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DEVELOPMENT OF A COMPUTER SIMULATION TO EVALUATE THE EFFECTIVENESS OF VEHICLE REAR MARKING AND SIGNALING SYSTEMS

William L. Carlson
Rudolf G. Mortimer

Highway Safety Research Institute
The University of Michigan
Ann Arbor, Michigan 48105

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Motor Vehicle Manufacturers Association
320 New Center Building
Detroit, Michigan 48202

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16. Abstracts An analysis of individual car-following behavior was developed using a Monte Carlo computer simulation model. The period during which the headway distance between the vehicles is being reduced is divided into a detection phase, a decision phase, and an action phase. The relationship of these phases to distance and relative velocity between moving vehicles was studied both analytically and empirically. Data sources included: velocity and headway measures from an instrumented highway, qualitative and quantitative glance patterns of drivers recorded by an eye camera, and video tape recordings of vehicles closing on slow moving vehicles. These data were combined with the analytic results to indicate the infrequency of "critical events" in actual highway driving. Thus, a Monte Carlo simulation model was prepared in order to study more completely the variables leading to critical events. As an example of an application of the simulation model, a lead vehicle velocity signal was evaluated, which was a display concept that reduced the predicted number of crashes.

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OBJECTIVES

The objectives of this study were:

1. To obtain some empirical data of relative velocity and headway distance in car-following and in passing, and Eye Marker measurements of drivers in closing situations.

2. To develop a digital computer simulation of a situation in which a vehicle, moving in the same direction as another slower moving vehicle, creates a potentially hazardous situation which requires the driver to take action to avoid a crash.

3. To conduct analyses, using the model, to evaluate its sensitivity to changes in some parameters of the car-closing situation.

4. To obtain insights into elements of the closing situation that can be applied to deriving some information useful to the following driver.

5. To make some preliminary analyses of rear lighting displays of lead vehicle speed category upon rear-end crashes in a closing situation.

6. To show some of the additional data, of driver perception and response in closing situations, needed to be obtained by human factors experiments for inclusion in the model to increase the scope and fidelity of the evaluations that can be made with it, and to suggest vehicle rear marking and signaling systems that warrant further study in simulation and driving tests.

SUMMARY OF FINDINGS

1. Data of inter-vehicle headways and relative speeds show that there are few cases where critical boundaries, in terms of headway distance and relative speed, are exceeded. When they occur, such cases can be characterized by headways of less than 150 feet and relative speeds of 40-50 ft/sec.

2. While there is no relationship between headway and relative speed for unconstrained vehicles, for headways greater than about 150 feet, at smaller headways a relationship was noted. This suggests that drivers are primarily using headway distance information at distances greater than about 150 feet, and become concerned about relative velocity and headway at distances less than this.

3. In the three cases where vehicles were constrained from passing, on a multi-lane limited access road, there was a linear relation between headway and relative velocity, for headways of up to 200 feet. More data should be obtained to verify such a relationship, particularly at longer headways.

4. Based on these data the concept of "relative headway," the instantaneous time to crash, was derived as headway distance/ relative velocity as a perceptual or risk threshold which a driver does not willingly ignore in initiating a response to a car in front of him. The empirical data also showed that values of relative headway as low as 2.0 seconds can be readily observed, albeit rarely.

5. Eye Marker data obtained in freeway driving were obtained and analyzed by glance duration and location to provide empirical distributions of these variables, and an equation was derived to describe them.

6. These data were combined with other empirical distributions such as braking deceleration and reaction time to stop/turn signals, to form a vehicle closing Monte Carlo simulation model.

7. Results of sensitivity analyses of model parameters showed that the predicted percentage of events resulting in a crash was most clearly influenced by: relative headway, the driver's spatial viewing pattern, relative velocity, and the maximum distance at which passing can occur.

8. In illustrating a use of the model to evaluate velocity displays given by vehicle rear lamps, it was found that such displays may aid in reducing rear-end collisions.

9. The model offers a means of determining information requirements of drivers, of assisting in the definition of driver behavior data that remains to be gathered, and of providing preliminary evaluation of the effectiveness in reducing crashes of various vehicle rear lighting and signaling displays.

INTRODUCTION

The evaluation of proposed improvements to vehicle marking and signaling systems should be conducted on several different levels. The first of these concerns the value of the information to be transferred. Thus, it should be determined whether the information displayed is redundant or whether it may overload the driver's information input channels. For example, a coasting signal may alert a driver to an upcoming brake signal. However, if this signal comes on frequently without being followed by a brake signal, the signal may be ignored. Next it should be determined how a driver might use the information. One limiting case of this analysis is that he might ignore the information. Another important question is whether or not the anticipated use of the information will enable the driver to operate his vehicle better, and result in fewer crashes. In addition, there is the question of how to best transfer the given information once it has been determined that the information would be valuable. A great deal of effort has been devoted to this problem, as it concerns the vehicle rear marking and signaling display. Generally, this involves questions such as signal intensity, intensity ratio, color, lamp separation by function, etc. (e.g., Mortimer, 1970a).

In this study the effort is directed toward an evaluation of the potential usefulness of a unit of information, given that it is used in the anticipated manner. In a previous study a Monte Carlo simulation model was developed for comparing various brake signal configurations, given an emergency conflict situation (Carlson, 1972). That model was run using actual measured driver perception times for several different rear lighting configurations (Carlson & Mortimer, 1970). The results of the analysis indicated a potential reduction in frequency and severity of rear-end crashes for some experimental rear signaling systems. In that case the assumption was made that a lead car made an emergency stop and the driver of the following car had to react to a brake signal and stop in order to avoid a crash.

The present study has the same methodological basis. In particular it deals with the value of information coded in rear lighting signals, given a vehicle approaching at a high relative velocity another vehicle from a long distance (e.g. greater than 600 feet). In this situation the approaching driver either detects the slower moving vehicle and takes appropriate action, i.e., reduces velocity or passes, or he crashes into the rear of the lead vehicle. This situation was studied both empirically and analytically. Based upon this analysis, a Monte Carlo simulation was developed for use in further study of the situation and evaluation of potentially useful vehicle rear lighting systems.

ANALYSIS OF VEHICLE CLOSING SITUATIONS

For the development of this analytic model two parameters--relative velocity of two vehicles and distance between vehicles--will be used. Using these parameters it is possible to describe each closing situation as a series of points--defined by a distance and relative velocity in a two-dimensional space. The model begins with the following principle:

> In every two vehicle closing situation there is a maximum time available before a crash occurs. During this time some action must be taken to avoid a crash. Therefore, it is possible to develop relationships which define critical or boundary conditions.

The boundary conditions can be described as:

Total time available to reduce relative velocity to zero	$\geq$	Time to detect closing	+	Time of no action by driver and reaction time to apply brake	+	Braking time available to reduce relative velocity to zero

In mathematical terms:

$$\frac{D_o}{\Delta\bar{V}} \geq T_1 + T_2 + \frac{\Delta V_o}{\bar{a}} \qquad (1)$$

Where,

D_o Initial distance at which the lead vehicle becomes apparent to the following vehicle.

$\Delta\bar{V}$ Average closing velocity over the critical period.

T_1 Time required by the driver of the following car to detect that closing is occurring.

T_2 Time during which the driver of the following car does not take any action.

ΔV_o Initial relative velocity.

$\bar{a}$ Average braking rate for following vehicle.

From this basic relationship it is possible to establish certain threshold levels for car-following behavior.

These threshold levels can be defined as functions or boundaries which divide the two dimensional space into zones. One of these, the critical boundary, is defined as the latest time at which the following car must begin decelerating in order to avoid crashing into the lead vehicle, given the constraint that the driver does not steer away. Another boundary, the early closing detection boundary, is defined as the earliest time at which the driver of a following car could detect that he was closing on the lead vehicle. The third boundary, the late closing detection boundary, is defined as the time at which the driver of the following car should begin looking at the lead car, and allows the driver some time to detect closing, to make a decision to brake, and to reduce velocity before striking the lead vehicle. If drivers operated such that their relative velocity and distance were on this boundary they would be at a uniform risk level throughout the closing maneuver. These three boundary functions are shown in Figure 1. The details of their development follow below.

Cirtical Boundary. This relationship can be developed from equation 1 by assuming that T_1 and T_2 equal zero and that the average closing velocity is equal to one half of the initial relative velocity. This assumes a uniform braking rate over the entire deceleration.

$$\frac{D_o}{\frac{\Delta V_o}{2}} \geq \frac{\Delta V_o}{\bar{a}} \qquad (2)$$

$$(\Delta V_o)^2 \geq 2\,\bar{a}\,D_o \qquad (3)$$

If the relative velocity is greater, or the distance or deceleration smaller, than the boundary conditions in equation (3), a crash will occur.

In Figure 1 the critical boundary is obtained from equation 3 by assuming a moderate brake deceleration of 10 ft./sec.^{2} Thus, any car-closing situations, defined by relative velocity and distance, which are above the critical boundary will result in a crash if braking is limited to 10 ft/sec^2. This also assumes that brakes are applied immediately.

Early Closing Detection Boundary. From Hoffman (1968) and Mortimer (1971) expected median detection of closing occurs when

$$\frac{\Delta D}{D} \geq \frac{1}{8} \qquad (4)$$

When D is "large." when D is "small" (Hoffman, 1968) coasting is expected to be detected when

$$\frac{d\theta}{dt} = \frac{W\Delta V}{D^2} \geq 3.86 \times 10^{-3} \quad \text{rad/sec.} \qquad (5)$$

W - width of lead vehicle

From equation (4)

$$8\Delta D \geq D$$

let $D = (T_1 + T_2)\,\Delta V + T_A\Delta V$

$$8\,T_A\Delta V \geq D \qquad (6)$$

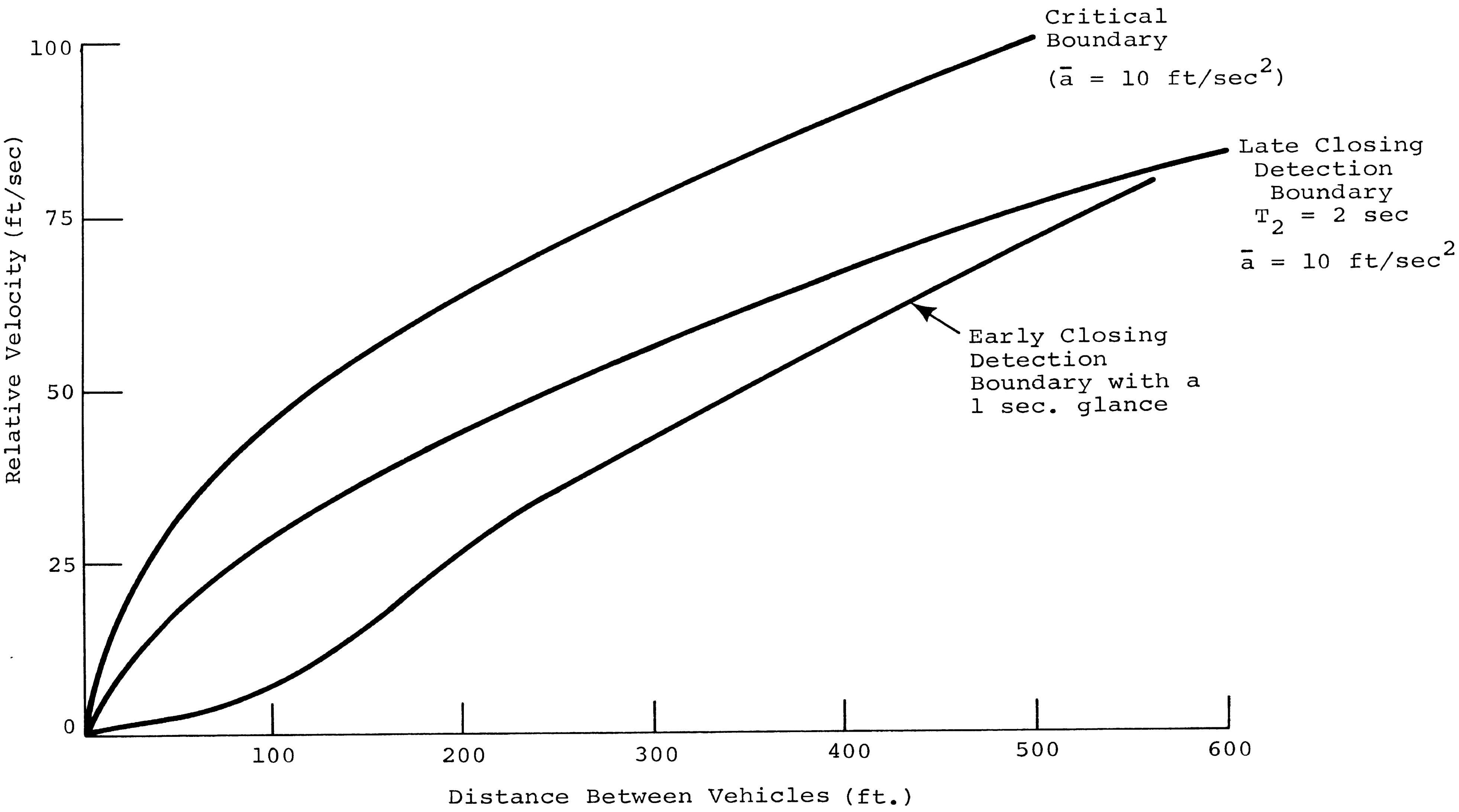


Figure 1. Boundary conditions for the car closing problem.

The boundary between "large" and "small" distances is found by equating ΔV from equations (5) and (6).

from (5)

$$\Delta V \geq 3.86 \times 10^{-3} D^2/W \qquad (7)$$

from (6)

$$\Delta V \geq \frac{D}{8T_A} \qquad (8)$$

then, $3.86 \times 10^{-3} \frac{D^2}{W} = \frac{D}{8T_A}$

if: $W = 6$ feet, $T_A = 1$ second

then, $D = 194$ feet.

Thus, below 194 feet equation (7) can be used for closing detection and above 194 feet equation (8) can be used. By this procedure a lower boundary on the relative velocity versus distance curve can be generated and is shown in Figure 1 as the early closing detection boundary. Below this curve the driver does not detect closing with a glance time of 1 second at the preceding vehicle.

Late closing Detection Boundary. This boundary is developed by assuming that the driver first detects closing--using the change in relative distance--and then delays T_2 seconds before brake application. To simplify the development of this boundary the following terms will be defined:

$\frac{\Delta V}{a}$ - Time required to reduce the relative velocity to zero.

a - Brake deceleration

$\frac{D}{8}$ - The distance covered while the driver is detecting closure of the lead vehicle.

T_2 - The time that the driver has available after he detects closure and before he begins to brake.

We can now determine the distance at which the driver begins braking as follows:

Distance at which braking begins = Original Distance − Detection Distance − Distance covered after detection of closure but before braking.

$$D_B = D - \frac{D}{8} - T_2 \, \Delta V \qquad (9)$$

If the braking occurs at a constant rate the average velocity over the distance D_B is equal to one half of the initial velocity. We can then use this distance and average velocity to obtain a second expression for time to brake:

$$\text{time to brake} = \frac{D_B}{\Delta V/2}$$

Therefore,

$$\frac{\Delta V}{a} \geq \frac{D_B}{\Delta V/2} \qquad (10)$$

by appropriate substitutions and algebra we obtain:

$$\frac{\Delta V}{a} \geq \frac{D - \frac{D}{8} - T_2 \, \Delta V}{\Delta V/2} \qquad (11)$$

$$\Delta V \geq \frac{a}{2}\left[-2T_2 \pm \sqrt{4T_2^{\;2} + \frac{7D}{a}}\right] \qquad (12)$$

For example let:

$a = 10$ ft/sec^2

$T_2 = 2$ secs.

$$\Delta V \geq 5 \left[-4 + \sqrt{16 + \frac{7D}{10}}\right] \quad \text{ft/sec.}$$

This relationship is shown in Figure 1 as the late detection boundary. This detection boundary is the point at which the driver will have to begin to observe the lead car if he is to have T_2 seconds free after detection of closure and before beginning to brake.

These boundaries define zones with increasing risk as one moves from the lower right to the upper left section of the graph. If a driver had perfect information on distance and relative velocity and operated rationally he would reduce his velocity as the distance between vehicles reduced in a manner that would provide a uniform level of "risk." One rational strategy might be to move along the late closing detection boundary--defined by the T_2 and $\bar{a}$ parameters--which best expressed his choice of "risk." An interesting insight results from the observation that the late closing detection boundary and the early closing detection boundaries cross at a distance of approximately 570 feet. At distances greater than 570 feet a driver would have to glance at the lead vehicle for longer than one second in order to detect closing. Thus, an idealized model has been developed which indicates how relative velocity and distance information can be used to avoid crashes. The next step in the analysis was a comparison of actual highway data with this model.

COMPARISON OF IDEALIZED CLOSING MODEL WITH ACTUAL HIGHWAY DATA

The objective of this task was to determine how drivers actually behave during high relative velocity closing situations. By comparing actual behavior with the idealized model it was anticipated that a better understanding of this process would result, which might lead to specific recommendations concerning information requirements. The ideal comparison would involve the actual closing relationship--relative velocity as a function of distance--for a randomly selected sample of drivers. It was considered desirable to avoid problems that can occur when drivers are placed in an instrumented vehicle since they might operate differently from their normal behavior because they are aware they are under observation. Thus, it was decided to obtain some measurements from actual highway situations, in which measurements were made by drivers in an unobtrusive way. Data were collected from both two-lane rural highways and four-lane divided limited access expressways. In this way it was possible to study drivers in situations where passing was restricted and where it was not restricted.

LIMITED ACCESS EXPRESSWAY DATA. Expressway data were obtained by observing cars approaching a station wagon traveling at 45 mph on an expressway where the speed limit was 70 mph. This was done on a clear day at a time when traffic flow was light. It allowed passing cars to see the station wagon from a long distance and to pass whenever they chose. A TV camera, mounted facing rearward in the station wagon, was used to record on video tape the behavior of each approaching vehicle. These tapes were then played back and the distance at which the vehicle began to pass was measured. In addition, the time required to cover the distance from that point to the vehicle was measured and used to compute relative velocity.

ANALYSIS OF EXPRESSWAY CLOSING PATTERNS. The data collected from the video tape of vehicles closing on a station wagon moving along US-23 from Ann Arbor to Toledo is presented in Figure 2. Following our risk model we have plotted all cases in distance vs. relative velocity space. In addition, the typical boundaries have been superimposed on the graph. The following observations are appropriate:

1. As we have seen in other data of this type, none of the drivers were above the critical boundary (e.g. the critical boundary is the set of conditions such that if the driver of the following car began braking--in this case at 10ft/sec^2--he would reduce his relative velocity to zero at the point that the two vehicles touched).

2. A few drivers are above the late detection boundary (e.g. this is based upon the time required for a driver to detect closing, allow 2 secs. for decision, and brake at 10 ft/sec^2).

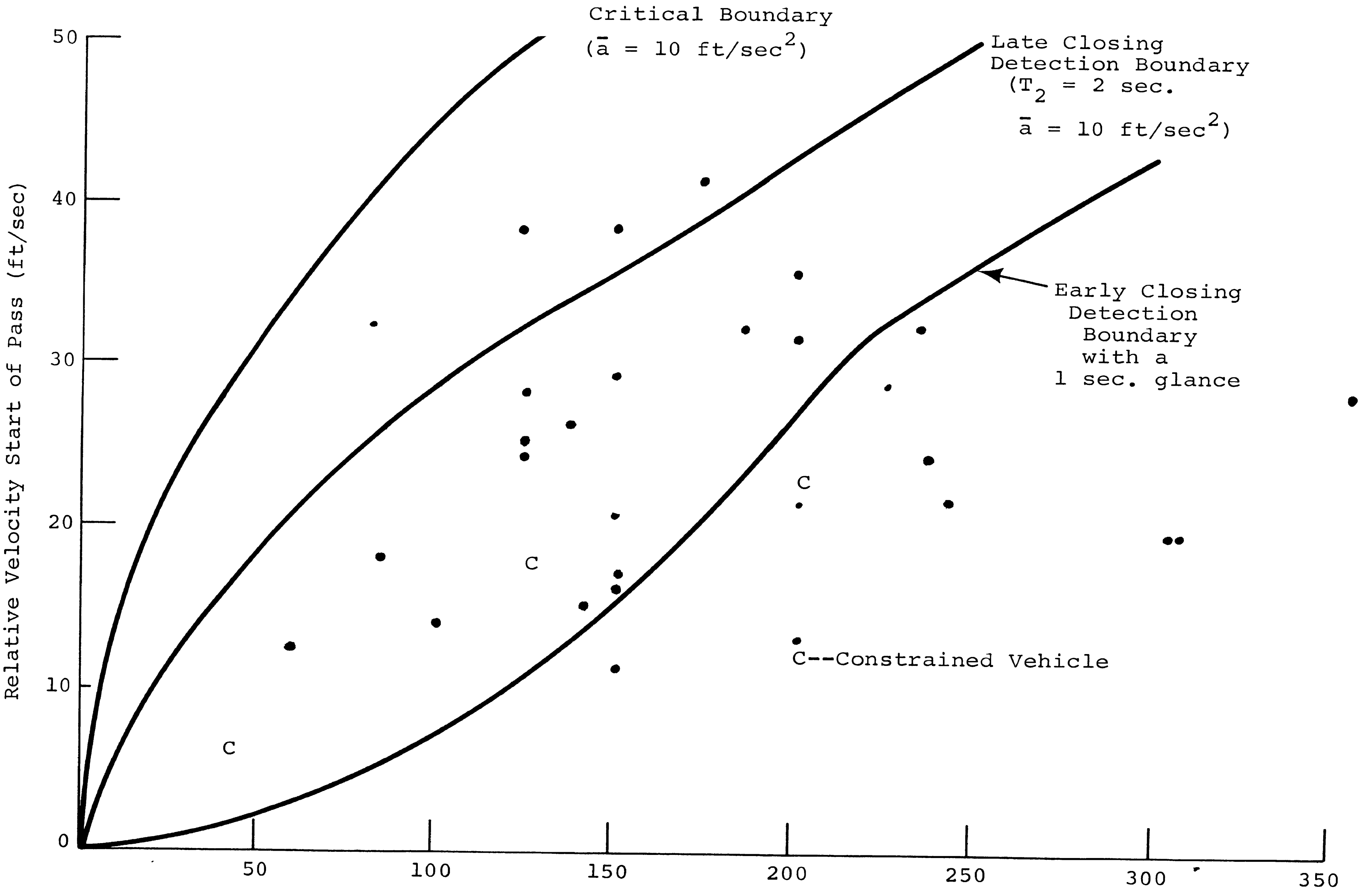


Figure 2. Start of pass point expressway drivers following a slow-moving vehicle.

3. Based on 1 and 2 it can be seen that even on the expressway, where passing is easy, there are very few critical closing situations.

4. Distance between vehicles and relative velocity are independent, except at distances less than 100 feet for unconstrained vehicles.

5. It is of some interest to note that for the three cases marked with C, in which vehicles were constrained to one lane, the relationship between relative velocity and distance appears to be linear. In a study by Rockwell and Banasik (1968), drivers in a test vehicle closed on a lead car at a fairly uniform relative speed until they were within about 200 feet of it, when they reduced the relative velocity. Thus, they exhibited similar behavior as the unconstrained drivers, although they were instructed to approach, but not pass, the lead car. This suggests that it would be useful to try to obtain additional data on the closing behavior of constrained vehicles on expressways, but it appears doubtful that a linear relationship would be found at headways longer than 200 feet.

6. The cases which are closest to critical boundaries are those between 100 and 200 feet and with relative velocities around 40 ft/sec.

ANALYSIS OF HIGHWAY DATA FROM TWO-LANE RURAL HIGHWAYS. Data for two-lane highway closing situations were obtained from a project conducted at the Public Safety Research Institute, University of Indiana. That project used sensors, buried in the road, to measure the velocity and clock time for all vehicles passing particular highway locations. From those data it was possible to compute relative velocity and distance between vehicles for all vehicles passing a particular location on the highway.

These data have a number of potential uses in the study of car-following behavior. In particular, Figure 3 was prepared to compare actual driver behavior with the model presented in Figure 1.

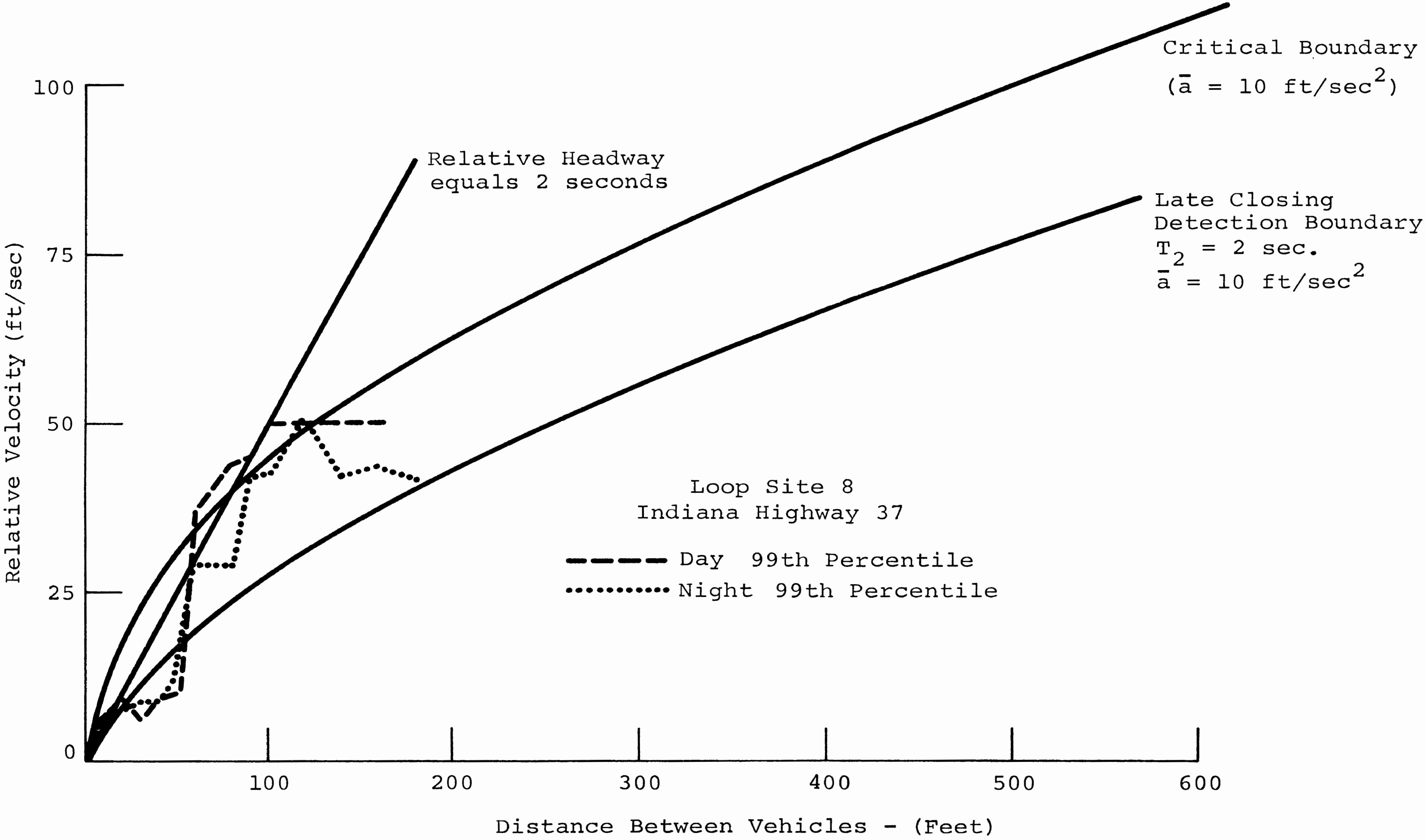


Figure 3. Vehicle spacing on a two-lane road.

The location used for these data is not typical of two-lane highways. It is on an uphill section of the road which occurs immediately after a downhill section. In addition, slow moving stone trucks enter the highway at the bottom of the hill. Thus, the site was chosen as one at which large closing velocities were expected.

The 99th percentile of the relative velocity distribution was determined for distances between vehicles grouped in 20-foot increments. These points represent "worst cases" of high closing velocities at short distances. As shown, drivers only operate close to the critical boundary at distances less than 140 feet. These critical 99th percentile cases, occurred at relative velocities between 40 and 50 feet per second, which were the highest relative velocities found at this location. As for the data collected on unconstrained vehicles on the limited-access road, it can be concluded that drivers do not equalize their risk of crash at various distances. Instead, they realize at some headway that the situation is critical and begin to reduce their velocity.

An interesting parameter results from dividing distance by relative velocity--defined as relative headway. Relative headway is the number of seconds until crash, given that no adjustment in relative velocity occurs. The maximum relative headway shown in Figure 3 is about two seconds. This appears to be a final decision point for drivers who avoid crashing into the lead vehicle.

ANALYSIS OF DISTRIBUTION OF GLANCE PATTERNS

An analysis has been performed on the eye movement data obtained in some driving studies, using the HSRI Eye Marker (Mortimer and Jorgeson, 1971). The analysis was restricted to cases of expressway driving in which the driver was closing on a lead vehicle, with both vehicles driving in the right lane. Data were available for five subjects in this situation.

The data were partitioned into glances made when the vehicles were more than 250 feet apart and 250 feet or less apart. Figure 4 presents the glance duration cumulative probability function at 25'-250', while Figure 5 presents the glance duration probability function at 250'-750'. A gamma probability function is included with each figure as a reference. These functions are not necessarily a "best fit" gamma chosen by a rigorous analysis. Since the data are limited we did not spend a great deal of effort on the selection process.

It does appear that the gamma function provides a reasonable approximation to the data, especially when the short distance case is considered. A major deviation occurs, in both cases, at the right tail. The data show a larger proportion of "long" glance times than would be expected from the gamma model.

It is also clear from these figures that, at the shorter car-following distance, individual glance times are longer than at the longer following distance (e.g. the 50th percentile glance time is 0.9 sec. rather than 0.6 sec.). As noted, the data from short distance car-following situations fit the gamma distribution much better. It is reasonable to expect that as a driver approaches a lead vehicle he concentrates on it more than when further away.

VEHICLE CLOSING MONTE CARLO SIMULATION MODEL

This model is designed to study the behavior of a vehicle that is closing the gap with one in front of it. Characteristics of the lead vehicle and following vehicle are specified by deterministic and probabilistic parameters. The objective is to determine whether or not the following driver can react to a defined situation in a manner which will avoid a crash. Since the lead vehicle's position can be described in terms of

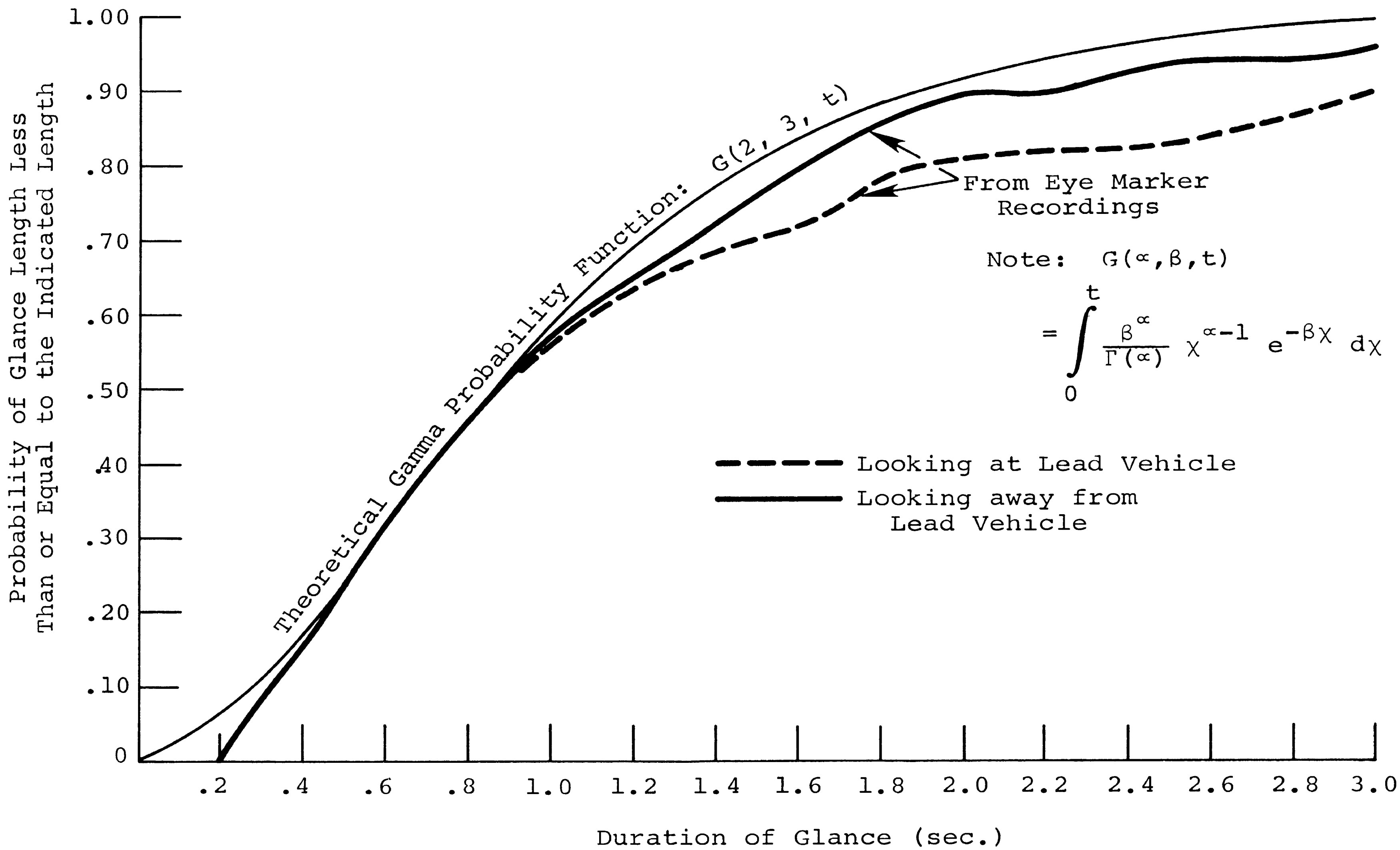


Figure 4. Cumulative probability function for duration of glances at closing distances of 25'-250', on a rural expressway (N=65 glances from five drivers).

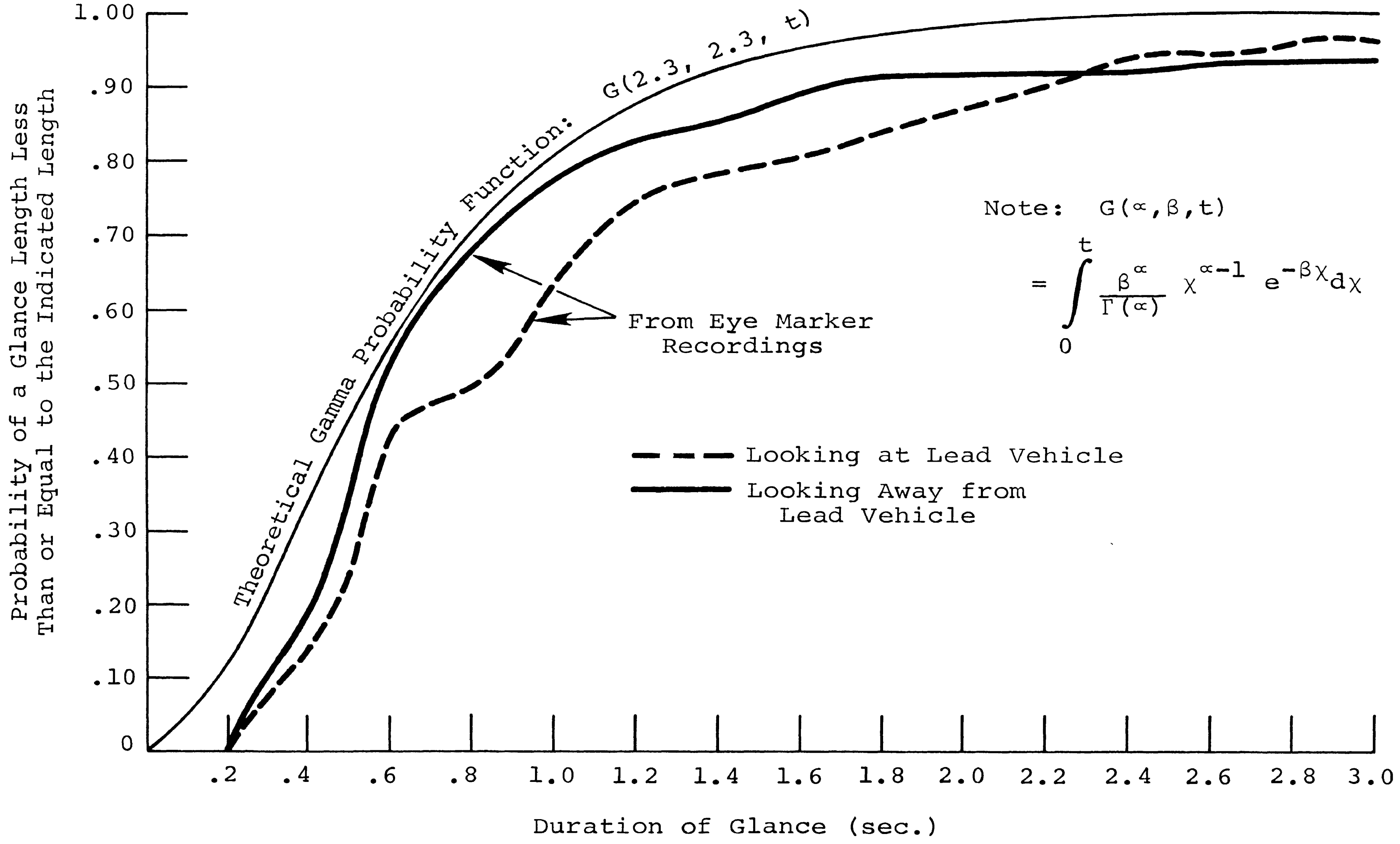


Figure 5. Cumulative probability function for duration of glances at closing distances of 250'-750', on a four-lane divided expressway (N=51 glances from five drivers).

a time and velocity vector it is also possible to use the model to study a platoon of vehicles and the manner in which variations are reflected back down the line.

GENERAL LOGIC OF THE MODEL

The model proceeds sequentially in a series of steps designed to represent a driver's decision train. These are indicated in Figure 6 and will be discussed in greater detail below. The first step consists of the random selection of a driver glance type and duration of glance. Values selected determine what information the driver can receive and, hence, what decisions he might make. The first type of information a driver tests for is a brake light on the lead vehicle. The probability of a stop signal is an option that can be set for any particular run. A zero probability is used to skip this option. Following the stop signal option is an option to model a lead vehicle velocity display. Next, a test is made to determine whether or not the driver can detect closing merely by observing changes in the distance to the lead vehicle. If closing is detected, the driver decides--on a probabilistic basis--to either reduce velocity or to attempt to pass. The final driver decision is a probabilistic determination of whether or not to pass, given that he is close enough to the lead vehicle. After moving through this decision sequence the velocities and positions of the vehicles are updated and the process is repeated. Analysis of a particular event ceases when the following vehicle has either passed the lead vehicle, or the relative velocity between the two vehicles has been reduced to zero. If none of these occur there is also an upper limit for each run of the model on the length of time available. The primary measure of effectiveness is the proportion of cases, for a particular option, which result in a crash.

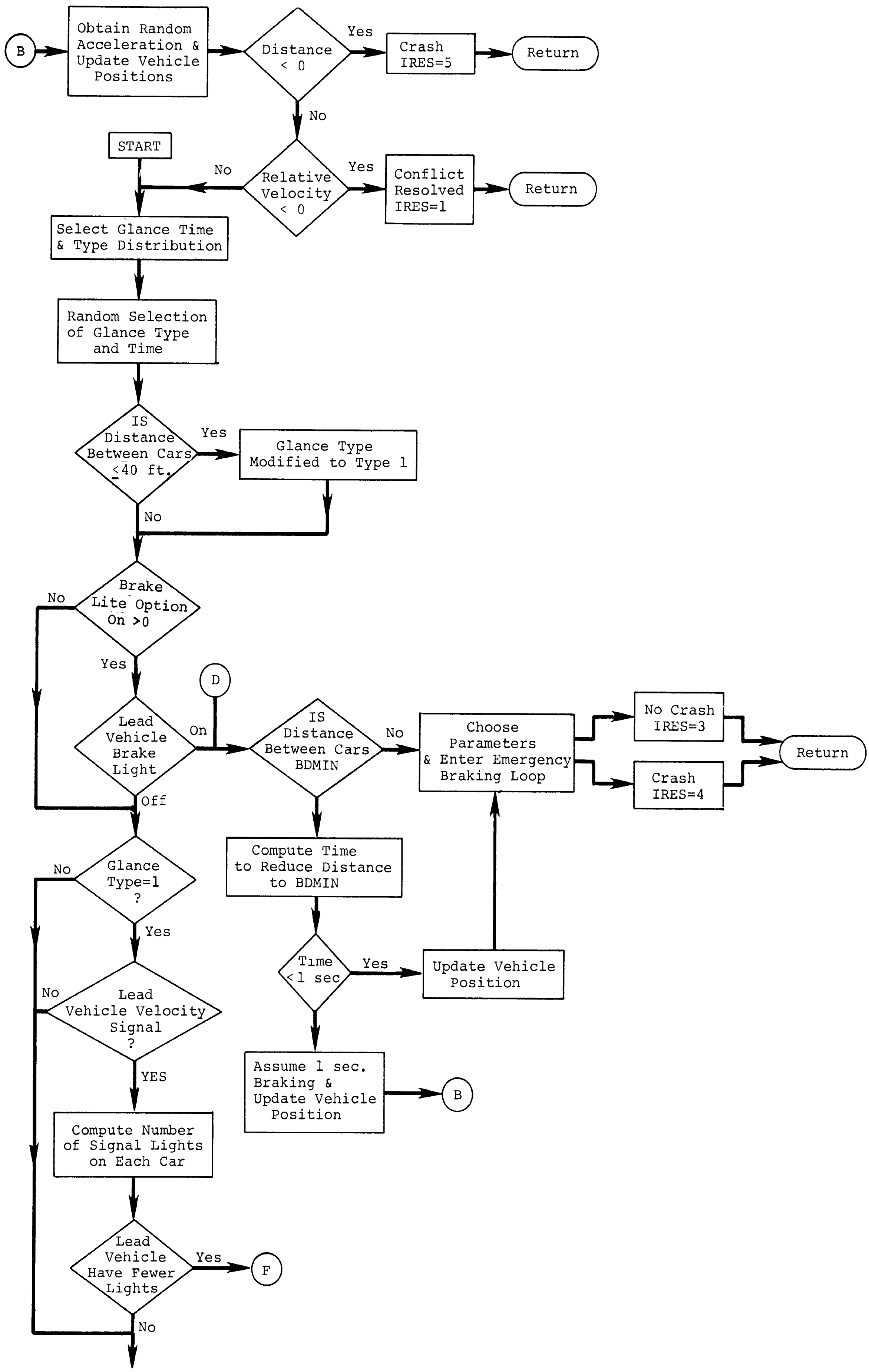
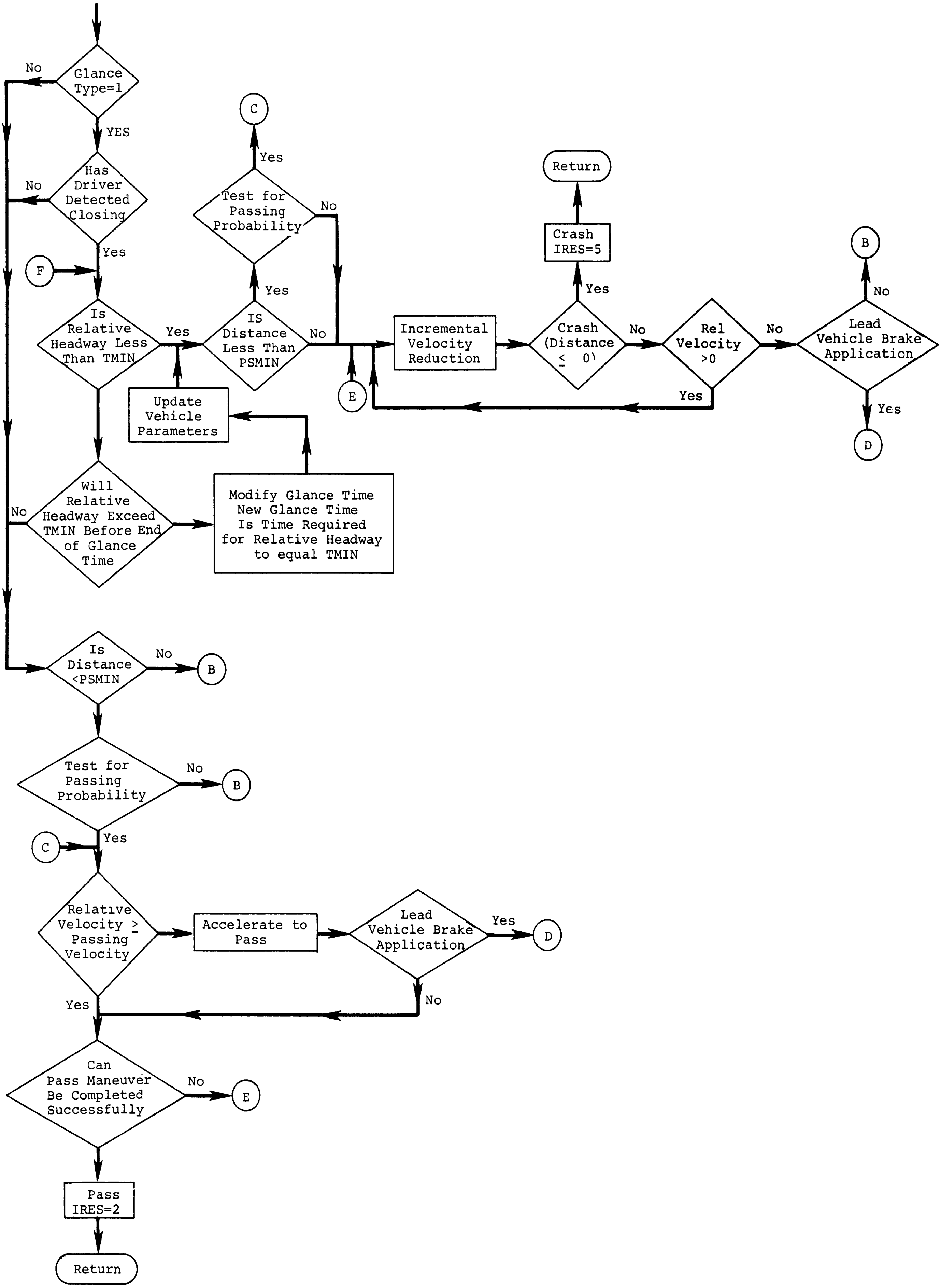


Figure 6. Closing conflict subroutine.


Glance Type=1
No
YES
Has Driver Detected Closing
No
Yes
F
Is Relative Headway Less Than TMIN
Yes
C
Yes
Test for Passing Probability
No
Yes
IS Distance Less Than PSMIN
No
Update Vehicle Parameters
E
Incremental Velocity Reduction
Return
Crash IRES=5
Yes
Crash (Distance ≤ 0)
No
Rel Velocity >0
No
Yes
B
No
Lead Vehicle Brake Application
Yes
D
Will Relative Headway Exceed TMIN Before End of Glance Time
No
Modify Glance Time New Glance Time Is Time Required for Relative Headway to equal TMIN
Is Distance <PSMIN
No
B
Test for Passing Probability
No
B
Yes
C
Relative Velocity ≥ Passing Velocity
Accelerate to Pass
Lead Vehicle Brake Application
Yes
D
No
Yes
Can Pass Maneuver Be Completed Successfully
No
E
Pass IRES=2
Return

EYE GLANCE PATTERNS

Drivers are assumed to operate in one of three different types of glance location modes. Under glance type-1 the driver is looking directly at the lead vehicle, thus all signal lights and changes in relative distance can be detected, provided a glance is sufficiently long. Glance type-2 implies that the driver observes the lead vehicle only in peripheral vision, and only brake light signals from the lead vehicle can be detected. Finally, with glance type-3 the driver is assumed to be looking completely away and receives no information concerning the actions of the lead vehicle. The glance time probability distributions are based on the assumption that duration of glance can be properly modeled using a gamma probability function which gives a reasonable fit to the experimentally determined distributions.

The probability of glance location is based upon examination of eye camera data and some reasonable judgments about driver behavior. This is an area that certainly requires additional effort. Simulation runs, in which different proportions of glance types were compared, have shown that model behavior is sensitive to this variable. Limited testing of the model has also shown that it is insensitive to reasonable changes in the probability function for duration of glances. Thus, the choice of these probabilities becomes part of the base condition of particular analyses made using the model.

The choice of the probability models for duration and type of glance are a function of distance between vehicles, relative velocity and following vehicle velocity. At present eight different probability functions are possible depending upon the combinations of these variables.

LEAD VEHICLE STOP SIGNAL OPTION

The initiation of this option results in a critical car-closing maneuver using the previously developed model described by Carlson (1972). That model determines whether or not a crash occurs under the condition that the lead vehicle begins an emergency braking maneuver and the driver of the following vehicle must react to the stop signal and attempt to stop prior to striking the lead vehicle. The use of this program option allows the lead vehicle brake sequence to be initiated in one of two ways: probabilistically, or by choosing a specific time from the start of the run for onset of the brake signal. Upon initiation of this option a check is first made of the distance between vehicles. If this distance is greater than a specified quantity it is assumed that the driver ignores the signal, and its effect is merely to increase relative velocity between vehicles. The stop light signal will be ignored, temporarily, if the following vehicle driver is looking away, i.e., glance type-3. If the signal is detected, perception times and braking decelerations are randomly selected from specified probability distributions. The analysis is then completed to determine whether or not a crash occurs. Output is developed and control returns to the main program.

LEAD VEHICLE VELOCITY SIGNAL

This option enables the user to evaluate a discrete lead vehicle velocity signal. Under this option it is assumed that the lead vehicle displays a discrete number of lights depending upon the velocity range in which the vehicle is operating. For example, the number of lights might decrease as the speed of the vehicle increases. The same display is assumed to be shown to a driver in his vehicle. Thus, a driver can compare the number of lights on the lead vehicle and the number of lights on his vehicle. If the lead vehicle displays more lights, a positive closing velocity is implied. Under this condition the following vehicle driver either begins to reduce his velocity or attempts to pass. The choice of these options are influenced by the distance between vehicles, and the probability of passing. Lights are assumed to be seen only if the driver is looking directly at the lead vehicle--glance type-1. The logic of the model is, of course, the same if it is assumed that lights are turned on with increasing velocity.

In order to perform a complete evaluation of a signal of this type it is, of course, necessary to determine experimentally the details of driver behavior. These include distances at which a reaction occurs and the proportion of drivers who react to a one-light difference in velocity in comparison to the number who react only to a two-light difference, etc. However, the model in its present state can be used to evaluate the result of hypothesized driver behavior.

NORMAL DETECTION OF CLOSING

Logic is included to represent the detection of closing given that a driver does not operate with the signal light discussed above. It should be noted, however, that the logic of the model is such that this closing detection model is applied even if the driver fails to detect closing by observing the above signal lights. Thus, a driver's normal reactions--as represented by this logic--are assumed to back up the velocity signal system.

The normal cues, which can only be perceived if the driver has been continually looking at the lead vehicle, are divided into a short distance and a long distance closing model. The choice of model is dependent upon the distance between the two vehicles, with the cut-point being designated by an input parameter.

The short distance model is based upon the rate of change of the angle subtended by the lead vehicle. Under the short distance closing model the following relationship applies:

$$\frac{(W)\ (V_r)}{D^2} \geq r$$

W - Width of the lead vehicle

V_r - Relative velocity of the two vehicles with a positive value representing closing

D - Distance between vehicles

At present the value used for r is 0.006 radians/sec., based on the finding that the parameter has been shown to vary between 0.0003 and 0.001 (Michaels & Cozan, 1963), while Hoffmann (1968) suggests it should be 0.0004. However, this parameter can be modified as an input parameter.

The long distance closing model is dependent upon a minimum fractional change in the distance between vehicles as expressed in the following relationship:

$$\frac{(T)\ (V_r)}{D} \geq \theta$$

T - Time that following driver spends observing the change in distance.

At present the value used for θ is 0.125.

Once the driver has detected closing he does not automatically begin deceleration. Data of relative velocity/headway (Figures 2 and 3) indicate that, while the fact of closing can be detected quite soon, the rate of closing is not as easily detected. Thus, drivers apparently do not "worry" or react to an immediate closing cue, but instead wait until the cue becomes "stronger." A reasonable model for the point at which a driver decides to either pass or reduce velocity is that of critical relative headway (distance between vehicles/relative velocity). This value--expressed in units of time--is read into the model at execution. Typical values lie in the range of 2.0 to 3.0 seconds. The occurrence of rear-end crashes in the model is quite sensitive to this parameter, as is shown in analyses presented later. It does appear from the empirical data that most alert drivers usually operate with a much higher value for their minimum decision point. However, since this model is concerned with critical emergency situations, lower values (2.0 to 3.0 seconds) are used for most runs.

When the model indicates that closing rates are "critical" the following car either reduces velocity or attempts to pass. Velocity reduction is performed using randomly selected decelerations, obtained from the specified distribution of decelerations read into the model. Braking initially occurs at a rate one half that of the deceleration obtained from the distribution. However, if the relative headway is further reduced to one half of the critical relative headway which initiated braking, the deceleration is increased to that of the actual randomly selected braking deceleration value. During the braking cycle it is also possible to specify that the lead vehicle begins braking with a given probability. The model control then goes to the emergency braking sub-routine and the analysis continues.

PASSING OPTION

The passing option is controlled by first specifying the probability of a driver deciding, or being able to pass. This can occur either after the driver discovers a critical closing velocity or purely as a random event. Variations in the probability of passing can be used to represent variations in oncoming traffic volume or other conditions that might normally restrict passing. If a decision to pass is made the relative velocity is checked. If it is below the specified passing velocity the model goes into an acceleration loop. During this acceleration phase it is also possible to specify that the lead vehicle brakes with a given probability. Once passing velocity is reached the passing maneuver is accomplished. However, it is also possible to specify a probability that the passing maneuver must be aborted. If this occurs control goes to the velocity reduction loop.

MODEL OUTPUT AND MODE OF OPERATION

The model repeats the above set of decision steps until either (1) a crash occurs; (2) the lead vehicle is passed; or (3) relative velocity is reduced to zero or a specified maximum time is exceeded.

Two modes of the model have been developed. The case study mode provides a detailed description of the entire closing maneuver. In addition, it provides for the capability of studying closing behavior for a platoon of vehicles. In that case each vehicle reacts to the vehicle immediately in front. If a crash occurs the platoon analysis is completed. Another mode of the program, dealing only with two vehicles, provides for the comparison of several hundred similar critical situations with various parameters being modified. Thus, it operates on a basis similar to a sampling of critical car-following emergencies.

SENSITIVITY ANALYSIS OF MODEL TO VARIATIONS IN EYE GLANCE PATTERNS

After the simulation model was programmed an extensive parameter sensitivity analysis was performed. Parameters dealing with eye glance patterns were examined first (i.e. proportion of time in various glance modes and probability density functions describing duration of glances). The objective was to determine how sensitive the model criterion measure--percent crashes--is to variations in these parameters. As previously indicated these parameters are extremely difficult to measure in the driving environment. Thus, it is important to understand the model's sensitivity to measurement errors so that an indication of the value of more accurate measurement can be made. The analysis which follows shows that the percent of crashes is sensitive to the proportion of time in various glance modes, but is not sensitive to the probability distribution of duration of glances with the glance mode.

The results of the analysis of eye glance patterns are presented in Tables 1-3. Because of the large number of model parameters it was important to establish a fixed base condition from which to compare parameter changes. The initial condition is as follows:

1. Initial velocity of following vehicle 88 ft/sec.
2. Initial relative velocity 50 ft/sec.
3. Initial distance between vehicles 400 ft.
4. Minimum relative headway 2.0 sec.
5. Probability of passing 0.40.
6. Probability of aborting passing maneuver 0.20.
7. Minimum distance for passing 100 ft.
8. No braking by lead vehicle.

As indicated previously the driver's glance patterns are related to vehicle velocity, distance between vehicles, and relative velocity between vehicles. The model provides for these differences in eye fixations by assuming eight different combinations of distance, velocity and relative velocity. Within each mode the proportion of the three glance types and the glance duration probability density function can be uniquely expressed. The division points between level 1 and level 2 on the three variables identifying glance pattern modes are:

Distance 1 $\geq$ 200 feet
Distance 2 $\geq$ 200 feet
Velocity 1 $\geq$ 60 ft/sec.
Velocity 2 $\geq$ 60 ft/sec.
Relative Velocity 1 $\geq$ 20 ft/sec.
Relative Velocity 2 $\geq$ 20 ft/sec.

The base condition glance type proportions for each of the eight glance pattern conditions are:

		Glance Type	Relative Velocity 1 (≥ 20 ft/s)	Relative Velocity 2 (≥ 20 ft/s)
Distance 1 (≥ 200')	Velocity 1 (≥ 60 ft/s)	1	.40	.50
		2	.30	.30
		3	.30	.20
	Velocity 2	1	.50	.50
		2	.30	.30
		3	.20	.20
Distance 2 (≥ 200')	Velocity 1	1	.30	.30
		2	.30	.40
		3	.40	.30
	Velocity 2 (≥ 60 ft/s)	1	.30	.40
		2	.30	.40
		3	.40	.20

As previously indicated the glance types are: (1) looking directly at lead vehicle, (2) looking at lead vehicle in peripheral vision, (3) looking away from lead vehicle. As shown above, shorter distances, greater velocity, and greater relative velocity imply more direct observation of the lead vehicle. These estimates are based on the previously discussed analysis of driver glance patterns.

GLANCE DURATION EFFECTS

Table 1 indicates the percent crashes--obtained from the simulation run--when various combinations of the α and β parameters are used to define the duration of glance probability density function. The proportion of glance types are fixed at base condition values. Notice that two separate combinations of α and β are used to define each condition. The percent crashes are grouped with the range 19 percent to 27 percent, with the exception of condition 2 which has 100 replications and resulted in 13 percent crashes. In order to examine the statistical significance of the difference between this case and the others a 95% confidence interval was constructed for p = 20 percent as follows:

TABLE 1. Sensitivity Analysis of Variations in Parameters of Gamma Distribution for Duration of Glance Times.

Condition	Short Distance		Aver. Glance Time	Long Distance		Aver. Glance Time	Number of Replications	Percent[3] Crashes
	α	β[2]		α	β			
base[1]	2.3	2.5	.92	2.3	3.0	.77	100	27
base	2.3	2.5	.92	2.3	3.0	.77	300	22
1	2.3	1.5	1.53	2.3	2.0	1.15	100	21
2	2.3	3.5	.66	2.3	4.0	.58	100	13
2	2.3	3.5	.66	2.3	4.0	.58	300	19
3	2.3	2.0	1.15	2.3	2.5	.92	100	22
4	2.3	3.0	.77	2.3	3.5	.66	100	24
5	1.5	2.5	.66	1.5	3.0	.50	100	25
6	3.5	2.5	.71	3.5	3.0	.86	100	24
	3.5	2.5	.71	3.5	3.0	.86	100	26

[1] The simulation runs reported in this table have the parameter values specified in the text as initial conditions.

[2] The base condition is defined by the particular values of α and β specified for the gamma probability distribution of duration of glance.

[3] Minimum significant difference in percentages for $P = 0.05$ are 8%(N=100); 5%(N=300).

$$S^2_{P_1-P_2} = \frac{P_1(1-P_1)}{n} + \frac{P_2(1-P_2)}{n}$$

$$C.I. = P_1 \pm MSD$$

$$MSD^* = 1.06\ S_{P_1-P_2}$$

n = sample size used to estimate P_1 and P_2

P_1 = Percentage of cases resulting in a crash under Condition 1.

P_2 = Percentage of cases resulting in a crash under Condition 2.

$S_{P_1-P_2}$ = Estimated standard deviation of the difference between P_1 and P_2.

*MSD = Minimum significant difference between P_1 and P_2.

C.I. = 95% conficence interval.

This is necessary to determine if Condition 1 and Condition 2 are different at any α level of 0.05.

The Minimum Significant Difference for comparing two samples each of size N from Condition 1 and Condition 2 is 8% when N=100 and 5% when N=300. Thus, the case from Condition 2 is at a borderline value of significant difference from the other cases. However, in general it is not possible to show that changes in the probability distribution of glance duration contribute to the frequency of crashes predicted by the simulation model.

GLANCE LOCATION EFFECTS

In Table 2 some variations have been made in the proportion of time a driver spends in the three types of glance locations (e.g. looking directly at lead vehicle; looking at the lead vehicle in peripheral vision; looking away from lead vehicle). For the conditions studied these variations had a greater effect than did variations in duration of glance. Conditions 1 and 2 are quite similar, but in Condition 2 there was an increase in the proportion of type 1 glances at the greater distance or relative velocity. The increase in crashes in Condition 2 (27% vs 22%) is barely statistically significant at the 0.05

TABLE 2. Sensitivity Analysis of Variations in Proportion of Glance Types.

(Gamma Parameters from Base Condition in Table 1: Initial Relative Velocity = 50 ft/sec.)

Minimum Relative Headway = 2.0 sec.

Condition 1

(Base Condition)

N=300 %Crashes 22%

		Relative Velocity 1		Relative Velocity 2	
		Glance Type	Prob.	Glance Type	Prob.
Distance 1	Velocity 1	1	.40	1	.50
		2	.30	2	.30
		3	.30	3	.20
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.50	1	.50
		2	.30	2	.30
		3	.20	3	.20
		Glance Type	Prob.	Glance Type	Prob.
Distance 2	Velocity 1	1	.30	1	.30
		2	.30	2	.40
		3	.40	3	.30
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.30	1	.40
		2	.30	2	.40
		3	.40	3	.20

Condition 2

(Small Increase in Type 1 Glances)

N=300 %Crashes 27%

		Relative Velocity 1		Relative Velocity 2	
		Glance Type	Prob.	Glance Type	Prob.
Distance 1	Velocity 1	1	.40	1	.50
		2	.30	2	.30
		3	.30	3	.20
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.50	1	.60
		2	.30	2	.30
		3	.20	3	.10
		Glance Type	Prob.	Glance Type	Prob.
Distance 2	Velocity 1	1	.30	1	.40
		2	.30	2	.40
		3	.40	3	.20
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.40	1	.50
		2	.40	2	.30
		3	.20	3	.20

Condition 3

(Reduce Type 1 Glances)

N=300 %Crashes 27%

		Relative Velocity 1		Relative Velocity 2	
		Glance Type	Prob.	Glance Type	Prob.
Distance 1	Velocity 1	1	.30	1	.35
		2	.30	2	.30
		3	.40	3	.35
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.35	1	.40
		2	.30	2	.30
		3	.35	3	.30
		Glance Type	Prob.	Glance Type	Prob.
Distance 2	Velocity 1	1	.20	1	.30
		2	.30	2	.40
		3	.50	3	.30
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.30	1	.35
		2	.40	2	.30
		3	.30	3	.35

Condition 4

(Increase Type 1 Glances)

N=300 %Crashes 21%

		Relative Velocity 1		Relative Velocity 2	
		Glance Type	Prob.	Glance Type	Prob.
Distance 1	Velocity 1	1	.50	1	.65
		2	.30	2	.30
		3	.20	3	.05
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.65	1	.70
		2	.30	2	.30
		3	.05	3	.00
		Glance Type	Prob.	Glance Type	Prob.
Distance 2	Velocity 1	1	.40	1	.50
		2	.30	2	.30
		3	.30	3	.20
		Glance Type	Prob.	Glance Type	Prob.
	Velocity 2	1	.50	1	.65
		2	.30	2	.30
		3	.20	3	.05

Condition 5

Condition 2 with maximum distance at which passing is allowable changed from 100ft. to 180ft.

N=300 %Crashes 14%

Condition 6

Condition 3 with passing distance changed from 100 ft. to 180ft.

N=300 %Crashes 16%

Condition 7

Condition 4 with passing distance changed from 100ft. to 180ft.

N=300 %Crashes 11%

NOTE: Minimum significant differences in percent crashes for a base percentage of 20 are: 0.06(N=300); 0.11(N=100).

level. Paradoxically, one would intuitively expect that an increase in type 1 glances would provide more information for the driver and hence reduce his crash involvement. Thus, the increase in percent crashes is surprising. In Condition 3, in which the percentage of type 1 glances was reduced to less than that for both Conditions 1 and 2, there is no change in crash occurrence. However, by considerably increasing the proportion of type 1 glances in Condition 4 from Conditions 1, 2, and 3, a statistically significant reduction (27% to 21%) in crashes was obtained compared to Conditions 2 and 3, but not with 1. Thus, at this point, it appears that there is a very complex functional relationship between these parameters and percent crashes.

However, it should be emphasized that none of the differences resulting from variations in glance types are as large as those resulting from variations in some other parameters such as the maximum distance at which passing can take place, relative headway time and initial relative velocity.

PASSING DISTANCE EFFECTS

Conditions 5, 6, and 7 in Table 2 indicate that, increasing the maximum start to pass distance from 100 feet to 180 feet, significantly reduces the probability of a crash. The 180 feet is more consistent with the data obtained from the video tape of vehicles passing a test car made on the US-23 expressway. Thus, percent crashes is greatly affected by a change in this parameter.

RELATIVE HEADWAY TIME EFFECTS

Table 3 presents analyses of the conditions discussed in Table 2 with the minimum relative headway increased to 2.5 seconds. Thus, we are assuming that the driver begins to decelerate sooner. The effect of this change on percent crashes is quite significant.

Table 3. Sensitivity Analysis of Variations in Proportion of Glance Types and in Minimum Relative Headway*

Condition 1	Condition 3	Condition 4
% Crashes = 9%	% Crashes = 13%	% Crashes = 6%
N = 300	N = 300	N = 300
Condition 6	**Condition 7**	
% Crashes = 7%	% Crashes = 3%	
N = 300	N = 300	

*Note: This table uses the conditions specified in Table 2 modified by setting the minimum relative headway equal to 2.5 sec.

SAMPLE SIZE

Since simulation models of the Monte Carlo type represent sampling from a theoretical population, an important question concerns how many observations should be made in order to obtain a stable estimate of the variable of interest--in this case percent crashes. Figure 7 indicates the variability from one sample of 25 to the next and the cumulative estimate of the percentage. Under Condition 6 the result after 100 observations was different from that obtained after 300 observations. This was not the case under Condition 7. Thus, it appears from this limited analysis that the simulation should be run for at least 150-200 cases, to provide a stable estimate of the proportion of cases resulting in a crash.

RELATIONSHIP BETWEEN CRASH OCCURRENCE AND RELATIVE VELOCITY, RELATIVE HEADWAY AND PASSING PROBABILITY

Table 4 presents the results of an analysis to determine the effects of relative velocity and the point at which a driver becomes concerned about relative velocity, on the occurrence of

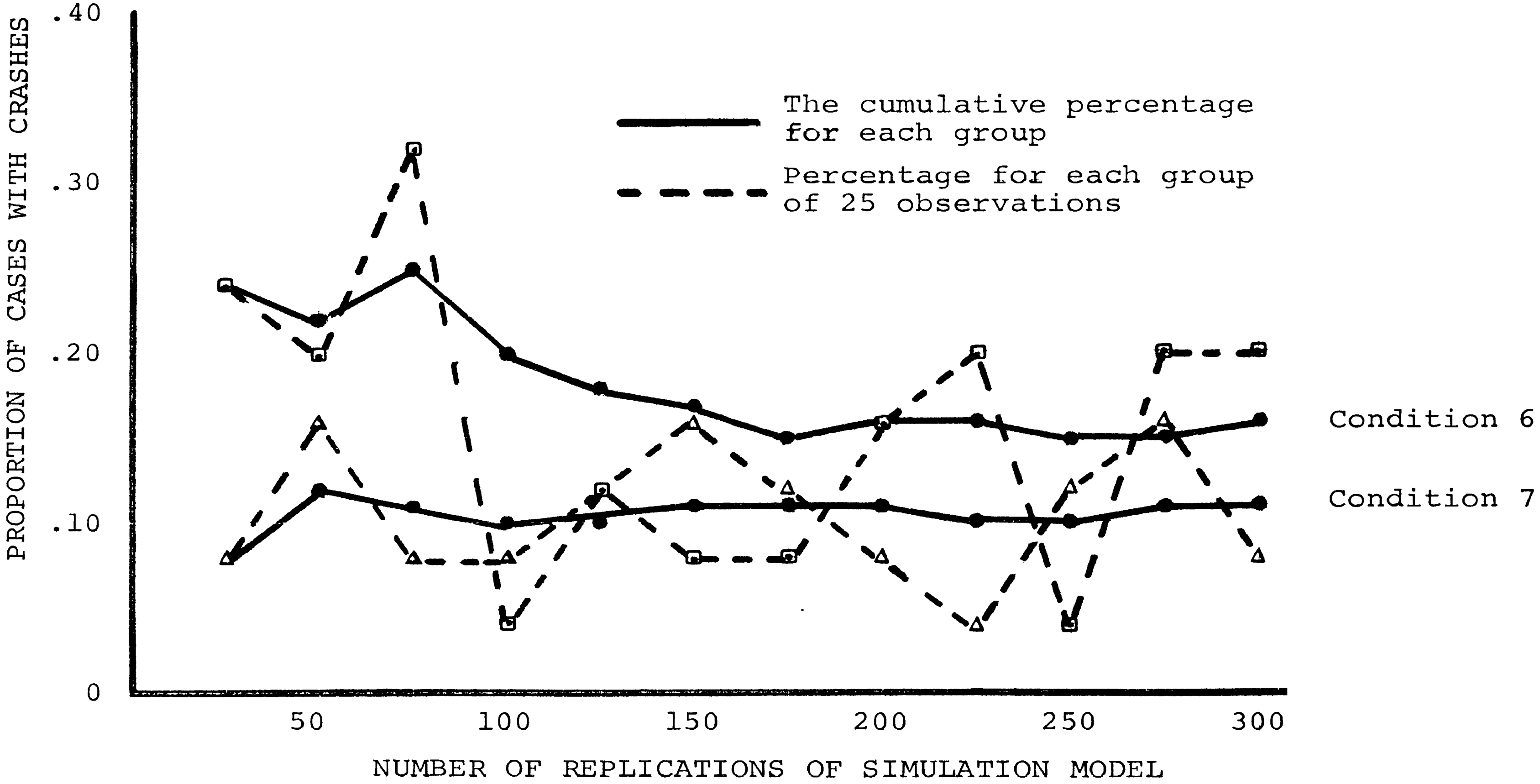


Figure 7. Rate of approach to steady-state estimation of percent crashes, for two conditions described in Table 2.

TABLE 4. Comparison of the Relationship Between Relative Velocity, Minimum Relative Headway Time, and Crash Involvement.* Each case has 100 Replications.

Relative Velocity		Minimum Relative Headway Time (seconds) (Driver Decision Point) 2.0			2.5			3.0		
40 ft/sec	Pass Percent		37%			22%			8%	
	Crash Percent		10%			2%			0%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	62%	42%	46%	63%	46%	-	61%	41%	-
	2	24%	37%	27%	22%	36%	-	24%	25%	-
	3	14%	21%	27%	15%	18%	-	15%	34%	-
	Average Cycle Time**	6.48	5.14	5.59	6.49	5.21		6.28	5.13	
50 ft/sec	Pass Percent		15%			3%			5%	
	Crash Percent		27%			8%			3%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	66%	42%	42%	67%	55%	49%	68%	20%	32%
	2	20%	36%	35%	20%	27%	23%	19%	33%	26%
	3	14%	22%	23%	13%	18%	28%	13%	47%	42%
	Average Cycle Time**	5.23	3.86	3.86	5.48	4.43	3.55	5.45	4.44	4.15
60 ft/sec	Pass Percent		1%			3%			1%	
	Crash Percent		47%			18%			13%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	70%	-	47%	71%	36%	36%	74%	-	47%
	2	20%	-	29%	18%	15%	28%	16%	-	23%
	3	10%	-	24%	11	49%	36%	10%	-	29%
	Average Cycle Time** (Secs.)	4.58		3.05	4.70	3.64	3.43	4.91		3.17

*Additional Standard Conditions:
Pass Probability - 0.40
Initial Velocity - 88 ft/sec
Initial Distance - 400 ft
No Braking by Lead Vehicle
Pr (Passing Aborted) = 0.20
Maximum Distance for Passing = 100 ft

**The average cycle time is measured from the start of a particular car closing event until its completion by either velocity reduction, passing, or crashing.

rear-end crashes. In each case the model was run for 100 cases of the defined traffic situation. Eye glance patterns are randomly selected from an appropriate gamma distribution. These are then used to control the behavior of the following car driver with respect to the lead car. Thus, the cases represent random samples of the traffic situation.

In all cases the situation began at a distance of 400 feet between vehicles and with the following car moving at a velocity of 88 ft/sec. Additional parameter values are indicated on the table. The situation proceeds with the two vehicles approaching each other until the following car driver begins to act to overcome the hazardous situation. He has two options--brake or pass. In the model his point of concern, or decision point, is expressed in terms of the minimum relative headway time. The use of this ratio is based upon analytical work and data analysis presented earlier. The driver is allowed to pass the lead vehicle with a certain probability (e.g., in this case 0.40). This is used to reflect the fact that passing may be restricted by approaching traffic and road geometry. In addition, there is a defined probability (e.g., 0.20) of the driver not being able to complete his passing maneuver.

The analysis shown in Table 4 indicates, as expected, that the probability of a crash increases greatly with increased initial relative velocity. This is in agreement with data (Solomon, 1964) showing that rear-end crash rates increase as relative velocities increase.

Also, the crash percentage was very sensitive to even small changes in the minimum relative headway decision criterion. Since this criterion expresses the amount of time that the following driver has available before crashing into the lead vehicle--given nothing is changed--one can appreciate the criticality of the driver's decision point. This analysis shows that increasing this sensitivity level has a potential for improving a critical situation, such as where the relative headway is as low as 2.0 seconds. This value is quite realistic, however, since relative headways as low as two seconds were observed in the data obtained from Indiana University (Figure 3).

An additional statistic presented is the percentage of time that a driver spent in the various types of glance locations. These glance locations are selected randomly by the model unless the driver is passing or reducing his velocity relative to the lead vehicle. Of interest is the fact that, in those situations resulting in a crash, the percentage of time the driver spent looking away from the lead car is higher than when the following vehicle's speed was reduced sufficiently to avoid a crash or it passed the lead vehicle. If the driver is looking away he may go below his critical relative headway decision point, thus decreasing his probability of taking suitable action to avoid the crash.

The analysis presented in Table 5 has the same basic philosophy except that minimum relative headway is kept constant at 2.0 seconds and the probability of passing was varied. As indicated there is essentially no difference in the occurrence of crashes over quite wide fluctuations of this percentage. Thus, the logic of this model implies that restricting the occurrence of passing has little effect on rear-end crashes resulting from high initial relative headways.

The model also has an option that the lead vehicle may be allowed to brake at some point in the closing situation--determined randomly or deterministically by time or distance traveled. Initial tests of this option showed that if the lead vehicle brakes the occurrence of a crash is considerably increased.

EVALUATION OF A VELOCITY DISPLAY SIGNAL

In order to illustrate how the model can be used to evaluate the effects of displaying new information by vehicle rear lighting, an analysis was made of a signal indicating the speed at which a lead vehicle is traveling.

TABLE 5. Comparison of the Relationship Between Relative Velocity Probability of Passing and Crash Involvement.* 100 Replications.

Relative Velocity		Probability of Passing 0.0			0.20			0.40		
40 ft/sec	Pass Percent		0%			14%			37%	
	Crash Percent		12%			11%			10%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	60%	-	45%	58%	41%	46%	62%	42%	46%
	2	25%	-	36%	26%	36%	30%	24%	37%	27%
	3	15%	-	19%	16%	23%	24%	14%	21%	27%
	Average Cycle Time	6.70		5.39	6.55	5.43	5.07	6.48	5.14	5.59
50 ft/sec	Pass Percent		0%			11%			15%	
	Crash Percent		31%			30%			27%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	65%	-	44%	64%	45%	42%	66%	42%	42%
	2	23%	-	30%	24%	30%	29%	20%	36%	35%
	3	12%	-	26%	12%	25%	29%	14%	22%	23%
	Average Cycle Time	5.30		4.05	5.23	4.03	4.08	5.23	3.86	3.86
60 ft/sec	Pass Percent			0%		1%			1%	
	Crash Percent			51%		47%			47%	
	Glance Type	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash	Velocity Reduced	Pass	Crash
	1	69%	-	48%	70%	-	47%	70%	-	47%
	2	20%	-	28%	20%	-	29%	20%	-	29%
	3	11%	-	24%	10%	-	24%	10%	-	24%
	Average Cycle Time	4.57		3.05	4.58		3.05	4.58		3.05

*Additional Standard Conditions
Relative Headway Time - 2.0 sec
Initial Velocity - 88 ft/sec
Initial Distance - 400 ft
No Braking by Lead Vehicle
Pr (Passing Aborted) = 0.20
Minimum Distance for Passing = 100 ft

The simulation program logic which models a velocity signal was used to study the effects of such a system given some typical parameters defining a critical highway closing situation. The criterion of effectiveness is the proportion of cases in which a crash occurred. The evaluation methodology consists of defining some critical emergency situations using important parameters.

Table 6 presents a situation in which a lead vehicle traveling 68 ft/sec is approached by a following vehicle at a velocity of 88 ft/sec. The velocity signal--when it exists--is assumed to be able to be recognized by the following driver at 300 feet. The minimum relative headway was taken as 2.0 seconds, maximum distance at which passing is allowed is 100 feet and the probability of passing is 0.40. The lead car was assumed to brake, with a probability of 0.20 in any one-second interval, at a randomly selected level of deceleration.

With the two-light signal the following driver observes two lights on each side of the vehicle at speeds of less than 30 ft/sec, one light on each side at speeds between 30 and 70 ft/sec, and none above 70 ft/sec. In this way this display provides three categories of lead car speed information. For example, if the lead car were traveling at 50 ft/sec, the following driver sees one lamp lighted on each side of the car ahead and assumption is made that the driver begins to reduce velocity to 70 ft/sec. The target velocity is assumed to be 70 ft/sec rather than 50 ft/sec because the highest lead car velocity possible with one light on is 70 ft/sec. Thus, at 300 feet, or less, the driver was assumed to be able to reduce speed to the upper limit of the speed category displayed, dependent upon the eye glance pattern being sampled.

In Table 6 are shown the results of simulations of these situations without a velocity signal on the lead car, with a three-category speed display and an eight-category speed display. The speed cut-point for these displays, by number of lamps lighted per side, are also shown in Table 6.

TABLE 6. The Effect of Velocity Signals on Crash Occurrence: Moderate Relative Speed with Braking Probability, 0.20.[1]

Velocity Display Categories	% Crashes	% Passing
0	15.5	30.6
3*	6.6	9.6
8**	3.2	6.9

[1]Test Conditions:

No. of Samples, N=300
Minimum Relative Headway = 2.0 secs.
Maximum Velocity Signal Visibility Distance = 300 ft.
Maximum Passing Distance = 100 ft.
Passing Probability = 0.40
Initial Distance = 200 ft.
Velocity of Following Car = 88 ft/sec.
Relative Velocity = 20 ft/sec.
Probability of Lead Car Braking = 0.20.

Number of Lamps Lighted Per Side in the Velocity Signal Display as a Function of Lead Car Speed

Velocity Display System	Speed (ft/sec)							
	<20	20-30	30-40	40-50	50-60	60-70	70-80	>80
*3-Category	2	2	1	1	1	1	0	0
**8-Category	7	6	5	4	3	2	1	0

In the situations modeled, there were 15.5% of them which resulted in a crash without the velocity display, 6.6% with the three-category display and 3.2% with the eight-category display. The latter each represent statistically significant reductions from the percent of crashes found without the velocity display and each other.

Table 7 shows results of the simulation for the same three displays, the major differences in the test conditions being that the relative velocity was 50 ft/sec and the lead vehicle did not brake. In this situation also, the velocity displays significantly reduced the percent of crashes, but there was no statistically significant difference between the three- and eight-category display. Without the velocity display there were crashes in 30.9% of the events, while the three- and eight-category velocity displays reduced crashes to about 7.6% and 8.2%, respectively.

It should be emphasized that one of the assumptions made in these analyses was that the following driver began to reduce his speed to the upper limit of the speed category displayed as soon as it was perceived by him. The extent to which drivers would actually behave in this way is not known at the moment, but could be evaluated in experimental tests in a simulator and in driving. The results indicate that a velocity display may have value in reducing rear-end crashes and warrants further investigation, as suggested previously (Mortimer, 1971).

CONCLUSIONS

Simulation models have proven to be valuable tools for the study of complex systems. However, their usefulness is limited by the degree to which the model operates like the system being studied. The simulation runs made in this section provide an indication of model performance. More importantly the sensitivity of the criterion variable, percent crashes, to model parameters is indicated. For example, the criterion variable is sensitive to the percentage of time spent in various glance modes but it is not sensitive to the probability distribution

TABLE 7. The Effect of Velocity Signals on Crash Occurrence: High Relative Speed, Without Braking.[1]

Velocity Display Categories	% Crashes	% Passing
0	30.9	29.4
3	7.6	57.3
8	8.3	33.6

[1]Test Conditions:

No. of Samples, N=300
Minimum Relative Headway = 2.0 secs.
Maximum Velocity Signal Visibility Distance = 300 ft.
Maximum Passing Distance = 100 ft.
Passing Probability = 0.40
Initial Distance = 400 ft.
Velocity of Following Car = 100 ft/sec.
Relative Velocity = 50 ft/sec.
Probability of Lead Car Braking = 0

Velocity Displays are as Described in Table 6.

of duration of glances. Therefore, experimental study of driver glance patterns should concentrate on the total time in each glance mode rather than the distribution of individual glance durations.

Analysis of the effect of the relative velocity, relative headway, and passing parameters confirms the analytic results that the combination of conditions necessary for crash occurrence are very rare. This provides evidence of model validity. However, additional verification obtained by studying the effects of other parameters on crash occurrence would certainly be beneficial. A particularly important result is the sensitivity of the criterion variable to small changes in relative headway (Distance Velocity/Relative). This provides some evidence that the statistically significant, but small magnitude of reductions in response times to signals of various rear lighting systems, obtained in simulator (Campbell and Mortimer, 1972; Mortimer, Domas and Moore, 1973) and driving tests (e.g. Mortimer 1969, 1970) are relevant to reducing rear-end crashes.

The model provides insights into the role of parameters that can influence rear-end crash likelihood, and stimulates thinking about the types of behavioral experiments that should be done to provide needed empirical data for expansion of the model, and to be able to reduce the number of assumptions of the manner in which drivers perceive cues in car-following and crash avoidance and how they respond in such situations.

Another important potential application of the model is to provide estimates of the reductions in crashes associated with specific situational variables. Certainly this is a necessary first step in evaluating the benefits likely to accrue from a change in vehicle rear marking and signaling.

Obviously, the model is not in a finished state. As mentioned, much more basic behavioral data are needed. But, it is sufficiently developed to point to areas of further study and to provide preliminary indications of concepts that provide useful information to drivers to reduce rear-end crashes.

REFERENCES

Campbell, J.D. and Mortimer, R.G. The HSRI Part-Task Driving Simulator for Research in Vehicle Rear Lighting and Related Studies. Contract UM-7101-C128, Motor Vehicle Manufacturers Association, Inc., Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-HF-72-12, 1972.

Carlson, W.L. Application of Simulation to Assessment of Component Changes on Rear-End Highway Accidents. Transportation Science, Vol. 6, No. 1, Febryary 1972, pp.1-102.

Carlson, W.L. and Mortimer, R.G. Rear Lighting Systems Evaluated with Empirical Driver Performance Data in a Car-Following Model. Presented at the Annual Meeting of the Operations Research Society of America, Detroit, Michigan, October 29, 1970.

Hoffman, E.R. Detection of Velocity Changes in Car Following. Fourth Conference, Australian Road Research Board Proceedings, 1968.

Mortimer, R.G. Dynamic Evaluation of Automobile Rear Lighting. Configurations. Highway Research Record, No. 275, 12-22, 1969.

Mortimer, R.G. Psychological Research in Automobile Rear Lighting. SAE Report No. 700388, 1970a.

Mortimer, R.G. Automobile Rear Lighting and Signaling Research. Contract FH-11-6936, U.S. Department of Transportation, Highway Safety Research Institute, University of Michigan, Report HuF-5, 1970b.

Mortimer, R.G. Car and Truck Rear Lighting and Signaling: The Application of Research Findings. Proceedings, International Symposium on Psychological Aspects of Driver Behavior, Noordwijkerhout, Netherlands, 1971.

Mortimer, R.G., Domas, P.A. and Moore, C.D. Surveys and Simulator Evaluations of Malfunctions in Automobile Rear Lighting and Signaling Systems. Contract No. UM-7203-C128, Motor Vehicle Manufacturers Association, Inc., Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-HF-73-19, 1973.

Mortimer, R.G. and Jorgeson, C.M. Eye Fixations of Drivers as Affected by Highway and Traffic Characteristics and Moderate Doses of Alcohol. Proceedings, Annual Meeting of the Human Factors Society, October 1972.

Rockwell, T.H., and Banasik, R.C. Experimental highway testing of alternative vehicle rear lighting systems. Contract FH-11-6552, U.S. Department of Transportation, Systems Research Group, Ohio State University, 1968.

Solomon, D. Accident on main rural highways related to speed, driver and vehicle. U.S. Department of Commerce, Bureau of Public Roads, 1964.

APPENDIX

CAR CLOSING MODEL DATA FORMAT

The following input variables must be specified in order to perform a given simulation run:

CAR CLOSING MODEL DATA FORMAT

Parameter Card 1

		Variable Name	Typical Base Condition Values*
1	Blank		
2	# of eye patterns entered (Max=8)	NTYP	8
3-4	Random acceleration applied if greater than 0	IACEL	1
5-6	Lead vehicle brake light. Turn on option =0 no brake light =1 brake light turned on with probability of PB in any second =2 brake light turned on after elapsed time of TBRK seconds	LITE	0
11-15	Division point between long and short distance for eye pattern selection	CDIST	200
16-20	Division point between high and low velocity for eye pattern selection	CVEL	60
21-25	Division point between high and low relative velocity for eye pattern selection	CRVEL	20
26-30	Minimum distance at which a driver will react to a brake light	BDMIN	150
31-35	Time required to move foot from gas pedal to brake given he has detected a brake signal	TACBR	0.2

*Any of these values can of course be specified by the user. The values given in this column are merely for base condition reference.

36-40	Distance between vehicles at which the closing detection mode is changed	DTECT	200
41-45	Ratio of $\Delta D \div D$ at which closing is detected	CLCN	0.125
Parameter Card 2			
1-5	Probability of an emergency - e.g. lead vehicle puts on brakes - in each Time period of length 1 sec. when following vehicle is (1) reducing relative velocity as a result of discovering that distance $\div$ relative velocity is too short or(2)accelerating to pass the lead vehicle	PEMER	0
6-10	Probability of passing in any one second time period given distance is less than PSMIN	PSPRB	.40
11-15	Maximum distance at which driver will consider passing	PSMIN	100
16-20	Velocity of passing vehicle relative to vehicle being passed at the time pass occurrs	PSVEL	20 ft/sec
21-25	Acceleration rate used to get to passing velocity	PSACL	8
26-30	Width of lead car (in feet) in the short distance closing detection relationship	W	6
31-35	Constant in the short distance closing detection relationship	CONST	.006
41-45	Probability of lead vehicle brake light coming on during any particular 1 second time period	PB	.20 N.A.
46-50	Length of time the case is to be run until the lead vehicle brake lights are turned on	TBRK	12 N.A.

51-55	Minimum relative headway (distance divided by relative velocity) at this relative headway a driver will begin to reduce his velocity	TMIN	Variable
56-60	Maximum length of time that a particular case will be modeled	TMAX	30 sec.
61-65	Probability of passing maneuver being stopped during any second. This stopping requires a velocity reduction	PBORT	.20

Parameter Card 3 - Vehicle Velocity Light Signal

5	Number of speed division points identified by the signal. The number of signal lights also equals LVEL. If equal to zero the signal does not exist	LVEL	
6-10	Maximum distance between vehicles at which driver can use the signal information	DMAX	
11-15	Minimum distance between vehicles at which driver can use the signal information	DDMIN	
16-20 . . .	Velocities at which the number of lights changes e.g. Velocity $\leq$ SVEL(1) No Lights	SVEL(J) J=1,7	
46-50	Velocity $\leq$ SVEL(6) 6 Light		

Parameter Card 4

1-5	Initial distance between vehicles when simulation begins (feet)	XDAST	400
6-10	Initial velocity of following vehicle when simulation begins (feet/second)	XVAL	88
11-15	Initial relative velocity between vehicles when simulation begins (feet/second)	XRVAL	4.0

16-20	Number of replications of the particular model configuration specified. Caution: If the case study option is being run this parameter should be set low (e.g. <15) since there is considerable output, which is not summarized for each replication	KRUN	5