A COMPUTER SIMULATION MODEL OF DRIVER VISION WHILE MERGING FROM A FREEWAY ON-RAMP

Kumares C. Sinha
Assistant Professor of Civil Engineering
Marquette University
Milwaukee, Wisconsin

and

Philip H. DeCabooter
Design Engineer, District II
Wisconsin Department of Transportation
Waukesha, Wisconsin

Summary

This paper is concerned with the development of a digital simulation model for use as a tool in the analysis of the visual quality of a freeway on-ramp.

During the process of merging, a driver on an on-ramp is required to assess the dynamic and highly complex traffic situation occurring in the adjacent freeway lane into which he must merge. Vision is the key biomechanism which he has at his disposal to aid him in his merging decision process. The visual part-task is hindered by physical limitations on 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. Both the horizontal and vertical visions are further restrained due to the freeway-ramp geometric configurations, as well as to obstructions resulting from the physical dimensions of vehicle.

A general model was developed to investigate twelve types of ramp entrance terminals. Freeway and ramp vehicle parameters, as well as driver physiological characteristics, were assigned randomly on the basis of a Gaussian distribution. The freeway traffic flow was generated according to a shifted exponential distribution of intervehicular headways. The component micro-models were formulated on the basis of field investigations and present understanding of traffic flow theory and driver visual physiology.

The simulation model was programmed utilizing both open and closed subroutines under the control of a monitor or master program. These programs were coded in the FORTRAN IV and were run on an IBM 7040. Separate routines were prepared for preloading the freeway system with vehicles, generating ramp vehicles with randomly assigned characteristics, determining vertical sight angles, determining horizontal sight angles, and for updating the system. The input information includes freeway traffic volume, means and standard deviations of driver-vehicle parameters, and the freeway-ramp geometric configuration data. The exact nature of the output information depends upon the specific aspects of the ramp geometrics to be analyzed. In general, the proposed model provides information about the distribution of successful observations of vehicles on the adjacent freeway lane by the driver on an on-ramp as he proceeds along the ramp. Alternative on-ramp designs can also be evaluated to aid in the selection of the ramp type which will optimize ramp driver vision and enhance safety.

Introduction

Automobile drivers are required to perceive, collate, analyze and act on complete or incomplete information which impinges itself on their conscious intellect in a matter of divided seconds. This information is composed of a multitude of elements, each of which must be instantly placed in its proper relationship with respect to all other components of the system in which the driver and automobile travel. Consequently, human factors engineering and driver behavior within the automotive capsule must be given more consideration with respect and in relation to roadway system variables which impose themselves on the driver-auto subsystem. One situation in which human factors engineering becomes critical occurs at the entrance to a freeway, when an automobile is attempting to merge with the freeway traffic from an on-ramp. The driver's ability to safely make his merge may be adversely affected by a reduction of quality of his vision out of his automobile caused by the type of freeway-ramp geometry. This study describes the development and results of a digital computer simulation model which duplicates the dynamic event of freeway merging and examines vision quality out of automobiles which are traveling on a freeway on-ramp.

General Features of the Model

The proposed merge vision simulation model was developed as a general model incorporating ramp and freeway geometry, driver physiological abilities, vehicular structure, and traffic data including freeway lane traffic volume, freeway lane speed distribution, and ramp vehicle speeds. The proposed model is capable of processing both right and left hand merging situations. Although any type of ramp terminal could be included only six geometric configurations were considered. The required data establishing the relative locations of the ramp and freeway vehicles in both horizontal and vertical planes for a given geometric configuration of a terminal are generated by use of the Massachusetts Institute of Technology Coordinate Geometry program[6].

The length of the freeway segment considered was the five hundred feet of the freeway lane behind or upstream of the ramp nose, or point at which the ramp and the freeway act as a single roadway. The section of ramp roadway included in model was a three hundred foot length upstream of the ramp nose. This ramp section was considered to be the dilemma zone for the ramp driver. The dilemma zone is defined as that segment of ramp roadway in which a driver must decide whether or not to merge.

The model was structured to examine the eye and head movements required of a driver attempting to merge into a live freeway lane. The flow of traffic on the freeway lane is dynamically simulated as a random process. The ramp driver is assumed to scan the freeway traffic situation in both vertical and horizontal planes. The angles of head rotation required of the ramp driver to see the freeway vehicle are computed at predetermined control points along the ramp dilemma zone both in a vertical and a horizontal plane. Any possible sight obstruction due to the vehicular structural constraints as well as ramp-freeway geometric configurations are also examined at the same control points along the ramp. The computed angle of head rotation is compared with the allowable angle for a particular ramp driver to determine if the ramp driver can actually see the freeway vehicle. An additional feature of the model is that the use of the exterior mirror can be investigated through a subroutine whenever it is determined that this mirror might act as an aid to the driver while in the merging process.

After sufficient data are gathered regarding the merging vision for the given ramp situation through simulation runs, a statistical analysis is made to examine the respective visual quality of a ramp terminal. This is accomplished by evaluating the number of times a ramp driver has clear vision at selected points along the ramp. Alternative on-ramp designs can also be evaluated to aid in the selection of the ramp type which will optimize ramp driver vision and enhance safety. Furthermore, statistical analyses can be set up to correlate such variables as freeway and ramp degrees of curvature through the ramp dilemma zone, vertical geometrics of the ramp area, and ramp vehicle speed with the ramp driver's ability to see freeway vehicles in the freeway lane adjacent to the ramp.

Programming of the Model

Basic Considerations

As a ramp driver proceeds along the ramp he consciously perceives the freeway stream in the lane adjacent to the ramp. It was assumed in the development of the simulation model that the driver must turn his head toward the freeway at least once, to actually allow him to see the freeway vehicle across or immediately behind him, while he is traversing the ramp dilemma zone during a high speed merge. This is his only means of gathering visual data which will enable him to decide to accelerate in order to achieve a smooth merge ahead of this vehicle or to ascertain that it is not possible to achieve this merge and therefore to decide to decelerate.

It would be far too rigid and unrealistic a requirement to assert that all the ramp drivers attempting to merge would look toward the freeway at only one particular point in the dilemma zone. Since each driver would adhere to his own particular behavior pattern while he is making his decision, each would choose his own distinct point in the dilemma zone at which to visually evaluate the freeway traffic situation. In addition, each ramp driver would be traveling at a particular speed within the assumed range for the ramp. This would, in turn, have the effect of shortening or lengthening the dilemma zone in approximate inverse proportion to the square of the speed. Although there are an infinite number of combinations of points along the ramp dilemma zone at which the driver could elect to turn his head, it was decided to scan the system as the ramp driver passes a series of predetermined control points along the ramp. These control points are established at 50 foot intervals. Further refinement can easily be made by dividing the zone into smaller segments.

Outline of Simulation Logic

The model was coded in the FORTRAN IV and was run on an IBM 7040/16K computer. The computer coding included several subroutines under the control of a monitor or master program. The model follows an event-scan process in which the entire system is scanned as a ramp vehicle reaches one of the predetermined control points along the ramp dilemma zone. The freeway vehicles are advanced an appropriate distance for the time period in which a ramp vehicle travels from one control point to the next; and the vehicle characteristics are updated accordingly.

The simulation logic was divided into two parts to simplify the programming of the visual kinematics. Separate programs were prepared for right hand and left hand merge situations. The overall logic of the left hand merge is presented schematically in Figure 1.

After preloading the freeway lane adjacent to the ramp, the simulation time-clock is started. This is followed by the logic to generate a ramp vehicle and to assign randomly the driver-vehicle characteristics.

As a ramp vehicle is introduced into the system at the upstream end of the ramp, relative positions of the ramp vehicle and the freeway vehicle of concern 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 immediately behind. All possible modes of vertical and horizontal vision are checked at each ramp station to determine if the ramp driver can or cannot see that automobile while traveling in one of the two major types of terminal geometry.

When all prescribed tests have been conducted on the ramp driver, the ramp vehicle is moved forward to the next control point on the ramp. Subsequently, the freeway vehicles are updated. Those freeway vehicles passing the bounds of the simulation section at the end of the current scan period are processed out of the system; and new vehicles are introduced at the upstream end of the freeway lane according to the freeway vehicle generator logic.

After the specified number of ramp vehicles are processed through all the control points up to the ramp nose, the stored characteristics are printed out to describe the visual effects the type of ramp geometry has on ramp drivers attemptint to merge.

Generation of Vehicles on Freeway Lane

The generation of freeway vehicles is accomplished through a shifted exponential distribution of headways. Such model was observed to be a good descriptor of the intervehicular time spacings on multi-lane highways[7]. The shifted exponential model is described by the following equation:

$$P(h \geq t) = e^{-(t-t_{min})/(\bar{T}-t_{min})} \qquad (1)$$

where, $P(h \geq t)$ = probability that a headway, h, in seconds, is equal to or greater than t;

t = any time duration, in seconds;

t_{min} = minimum allowable headway in stream in seconds;

$\bar{T}$ = average headway in stream, in seconds.

By rearranging equation 1 to solve for t, the following equation is obtained:

$$\bar{T} = t_{min} - (\bar{T}-t_{min}) \log P(h \geq t) \qquad (2)$$

The probabilities are assigned through a random number generator routine which provides random numbers between 0 and 1. Because it was assumed that the freeway vehicles traveling in the lane adjacent to the ramp were moving in a high density traffic stream, the value of the minimum headway, t_{min}, was taken as 0.5 seconds. The value of the average headway in stream, $\bar{T}$, is computed on the basis of the input traffic volume.

Vehicle Speed Models

It has been observed that the vehicular speeds on freeways are normally distributed[7]. The parameters of the normal speed model were developed on the basis of information given in the 1965 Highway Capacity Manual[4]. Accordingly, mean and standard deviation of the speeds of freeway vehicles are computed from the following regression equations:

$$V_a = 58.7517 - 1.56646\,(vol/100) + 0.00647\,(vol/100)^2 \qquad (3)$$

and, $$S_a = 0.272\,V_a - 8.19668 \qquad (4)$$

where, V_a = mean speed of freeway vehicles, in mph;

S_a = standard deviation of freeway vehicle speeds, in mph;

vol = freeway lane volume in vehicles per hour.

The assigned freeway vehicular speed is the linear velocity of the freeway automobile and will enable determination of the relative position of the freeway vehicle in the system with respect to a datum when the time that this freeway vehicle has been in the system is known. For the new vehicles in the system the times are computed by keeping a continuous log of the time gap spacing between respective freeway vehicles and comparing this time with the simulator clock.

For this model any arbitrary datum point could be selected. However, since two separate subsystems, the ramp and the freeway, are being considered here, it would seem logical to select a point common to both. Therefore, since the ramp nose represents the junction of the ramp and the freeway, it was chosen as the datum to which all vehicular movements in the horizontal plane would be referred.

A vehicle on the ramp was also assigned with a randomly generated operating speed according to a normal distribution. No attempt was made to determine the speed parameters for a ramp vehicle on the basis of ramp volume because the ramp geometry is generally more restrictive than prevailing traffic conditions on the ramp. The parameters for the ramp speed distribution were assumed as:

Mean Ramp Operating Speed = 35 mph
Standard Deviation = 5 mph

Freeway-Ramp Geometric Configuration

Altogether twelve types of system geometrics can be considered in this model. They include left and right hand merging, as well as on-ramp approach from below and above the freeway for each of the following three common types of interchange geometrics.

Opposing Sense Freeway and Ramp Curvature - This ramp terminal could be characterized by two circles which come tangent at only one point and whose centers of curvature lie outside one another. The traffic on the ramp approaches the tangent point on a curvature which is opposite of the sense of that approaching on the freeway. This situation is presented schematically in Figure 2(a). For the purpose of this study the ramp curvature was taken to be a three-degree curve while a two-degree curve was chosen for the freeway. This approximates the extreme condition allowed for a ramp entrance terminal under AASHO specifications[2].

Tangent Freeway-Curved Ramp Converging Section - In this case, as shown diagrammatically in Figure 2(b), the curved ramp comes tangent to the straight line representing the edge of pavement of the freeway. Ramp curvature remains the same as in the previous case.

Similar Sense Freeway and Ramp Curvature - This terminal condition is exemplified by two circles which come tangent at only one point and whose centers of curvature lie inside one another. The traffic on the ramp approaches the tangent point on a curvature which is the same sense as that of the freeway. This situation is presented schematically in Figure 2(c). The magnitude of the arc definition degrees of curvature for both roadways were taken to be the same as for those in type I above.

Operation of the Dynamic System During Simulation

Horizontal Angular Components of Vehicle Location - It is assumed that the ramp vehicle enters the system at the first station in the dilemma zone. At this time the position of the first freeway automobile behind the point at which the offset line intersects the freeway path is determined. This position is computed as a distance upstream of the offset intercept point, as shown in Figure 2. This distance forms the second leg of an oblique triangle. The angle between the two adjacent sides may be readily determined. Referring again to Figure 2 it can be seen that in the case of a curved freeway section, the distance between the intercept point and the freeway vehicle along the curve line can be approximated by the chord between these points as well. The angle this chord makes with the tangent to the freeway curve at the intercept point may be computed directly from the deflection-angle formula for an arc definition curve:

$$\text{DELTA} = \frac{1/2D}{100} \times (\text{POST-CDIST}) \qquad (5)$$

where, DELTA = the circular curve deflection angle from the offset intercept point to the freeway vehicle;

D = the degree of curvature of the freeway curve, in minutes;

POST = the distance to freeway vehicle upstream of the ramp nose;

CDIST = the distance to the offset intercept point upstream of the ramp nose.

Therefore, the obtuse angle between the offset line and the chord can be stated as:

ANGINT = 180° + DELTA - ANGLE (for opposite sense ramp and freeway curves) (6)

ANGINT = 180° - DELTA - ANGLE (for same sense ramp and freeway curves) (7)

ANGINT = 180° - ANGLE (for the case where the freeway is tangent) (8)

where, ANGLE = the acute angle of intersection of the offset line and the tangent to the curve at the intercept point.
Then the required angle of rotation of the driver's visual centerline of regard past 90° may be computed by use of the law of cosines as:

$$\text{HDROT} = \text{ARCSIN}(\text{POST-CDIST}) \times \frac{\text{SIN(ANGINT)}}{\sqrt{\text{OFF}^2 + (\text{POST-CDIST})^2 - 2\text{OFF}(\text{POST-CDIST})\text{COS(ANGINT)}}} \qquad (9)$$

where, HDROT = the required angle of rotation of the visual centerline of regard past 90°;
OFF = the offset distance between the ramp driver and the freeway.

The angle, ANGINT, fixes the position of freeway vehicle in the horizontal plane for either a right-hand or left-hand merge. As the ramp vehicle is advanced through the remaining dilemma zone stations in the system, the same process is repeated.

Vertical Angular Components of Vehicle Location - Since the path of the leading edge of the freeway vehicle has been assumed to move along a horizontal line at zero elevation, it is unnecessary to be concerned with interpolating elevations of this path for the freeway vehicle lying between offset intercept points, even though, in this study grades on the freeway and the ramp are accounted for. Referring to Figure 3 it can be seen that by rotating the horizontal axis of the freeway chord or tangent to a level position and the ramp axis a like amount, very little realism is lost and much simplification is gained. It should be stated that a chord approximation to the freeway vertical alignment is valid since freeway parabolic vertical curves are generally long and flat and therefore may be easily represented by a series of short chords. The difference in relative vertical distance caused by rotation will also be quite small since freeway grades are likewise flat resulting in a rotation of less than two degrees for a 3 percent grade. Consequently, as a first approximation, these assumptions are quite sound and reasonable for the purpose of this study.

The vertical angle through which the driver would be required to move his sight line from his horizon is a function of the total horizontal distance between the ramp vehicle and the freeway vehicle and the relative vertical distance between them. Thus, as is shown in Figure 4, the vertical angle computation takes the form of:

$$VANG = ARCTAN \left[\frac{V}{HDIS} \right] \qquad (10)$$

where, V = the input elevation of the driver's sight line at given ramp station;

HDIS = the total horizontal distance between the ramp and freeway vehicles.

From the law of sines:

$$HDIS = \frac{SIN \ (ANGINT)}{SIN \ (ANGLE)} \ (POST-CDIST) \qquad (11)$$

These computations are repeated at every control point along the ramp dilemma zone.

Total System Function-Criterion for Safety

In order for the ramp driver to safely execute his merge, he must first be able to see the traffic stream into which he must merge. His ability to see is the major criterion which must be satisfied. The allowable horizontal angle through which the driver may physically turn his visual centerline of regard is the randomly assigned angle through which he may turn his head to the right or left, plus an average value for the movement of his eyes within his head. The movement of the eye within the head, called intercranial rotation, was taken as 45°. The allowable vertical angle is computed as the angle through which the driver may turn his head vertically without his vision being obstructed by his vehicle framework. The horizontal and vertical angles for the freeway vehicle location as obtained from equations 9 and 10 are then compared with the allowable head rotation angles to check if the ramp driver can actually see the freeway vehicle immediately behind him while he is moving through the ramp dilemma zone. In other words, the more times the ramp driver is able to see the freeway vehicle, if this car is within the possible horizontal scope of his vision, the better are the visual qualities of the ramp with respect to the driver-automobile system. Consequently, if elements of the automobile structure reduce the number of times the driver may possibly detect an automobile traveling on the freeway on one type of ramp configuration as compared to another, the geometric configuration of this ramp can be considered to be of lower quality.

Main Program

The main program serves as a monitor for the overall simulation system. The elements of the main program can be classified in the following manner:

1. Initialize all arrays, the general register and the vehicle index arrays.
2. Provide initial seed values for all of the random number generators.
3. Read all input information.
4. Increment the simulation time clock.
5. Select the proper geometry and related merge logic routines.
6. Locate the freeway vehicle immediately behind the ramp vehicle.
7. Perform computations involving the horizontal and vertical scan process of the ramp driver's visual part-task.
8. Provide micro-information describing the ramp driver's ability to see.

Subroutines

A number of subroutines were developed to enable the computer to branch through the required logic patterns necessary in this simulation program. These subroutines are briefly described and inventoried below:

1. PRLOAD preloads the freeway lane adjacent to the ramp with vehicles and randomly assigns their characteristics. Initially, a vehicle is placed at the downstream end of the lane, and subsequent vehicles are then spaced on the basis of a Poisson distribution of distance spacings.
2. RAMVEH introduces a single ramp driver and ramp vehicle at a time. It assigns 15 separate normally distributed characteristics involved in the mechanical perception of the freeway stream by the ramp driver in his vehicle.
3. ROTATE determines how far the ramp driver is required to turn his head in a horizontal plane in order to see freeway vehicle.
4. SVANGA computes the vertical angle between the driver's horizontal plane of vision and freeway vehicle when the ramp approaches the freeway from above.
5. SVANGB computes the vertical angle between the driver's horizontal plane of vision and freeway vehicle when the ramp approaches the freeway from below.
6. UPDATE is the internal bookkeeping system for the freeway vehicles in the simulator. As a ramp vehicle moves from one station to the next station this subprogram moves the freeway vehicles in the system as well as assigns random parameters to them.

7. QMRAND generates uniformly distributed pseudorandom numbers.

8. GAUSS generates normally distributed pseudorandom numbers.

Input-Output Information

The input information required for the model can be classified into the following general categories:

1. Freeway-Ramp Geometric Data
2. Traffic Characteristics
3. Vehicle Characteristics
4. Driver Characteristics
5. Program Control Data

The details of specific items under each category are presented in the example problem discussed later in this paper.

The computer output is the product of an integration of the roadway geometrics, structural features of the vehicle, and physiological characteristics of a driver attempting to merge into a high speed freeway lane from a ramp. In general, output information includes the following:

1. Number of times a ramp driver can possibly see the freeway vehicle at each control point and under each ramp terminal situation.
2. Number of times ramp driver can successfully see the freeway vehicle in the vertical plane, at each control point and under each ramp terminal situation.
3. Number of times a ramp driver can successfully see in the horizontal plane, at each control point and under each ramp terminal situation.
4. Number of times a ramp driver can successfully see in horizontal plane, vertical plane and in both planes through the outside left hand rear view mirror, at each control point and above type merging.
5. Number of times a ramp driver's vision is precluded due to the cockpit interference, at each control point under left hand merging situation.

An Example Problem

As an illustration of the model's application, the problem of evaluating the visual qualities of the different types of ramp geometrics for right hand merging can be mentioned. A ramp dilemma zone of 300 feet with 6 control points including the ramp nose is considered. Included are the six types of ramp geometrics which consist of the three basic alignments each with above and below situations. All the simulation runs were made with high level of freeway traffic volume for each of the runs. All of the input information, except the ramp geometric input data, were held constant. The purpose of the study was to investigate the effect of different ramp alignments on the quality of ramp driver vision while merging. In the following paragraphs the input data that were specified for this problem and the results obtained from the simulation runs are discussed.

Input Procedure

Most of the freeway and ramp vehicle measurements were obtained from the Automobile Manufacturers' Association Specifications[5] for the 1969 American Motors line of automobiles. In some cases, field measurements were conducted in absence of available information. The driver characteristics were obtained by field investigations as well as from published information[1]. The details of the input data are listed below. The numbers within parentheses represent the information for the example problem.

1. Roadway characteristics
   a. Offset distances between the ramp and the freeway measured at right angles to the ramp at each of the six stations through the ramp dilemma zone of six different ramp geometric configurations.
   b. The acute angles of intersection between the offset line and the freeway tangent at the intercept points through the projection of the ramp dilemma zone for the six ramp geometric configurations.
   c. The elevation differences between the individual ramp stations and the freeway for six different ramp geometric configurations.
   d. The distances from the ramp nose to the offset intercept points for six ramp terminal situations.

   The items a,b,c and d are presented in Tables 1 and 2.

   e. The length of the freeway section, in feet (500).
   f. The length of the ramp in numbers of 50 foot stations (6).

2. Traffic characteristics
   a. Total volume on the freeway lane adjacent to the ramp, in vehicles per hour, (2000).
   b. The mean and standard deviation of ramp vehicle speeds, in mph (35,5).

3. Vehicle characteristics
   a. The mean and standard deviation of each of the following parameters for ramp vehicles: vehicle sill height, side window opening, frame to ground clearance, length of cockpit, "H" point distance to the front of the windshield at the base, the distance from the steering wheel centerline to the vehicle

centerline, hiproom, vehicle width, and distance from the front of the windshield at its base to the face of the rear view mirror.

b. The mean and standard deviation of the values for the freeway vehicle height and ground clearance.

The items a and b are included in Table 3.

4. Driver characteristics

a. The mean and standard deviation of driver's eye height.

b. The mean and standard deviation of both right and left hand rotation angles.

The data relating to driver physiology are summarized in Table 4.

5. Program control

a. The number of ramp vehicles to be processed (500).

b. The number of geometric configurations to be considered (6).

Simulation Results

On-Ramp Approaches Freeway From Above - The results of the simulation runs in the three cases of the right hand ramp merging from above are tabulated in Table 5. In all three geometric situations, only the horizontal vision angle was examined. It was assumed that a ramp driver is able to look over his side door sill in the vertical plane and experience no difficulty in observing a freeway vehicle on the roadway beneath him.

It may be noted from the simulation results that the geometric configuration of Case I offers the ramp driver the best quality of vision of the freeway vehicle; Case II is somewhat inferior to Case I; and Case III appears to be the least adequate.

On-Ramp Approaches Freeway From Below - The results of the simulation runs in the three cases of the right hand merging from below are presented in Table 6. The major difference between this merging situation and the previous one is that the ability of the ramp driver to see freeway vehicle in the vertical plane may be impaired by the top of his side door. Therefore, for this situation, in addition to the vision in the horizontal plane, the vision in the vertical plane was also examined.

From an inspection of the output data it can be found that vertical vision in Case II and III type ramp terminals is somewhat better than in Case I, although in all three cases, the number of drivers able to see the freeway vehicle was quite high. This indicates that impairment of vertical vision is probably not a major problem for right hand ramps merging from below.

Vision in the horizontal plane was of the best quality for Case I. It diminished for Case II ramps approaching the freeway from below and was lowest for Case III situations.

Effect of Ramp Vehicle Location and Ramp Geometry - It may be noted from the simulation results that in all ramp geometric configurations, quality of clear vision decreases as the ramp vehicle approaches the ramp nose. This decrease in vision quality is caused because the length of the freeway segment scanned by the ramp driver in the horizontal plane is reduced as the ramp vehicle moves in a lateral direction toward the freeway. Therefore, the driver's ability to detect freeway vehicle is reduced accordingly since there would be less chance of this car being in the shorter space.

Vision in the Outside Rear View Mirror - In order to fully examine vision quality for the right hand merge from above, it was decided that rear vision should be tested in both the horizontal and vertical planes to determine whether it might have a significant effect on merge vision. As shown in Table 7 rear view horizontal vision appeared to be significant, especially for Case III ramps. However, in all three cases, rear vertical vision was negligible. Therefore, it is obvious that along the ramp dilemma zone, for a right hand merge from above, the outside rear view mirror is of little use in the visual detection of freeway vehicle because the driver is almost never able to see this car in the vertical rear vision plane.

Conclusions

1. The technique of Monte Carlo simulation offers a tool that can be well utilized in building a general model on a computer to describe visual kinematics while merging from an on-ramp. Such a model can be applied in the analysis of the problems associated with the geometric design of freeway merging areas.

2. A general simulation model was developed to investigate twelve types of ramp entrance terminals. It was designed to examine the ramp driver's ability to see the freeway vehicle behind which he must merge while he is driving through the ramp dilemma zone. An example problem involving six types of ramp geometric configurations for right hand merging was discussed to illustrate the use of the proposed model.

3. The development of the proposed model was realized in two steps. First, mathematical models were constructed to describe the various micro-aspects of the system--including the roadway, the vehicle, the driver and the traffic conditions. Then, a computer program was written to sequentially process the inter-related components, thereby effecting a dynamic solution of the abstracted system.

4. The program logic was divided into six parts. Separate routines were prepared for preloading the freeway system with random vehicles, generating vehicles with randomly selected characteristics, determining vertical sight angles for ramps approaching the freeway from above and below, determining horizontal sight angles and for updating the system.

5. The exact nature of output information would depend on the specific aspects of the ramp geometrics to be analyzed. In general, the proposed model provides information about the distribution of successful observations of freeway vehicle by a ramp driver attempting to merge either from a left-hand or a right-hand on-ramp. This enables the 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 which will optimize ramp driver vision and enhance safety.

6. 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.

7. For right hand merging situations Case I ramps provide better visual quality than do Case II ramps. Case II ramps, in turn, function better than Case III ramps.

List Of References

1. Alderson Research Laboratories, Human Simulations for Automotive and Aerospace Applications, Anthrolab, Stamford, Connecticut, 1968.

2. American Association of State Highway Officials, A Policy on Geometric Design of Highways, Washington, D.C., 1967.

3. Automobile Manufacturers' Association, Specifications--Passenger Car, S.A.E. Car and Body Dimensions for American Motors Automobiles of the 1969 Model Year, October 1, 1968.

4. Highway Research Board, Highway Capacity Manual, Special Report 87, National Academy of Sciences, pp. 40, 1965.

5. Matson, Theodore M., Wilbur S. Smith and Frederick W. Hurd, Traffic Engineering, McGraw-Hill Book Co., New York, 1955.

6. Massachusetts Institute of Technology, Engineer's Guide to ICES COGO I, Civil Engineering Systems Laboratory, Cambridge, Massachusetts, August, 1967.

7. Sinha, K.C., "The Development of a Digital Simulator for the Analysis of Freeway Traffic Phenomena," Research Report, Civil Engineering Department, University of Connecticut, 1968.

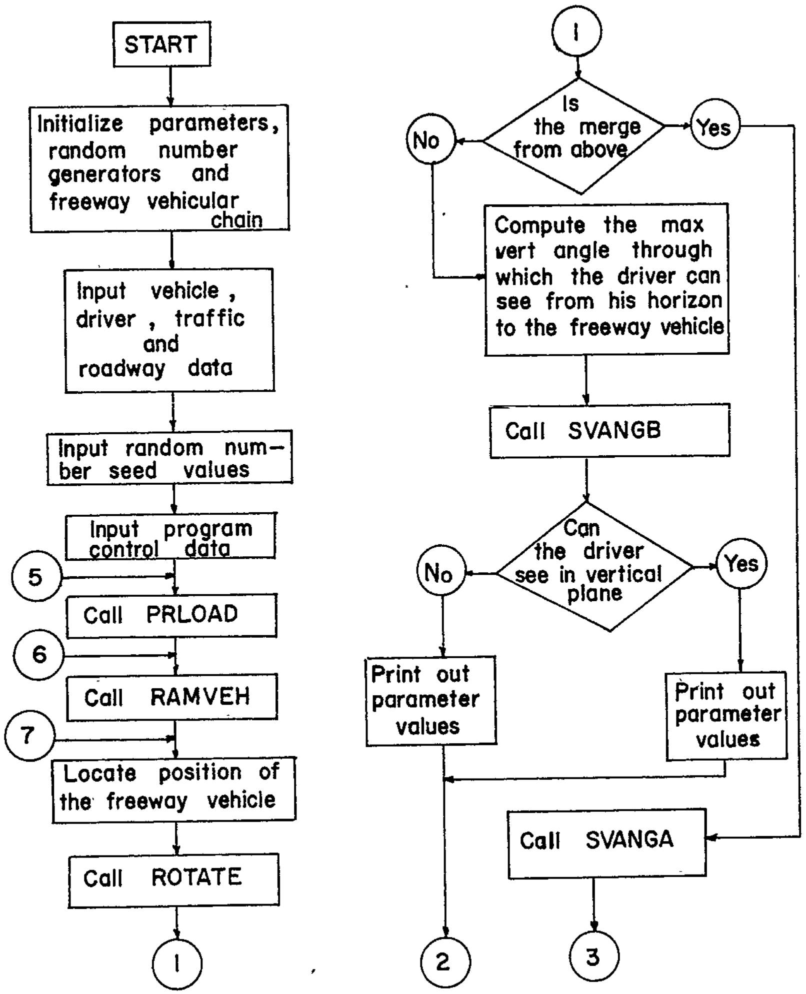

FIGURE I OVERALL LOGIC OF THE LEFT HAND MERGE

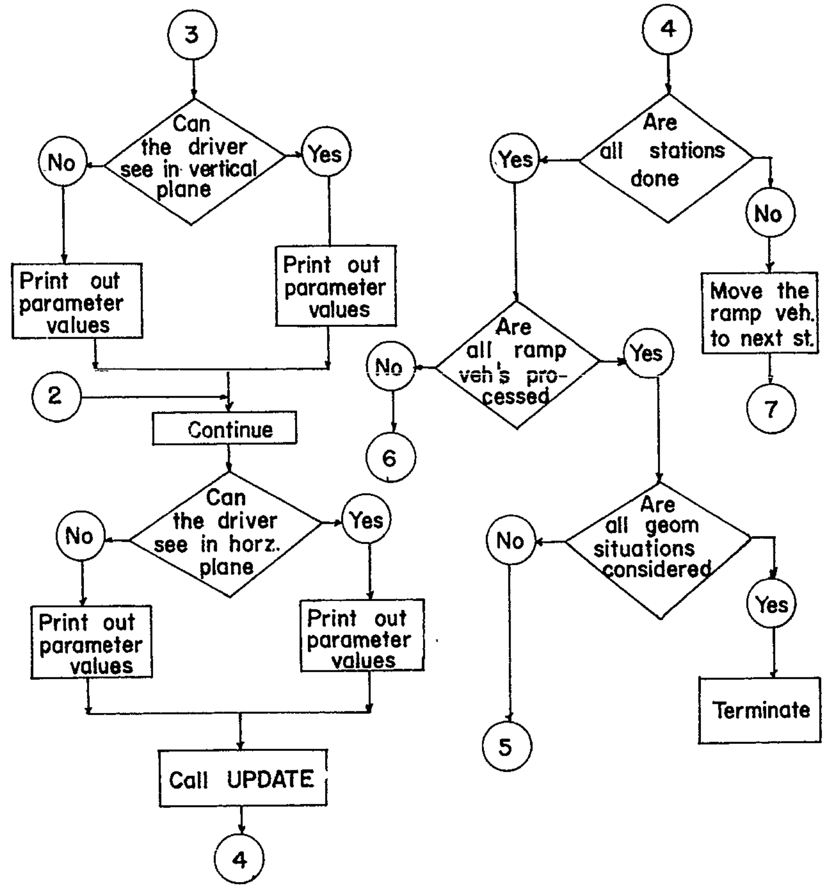

FIGURE I OVERALL LOGIC OF THE LEFT HAND MERGE (Continued)

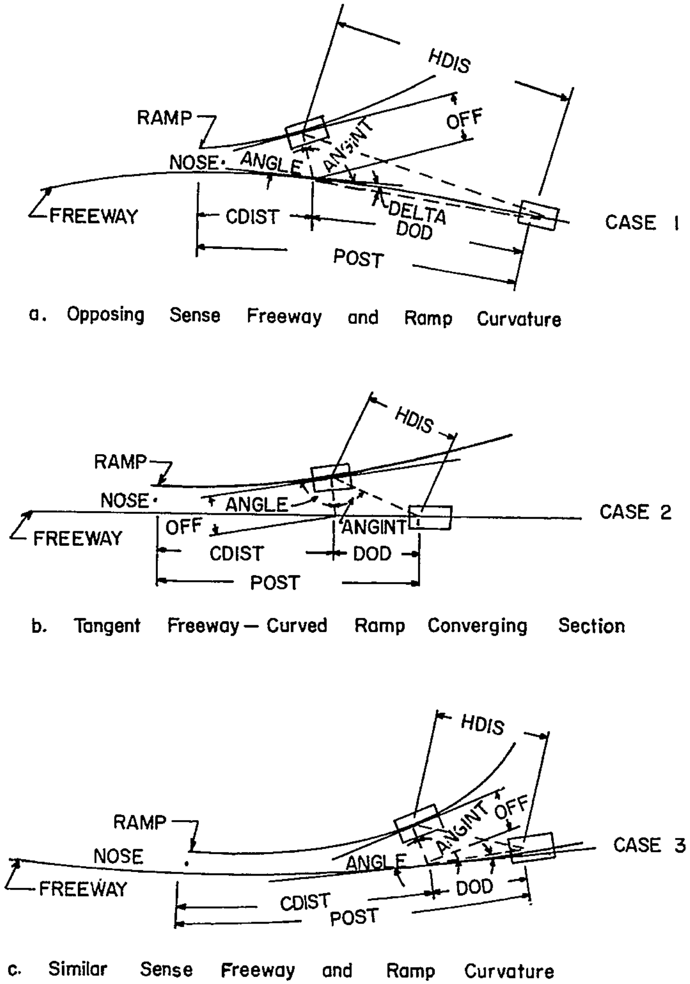

FIGURE 2 BASIC TYPES OF FREEWAY-RAMP GEOMETRIC CONFIGURATION

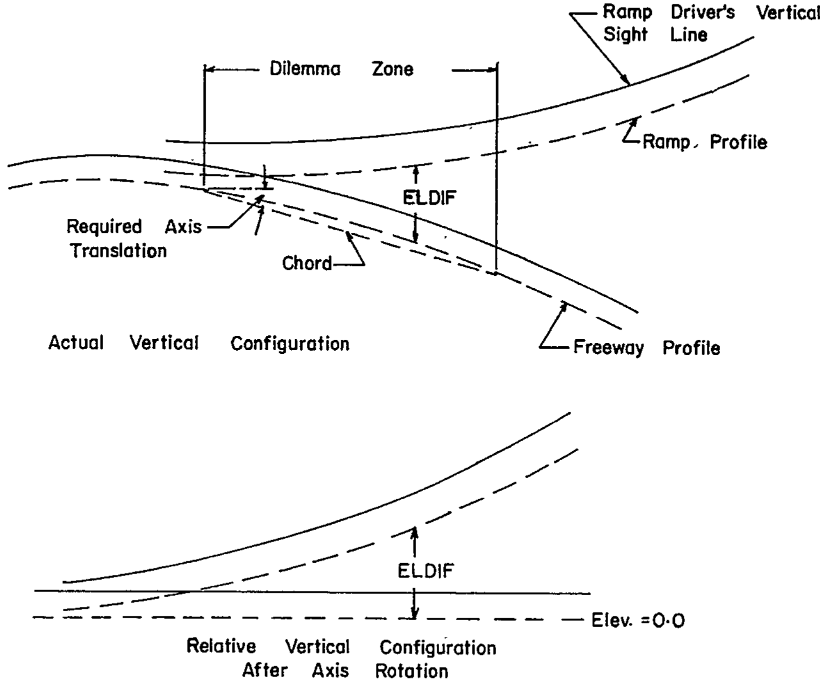

FIGURE 3 VERTICAL AXIS ROTATION OF THE DILEMMA ZONE

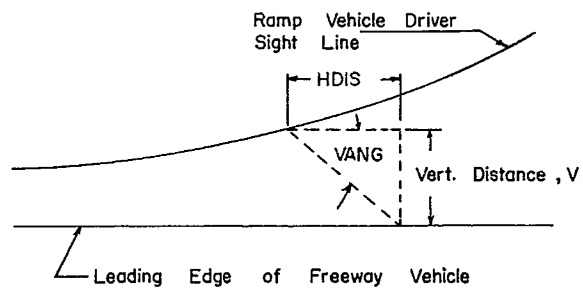

FIGURE 4 METHOD OF COMPUTING THE VERTICAL ANGLE BETWEEN THE RAMP VEHICLE AND FREEWAY VEHICLE

TABLE I

RAMP GEOMETRIC INPUT DATA FOR RAMPS APPROACHING FROM ABOVE

Ramp Control Point	Offset Distance (OFF) Feet	Distance Upstream From Ramp Nose to Offset Intercept Point on Freeway (CDIST) Feet	Acute Inter-Section Angle of Offset Line (ANGLE) Degrees	Relative Pavement Elevation Difference (ELDIF) Feet	Geometric Situation
1	143.52	331.80	63.083	3.26	Case I Opposing Sense Curves
2	118.01	272.55	65.895	1.63	
3	95.89	215.27	68.673	0.33	
4	76.90	159.64	70.403	-0.64	
5	60.82	105.37	74.117	-1.27	
Nose	47.47	52.23	76.800	-1.57	
1	102.04	317.71	73.271	3.26	Case II Ramp Curved Freeway Tangent
2	87.02	263.10	74.792	1.63	
3	73.58	209.26	76.312	0.33	
4	61.70	156.12	77.833	-0.64	
5	51.31	103.59	79.355	-1.27	
Nose	42.38	51.57	80.875	-1.57	
1	60.35	308.37	83.655	3.26	Case III Same Sense Curves
2	54.82	256.56	84.110	1.63	
3	49.73	204.94	84.577	0.33	
4	45.08	153.49	85.049	-0.64	
5	40.86	102.20	85.522	-1.27	
Nose	37.08	51.04	85.920	-1.57	

TABLE 2

RAMP GEOMETRIC INPUT DATA FOR RAMPS APPROACHING FROM BELOW

Ramp Control Point	Offset Distance (OFF) Feet	Distance Upstream From Ramp Nose to Offset Intercept Point on Freeway (CDIST) Feet	Acute Inter-section Angle of Offset Line (ANGLE) Degrees	Relative Pavement Elevation Difference (ELDIF) Feet	Geometric Situation
1	143.52	331.80	63.083	2.07	Case I Opposing Sense Curves
2	118.01	272.55	65.895	1.92	
3	95.89	215.27	68.673	1.80	
4	76.90	159.64	70.403	1.71	
5	60.82	105.37	74.117	1.64	
Nose	47.47	52.23	76.800	1.61	
1	102.04	317.71	73.271	2.07	Case II Ramp Curved Freeway Tangent
2	87.02	263.10	74.792	1.92	
3	73.58	209.26	76.312	1.80	
4	61.70	156.12	79.355	1.71	
5	51.31	103.59	79.355	1.64	
Nose	42.38	51.57	80.875	1.61	
1	60.35	308.37	83.655	2.07	Case III Same Sense Curves
2	54.82	256.56	84.110	1.92	
3	49.73	204.94	84.577	1.80	
4	45.08	153.49	85.049	1.71	
5	40.86	102.20	85.572	1.64	
Nose	37.08	51.04	85.920	1.61	

TABLE 3

PARAMETERS RELATING TO THE VEHICLE CHARACTERISTICS

Parameter Dimension (in inches)	Mean Inches	Variance	Standard Deviation (in inches)	Sample Size or Basis for Estimate
Vehicle sill height	37.06	1.2	1.1	12 vehicle models of AM line (1969 AMA specifications)
Side window opening	11.8	0.6	0.8	"
Frame to ground clearance ramp vehicle	6.3	0.2	0.4	"
Frame to ground clearance freeway vehicle	6.3	0.2	0.4	"
Length of cockpit	102.7	43.5	6.6	"
"H" point to front of windshield	30.9	2.9	1.7	"
Distance from steering column centerline to vehicle centerline	14.4	0.5	0.7	"
Vehicle hip room	58.8	2.2	1.5	"
Vehicle overall width	71.8	14.4	3.8	"
Overall vehicle height	54.3	2.2	1.5	"
Distance from the face of the outside rear view mirror to the front of the windshield	18.6	24.0	4.9	Field measurements of 20 vehicles ranging in age from 1 to 9 years
Distance between the centerline of the steering column and the centerline of regard of the rear view mirror	19.5	4.0	2.0	"
Distance from the pavement to the centerline of regard of the rear view mirror	39.2	1.7	1.3	"

TABLE 4

PARAMETERS RELATING TO DRIVER PHYSIOLOGY

Parameter	Mean	Variance	Standard Deviation	Sample Size or Basis for Estimate
Driver's Eye Height (EYEHT) in inches	34.9	12.25	3.5	Mean Value 50th Percentile Alderson Co. Anthropoid
Head Rotation Angle to Left (DHROTL) in degrees	67.8	63.4	7.96	40 Male Drivers 120 Measurements
Head Rotation Angle to Right (DHROTR) in degrees	63.9	60.4	7.77	40 Male Drivers 120 Measurements

TABLE 5

NUMBER OF DRIVERS THAT CAN SUCCESSFULLY SEE FREEWAY VEHICLE IN RIGHT-HAND MERGES FROM ABOVE

Ramp Control Point	Geometric Configuration	Horizontal Plane Vision	Number of Opportunities	Percent Clear Vision
1		340	401	84.7
2		324	457	70.8
3	Case I	302	479	63.0
4		276	489	56.4
5		232	494	46.9
Nose		165	496	33.2
1		257	416	61.7
2		274	468	58.5
3	Case II	251	485	51.7
4		221	492	44.9
5		203	496	40.9
Nose		145	497	29.1
1		187	426	43.8
2		155	472	32.8
3	Case III	174	484	35.9
4		152	493	30.8
5		156	494	31.5
Nose		113	494	22.8

TABLE 6

NUMBER OF DRIVERS THAT CAN SUCCESSFULLY SEE FREEWAY VEHICLE IN RIGHT-HAND MERGES FROM BELOW

Ramp Control Point	Geometric Configuration	Vertical Plane Vision	Horizontal Plane Vision	Clear Vision (Both Planes)	Number of Opportunities	Percent Clear Vision
1		392	358	340	414	82.1
2		444	342	323	467	69.1
3	Case I	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
1		409	292	278	430	64.6
2		444	266	253	467	54.1
3	Case II	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
1		407	175	167	424	39.3
2		449	156	151	464	32.5
3	Case III	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 7

NUMBER OF DRIVERS THAT CAN SUCCESSFULLY SEE FREEWAY VEHICLE IN THE REAR VIEW MIRROR IN A RIGHT-HAND MERGE FROM ABOVE

Ramp Control Point	Geometric Situation	Rear Vertical Plane	Rear Horizontal Plane	Vision to Rear in Both Planes
1		0	6	0
2		0	25	0
3	Case I	0	48	0
4		0	67	0
5		0	98	0
Nose		4	189	4
1		0	31	0
2		0	66	0
3	Case II	0	99	0
4		1	110	1
5		2	157	2
Nose		8	219	8
1		0	123	0
2		0	179	0
3	Case III	0	188	0
4		0	202	0
5		1	219	1
Nose		6	257	6