vehicle framework if the angle required for the driver to turn his head to see the freeway vehicle is greater than the sideward view allowed by the vehicle's horizontal window opening. As an added condition for perception of the freeway vehicle, the driver must be physically able to turn his head through an angle greater than or equal to the angle between his vision line ahead and the line between him and the freeway vehicle. Vertical and horizontal visual angles are computed and compared to the angles made by the driver's sight line and the potential obstructions to determine whether the ramp driver can see the freeway vehicle from his position on the ramp.

Left On-Ramp to Freeway From Above

This merge situation is the same as the preceding situation except that, in this case, vertical vision downward to the freeway vehicle may be obstructed by the vehicle doorsill. If the vertical angle downward is obstructed, the driver is assumed not to be able to see the freeway vehicle in the vertical plane. All other aspects of this situation are similar to those of the previous case. The angular computations and comparisons are made in the same manner as defined before.

Right On-Ramp to Freeway From Below

This is the reverse or mirror-image situation of the left ramp to the freeway from below. In right merge logic, it is assumed that no horizontal obstructions to left vision are caused by the vehicular structure because of the close proximity of the driver to the left side windows. The only limitations to horizontal vision would be the driver's physical ability to rotate his head and eyes to the left. However, the top of the driver's side door may act as an obstruction to vertical vision. If the ramp driver is to be able to see the freeway vehicle in the vertical plane beneath the top of his door, the allowable upward vertical vision angle must be less than or equal to the actual vertical angle between the driver's horizon and the freeway vehicle.

Right On-Ramp to Freeway From Above

This is the reverse of the left ramp approaching the freeway from above. However, it is the same as the previous case except for 2 important differences:

1. Side vision in the vertical and horizontal planes should be almost unconstrained. Therefore, only the driver's physical ability affects visual perception of the freeway vehicle. The vehicle framework should offer no obstructions to vision.
2. Rear vision is possible. Accordingly, the horizontal and the vertical scans of the outside left rearview mirror are computed only for this type of situation.

The procedure to determine whether the freeway vehicle falls within the horizontal rearward vision cone of the ramp vehicle's rearview mirror involves comparing the angle between the ramp and the freeway vehicle to the horizontal angle between the centerline of the rearview mirror and the driver's sight center. Figure 6 shows that, if the rear view horizontal angle (the angle between the ramp and the freeway vehicle) is greater than 90 deg, the ramp driver can see the freeway vehicle in his rearview mirror in the horizontal plane. Similarly, if the vertical angle over the vehicle doorsill is less than or equal to the rear view vertical angle, the ramp driver can see the freeway vehicle in his rearview mirror in the vertical plane.

MODEL RESULTS

For left or right merging, there were 3 types of system geometrics considered for both the above and the below situations. The results as obtained from the simulation runs are discussed below.

Merge Vision

Left On-Ramp to Freeway From Above—Table 4 gives the number of drivers that can successfully see the freeway vehicle of concern in horizontal and vertical planes as well as in both planes under each freeway-ramp geometric configuration. More

Figure 5. Elements of driver's vertical sideward vision from vehicle.

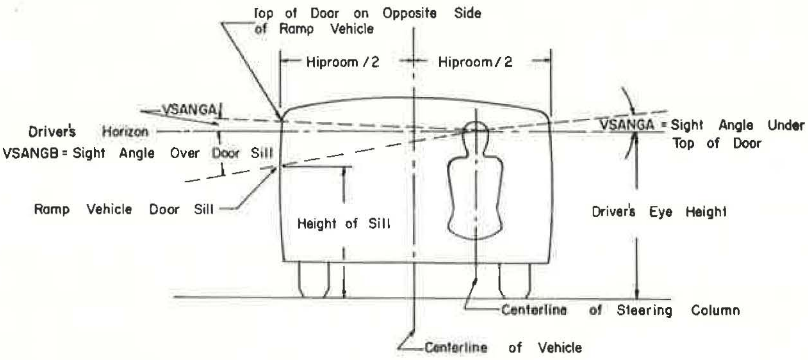

Figure 6. Geometric elements of rear vision.

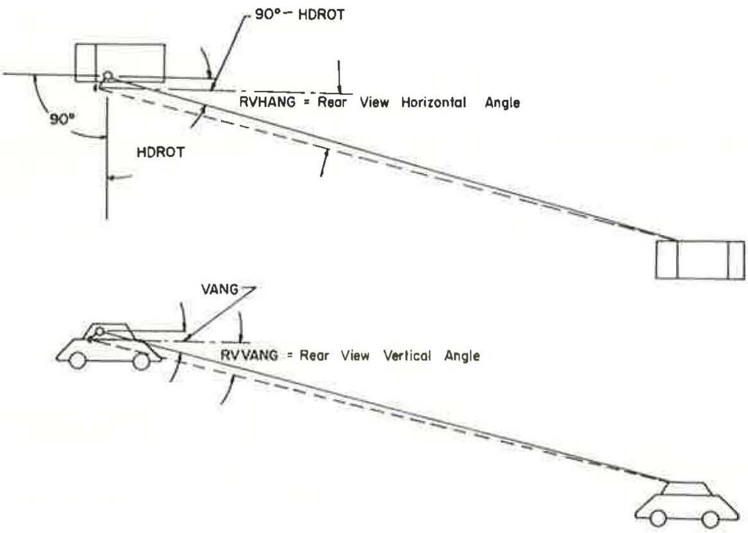

Table 4. Drivers who can successfully see freeway vehicle while they merge from above left.

Geometric Type	Ramp Control Point	Vertical Plane Vision	Horizontal Plane Vision	Clear Vision (both planes)	Number of Opportunities	Drivers Able to See Clearly (percent)
1	1	378	308	288	401	71.8
	2	436	389	274	457	59.9
	3	460	260	250	479	52.1
	4	471	234	223	489	45.6
	5	477	198	187	494	37.8
	Nose	478	131	127	496	25.6
2	1	393	234	218	416	52.4
	2	451	237	224	468	47.8
	3	474	211	208	485	42.8
	4	483	192	187	492	38.0
	5	484	157	149	496	30.0
	Nose	487	116	112	497	22.5
3	1	367	146	140	426	32.8
	2	440	131	129	472	27.3
	3	470	135	132	484	27.2
	4	493	129	129	493	26.1
	5	494	123	123	494	24.8
	Nose	494	99	99	494	20.0

Table 5. Drivers who can successfully see freeway vehicle while they merge from below left.

Geometric Type	Ramp Control Point	Vertical Plane Vision	Horizontal Plane Vision	Clear Vision (both planes)	Number of Opportunities	Drivers Able to See Clearly (percent)
1	1	402	301	391	414	70.2
	2	458	299	291	467	62.3
	3	474	259	252	484	52.0
	4	486	221	219	493	44.4
	5	492	191	190	496	38.3
	Nose	493	136	136	495	27.4
2	1	418	251	243	430	56.5
	2	454	215	209	467	44.7
	3	476	211	208	488	42.6
	4	489	189	187	498	37.5
	5	495	169	169	500	33.8
	Nose	493	108	108	498	21.6
3	1	417	150	145	424	34.6
	2	459	135	134	464	28.8
	3	479	123	121	482	25.1
	4	490	127	127	491	25.8
	5	492	108	108	494	21.8
	Nose	492	89	89	495	17.9

drivers can see the freeway vehicle clearly (that is, in both the vertical and the horizontal fields of vision) in geometric type 1 than in type 2 and in type 2 than in type 3. This would seem reasonable because a longer length of freeway segment is intercepted by the projection of the ramp dilemma zone in type 1 than in type 2. The same statement can be made for the comparison of types 2 and 3. It is evident, when these geometric types are examined, that the more nearly parallel the ramp and the freeway are, the less will be the likelihood that any particular ramp driver is able to see the freeway vehicle in the dilemma zone. Vision in the vertical plane in type 3, however, appears to be of slightly better quality than that in either type 1 or 2, especially near the ramp nose. This is probably due to closer proximity of the ramp pavement to the freeway pavement for a longer distance of the ramp dilemma zone.

Left On-Ramp to Freeway From Below—Table 5 gives the number of ramp drivers that are able to see in the vertical plane, in the horizontal plane, and in both planes when they merge from ramps below the freeway. The same basic generalizations may be made as for the ramp approach from above the freeway. Again, quality in the combined horizontal and vertical visual aspects deteriorates progressively from type 1 to type 3. Type 1 offers the most opportunities for clear vision, type 2 offers fewer, and type 3 offers the least number of opportunities for clear vision of freeway vehicles. There appears to be no discernible difference among the 3 geometric types for the ramp driver to see the freeway vehicle in the vertical plane.

Right On-Ramp to Freeway From Above—The result of the simulation run for merges on the right ramp from above are given in Table 6. In all 3 geometric types, only the horizontal vision angle was examined. It was assumed that a normal driver should be able to look over the driver's side doorsill in the vertical plane and experience no difficulty in observing a freeway vehicle on the roadway beneath him. Again, as in the left ramp merges, geometric type 1 appeared to offer the ramp driver the best quality of vision of the freeway; type 2 was somewhat inferior to type 1, and type 3 seemed to be the least adequate.

Right On-Ramp to Freeway From Below—Table 7 gives the results of the simulation run for the right merges from below. The major difference between this merging situation and the previous one is that the ability of the driver to see the freeway vehicle in the vertical plane may be impaired by the top of the driver's side door. Therefore, for this analysis, in addition to the vision in the horizontal plane, the vision in the vertical plane was also examined. Vertical vision in types 2 and 3 is about the same as that in type 1, although for all 3 types the number of drivers able to see the freeway vehicle was very high. This indicates that impairment of vertical vision is probably not a major problem for right-ramp merges from below. Vision quality in the horizontal plane was best for type 1, diminished for type 2, and lowest for type 3. Because of this, the quality of clear vision for the combined vision in the horizontal and vertical planes appeared to follow the trend of the horizontal vision quality.

Ramp Vehicle Location

For all geometric types, quality of clear vision decreases as the ramp vehicle approaches the ramp nose. This qualitative decrease is due to the length of the freeway segment scanned by the driver of the ramp vehicle as it moves in a lateral direction toward the freeway. Therefore, the driver's ability to detect a freeway vehicle was reduced accordingly because there would be less chance of that vehicle being in the shorter space.

Vision in Outside Rearview Mirror During Right Merge From Above

To fully examine the vision quality for the right merge from above, we tested vision in the outside rearview mirror in both horizontal and vertical planes to determine whether it might have a significant effect on merge vision. Table 8 gives data that indicate that rear horizontal vision appeared to be significant, expecially for type 3 geometrics. However, for all 3 types, rear vertical vision was negligible. Therefore, it is obvious that along the ramp dilemma zone, for a right merge from above, the outside rearview mirror is of little use in the visual detection of a freeway vehicle because the driver is almost never able to see that vehicle in the verticle rear vision plane.

Table 6. Drivers who can successfully see freeway vehicle while they merge from above right.

Geometric Type	Ramp Control Point	Horizontal Plane Vision	Number of Opportunities	Drivers Able to See Freeway Vehicle (percent)
1	1	340	401	84.7
	2	324	457	40.8
	3	302	479	63.0
	4	276	489	56.4
	5	232	494	46.9
	Nose	165	496	33.2
2	1	257	416	61.7
	2	274	468	58.5
	3	251	485	51.7
	4	221	492	44.9
	5	203	496	40.9
	Nose	145	497	29.1
3	1	187	426	43.8
	2	155	472	32.8
	3	174	484	35.9
	4	152	493	30.8
	5	156	494	31.5
	Nose	113	494	22.8

Table 7. Drivers who can successfully see freeway vehicle while they merge from below right.

Geometric Type	Ramp Control Point	Vertical Plane Vision	Horizontal Plane Vision	Clear Vision (both planes)	Number of Opportunities	Drivers Able to See Clearly (percent)
1	1	392	358	340	414	82.1
	2	444	342	323	467	69.1
	3	460	306	291	484	60.1
	4	470	269	259	493	52.5
	5	478	221	213	496	42.9
	Nose	478	176	175	495	35.3
2	1	409	292	278	430	64.6
	2	444	266	253	467	54.1
	3	466	253	243	488	49.7
	4	477	213	205	498	41.1
	5	481	205	196	500	39.2
	Nose	481	138	134	498	26.9
3	1	407	175	167	424	39.3
	2	449	156	151	464	32.5
	3	467	148	141	482	29.2
	4	475	152	144	491	29.3
	5	478	135	129	494	26.1
	Nose	479	112	109	495	22.0

Table 8. Additional drivers who can successfully see freeway vehicle in rearview mirror while they merge from above right.

Geometric Type	Ramp Control Point	Rear Vertical Plane	Rear Horizontal Plane	Rear Vision (both planes)
1	1	0	6	0
	2	0	25	0
	3	0	48	0
	4	0	67	0
	5	0	98	0
	Nose	4	189	4
2	1	0	31	0
	2	0	66	0
	3	0	99	0
	4	1	110	1
	5	2	157	2
	Nose	8	219	8
3	1	0	123	0
	2	0	179	0
	3	0	188	0
	4	0	202	0
	5	1	219	1
	Nose	6	257	6

Table 9. Interference of vehicle cockpit structure with horizontal vision of freeway vehicle.

Geometric Type and Merge	Ramp Control Point	Times Cockpit Prevents Vision		Number of Opportunities
		Number	Percent	
1, left above	1	0	0	401
	2	0	0	457
	3	0	0	479
	4	1	0.2	489
	5	7	1.4	494
	Nose	47	9.5	496
2, left above	1	0	0	416
	2	3	0.6	468
	3	13	2.7	485
	4	18	3.7	492
	5	33	6.6	496
	Nose	97	19.5	497
3, left above	1	20	4.7	426
	2	74	15.7	472
	3	90	18.6	484
	4	75	15.2	493
	5	95	19.2	494
	Nose	146	29.6	494
1, left below	1	0	0	414
	2	0	0	467
	3	0	0	484
	4	1	0.2	493
	5	5	1.0	496
	Nose	41	8.3	495
2, left below	1	0	0	430
	2	1	0.2	467
	3	8	1.6	488
	4	10	2.0	498
	5	24	4.8	500
	Nose	77	15.4	498
3, left below	1	36	8.5	424
	2	67	14.4	464
	3	84	17.4	482
	4	69	14.0	491
	5	106	21.5	494
	Nose	153	31.0	495

Cockpit Interference in Left Merge

A separate evaluation was made to determine how the structural framework of the ramp vehicle's cockpit interferes with the ramp driver's horizontal vision in left merging. Table 9 gives the number of drivers whose horizontal vision is interfered with by the cockpit structural framework.

The cockpit interference with horizontal vision is most when the ramp and the freeway alignments are converging circular curves of the same sense (type 3 horizontal geometry). This is due to the very nearly parallel nature of the ramp and freeway roadways through the dilemma zone area. That parallel nature causes the respective offset distances to be less at every ramp station, which in turn reduces the length of freeway that the ramp driver is able to scan. The freeway vehicle of concern, therefore, has a greater chance of being outside the maximum visual scan allowed by the cockpit, and that situation would make it impossible for the ramp driver to see the freeway vehicle because of the cockpit framework. For the same reasons, cockpit interference with vision in the horizontal plane is apparently greater for type 3 than for types 1 and 2.

Comparison of Left and Right Merge Vision

Because this study attempted to establish whether there is a difference between a driver's ability to see the freeway traffic from left ramps and right ramps in mirror-image situations, a statistical test was conducted to examine significant differences between the left and right merge vision. The description of the procedure used in conducting the analysis is beyond the scope of this paper. However, the results of the statistical tests clearly indicated that there is a significant difference in the ramp driver's ability to see while moving through the dilemma zone of a left ramp compared to his ability to see while moving through the dilemma zone of a mirror-image right ramp. In 5 of the 6 types of ramp geometrics examined, the hypothesis that the visual quality of right ramps is superior to left ramps was accepted at the 0.90 level of confidence. The visual quality of types 1 and 2 right ramps to the freeway from above and type 1 right ramps to the freeway from below is significantly better than the visual quality of the corresponding left ramps at the 0.95 level of confidence.

Only for type 3 ramps to the freeway from below did there appear to be no significant difference between the left and right ramps; thus, they function about equally for either type of approach. However, ramps of this type show the lowest average percentage of clear vision of all the 6 types.

In general, z-scores were less for the ramp stations closer to the nose than for ramp stations farther upstream. This indicates that sideward visual quality decreases for all ramps as the ramp driver gets closer to the ramp nose. However, there are still significant differences in visual performance between right and left ramps for the geometric types considered in this study.

CONCLUSIONS

1. The porposed model provides information about the distribution of successful observations of a freeway vehicle by a ramp driver attempting to merge behind that vehicle from either a left or a right on-ramp. The model permits analysis of any on-ramp individually for visual quality by comparing visual successes at selected points along the ramp. Alternative on-ramp designs can also be compared to aid in the selection of the ramp type that will optimize ramp driver vision and enhance safety.

2. It is apparent for all ramps that the closer to the ramp nose the ramp driver is before he can look at the freeway the less chance he has of being able to see the freeway vehicle. Therefore, if guardrails or other obstructions prevent the driver from seeing freeway vehicles until he is close to the nose, the probability that he will not see the critical vehicle is increased. His decision time is also shortened as he moves closer to the ramp nose. The model results show that cockpit interference during left merges increases close to the ramp nose, and vision in the left side rearview mirror during

right merges is almost nonexistent at this point. These observations further justify the assumption that a proper merge dilemma zone of an on-ramp lies upstream from the ramp nose. Therefore, it is apparent that ramps with open dilemma zones in which obstructions are absent at points 200 to 300 ft upstream from the ramp nose are most conducive to safe merges.

3. On the basis of statistical tests conducted on the model results, at the 0.90 level of confidence the hypothesis that left on-ramps are inferior to right on-ramps because there are more hindrances to clear vision associated with left on-ramps is accepted for all ramp types except type 3 ramps to the freeway from below. In addition, the same hypothesis is accepted at the 0.95 level of confidence for types 1 and 2 from above and type 1 from below.

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