REAR LIGHTING SYSTEMS EVALUATED WITH EMPIRICAL DRIVER PERFORMANCE DATA IN A CAR-FOLLOWING MODEL

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Presented at

The Annual Meeting of the
Operations Research Society of America,
Detroit, Michigan

October 29, 1970

ABSTRACT

An Evaluation Methodology which uses a Monte Carlo simulation model was developed to evaluate the effect, on crash reduction, of a change to the highway system.

The results of applying this model to rear lighting configurations showed:

a. The design, which featured a geometrical separation and color coding of the lighting functions, had a significant effect in crash reduction in the turn→stop mode.

b. Increased signal light intensity had a significant effect in the stop mode.

c. These changes were consistent for both two- and four-lane, high volume highways, with fewer crashes being recorded on the latter.

INTRODUCTION

The problem of highway safety is receiving increased emphasis. This is evidenced by the National Highway Safety Act of 1966 and by the various approaches to the problem being undertaken by various business, governmental and private groups. This effort is providing a large number of changes and proposed changes. These changes range from various projects having as their objective the "changing of driver behavior" to projects which deal with changes to the physical environment in which the driver operates. In the cases of all of these proposed changes the question of evaluation is of great importance because of the limited resources available for reducing the severity of the problem. In this paper we indicate an evaluation procedure for measuring the change in crash occurrence resulting from physical changes to the environment in which the driver operates. Specifically,an evaluation of a proposed new vehicle rear lighting system is presented.

The treatment of the highway safety problem in terms of a system model has been dealt with by a number of persons (e.g., Bonder et al., 1967). In the case of our problem we have considered a subsystem model in which vehicle rear lighting systems operate. The effect of any change which improves highway safety--i.e., which reduces the number and severity of crashes--proceeds from the change through an incompletely defined causal chain to the ultimate improvement. Therefore, it is difficult to attempt to relate any change directly to a reduction in the number of accidents without considering both the intermediate links in the causal chain and other variables which may modify these links. Figure 1 is a schematic sketch of a highway safety subsystem which describes the effect of improved rear lighting systems on crash reduction. It is impor-

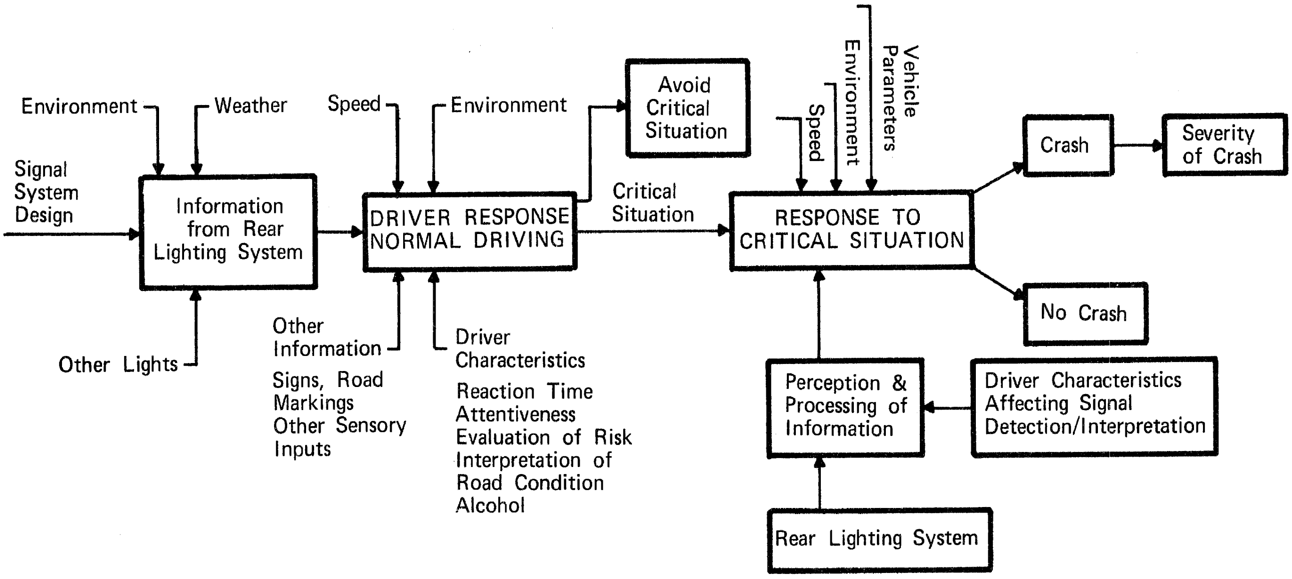

Figure 1. Schematic representation showing the effect of the rear lighting system on highway safety.

tant to note the large number of variables affecting the results at each step in the causal chain. Unless these factors are controlled the effect of improvements in lighting systems cannot be estimated.

In the schematic diagram two potential effects of improved lighting systems are indicated:

1. In the normal driving situation, information supplied to the driver enables him to avoid critical or emergency situations.

2. Once the driver becomes involved in an emergency situation, timely information can help him avoid a crash.

In an earlier study, Nickerson et al. (1968) dealt with the first effect. They found that, "The car-following task involves maintaining a desired headway and velocity in the presence of disturbances..." In this paper we have investigated the second effect: How improved rear lighting systems affect the driver's response given an emergency situation. The definition of a critical emergency will be developed in the paper.

From an analysis of the subsystem model an experimental procedure was developed to obtain driver reaction time to the lighting signals given a defined emergency. The reaction time data provides one criterion for comparing lighting system alternatives. A good first approximation is to conclude that shorter reaction times imply better systems. However, an important question remains: What is the value of an improvement in reaction time toward the ultimate objectives of reducing the number and severity of crashes? To answer this question we developed a Monte Carlo simulation model of a critical emergency conflict. By using various distributions of driver reaction time for alternative lighting systems it was possible to determine the frequency and severity of crashes given the modeled emergency situations.

DRIVER RESPONSE TIME TO SIGNALS FROM REAR LIGHTING SYSTEMS

The purpose of vehicle rear lighting systems is to provide following drivers with information of the status, changes in status and intended changes in status of a vehicle in front of them. Such information should enable the following driver to maintain safe headways and avoid rearend collisions. Currently rear lighting is used to indicate braking, intended turning, hazard warning, backing-up, and nighttime presence marking.

U.S. automobiles use red tail lamps to indicate presence, an increase in intensity of those lamps when the brake pedal is depressed to signal braking, and an increase in intensity and flashing of the lamp on the side in the direction of the intended turn for the turn signal. Studies were conducted to evaluate driver response to these signals when given by the conventional display and by experimental rear lighting and signaling configurations.

The experimental technique involved the use of two test cars. The lead car had six 4 1/4 inch diameter lamps mounted in a horizontal row at the rear, three lamps on each side (Figure 2). The intensity of the lamps was variable and could be set as needed, and the color could be quickly altered by insertion of color filters. Lamp function was controlled by switches.

The following car was driven by a test subject, with a second subject in the front passenger seat (Figure 3). Mounted on the hood of the subjects' car were two small lamps (Figure 2) which were lit in a randomized order, on an average of ten times/ minute. The subjects were instructed to depress a switch as soon as possible after a light was noticed. They were also instructed to depress another switch as soon as they noticed a stop or turn signal on the lead car. Reaction times to the latter signals were measured by means of a telemetry link between the two cars.

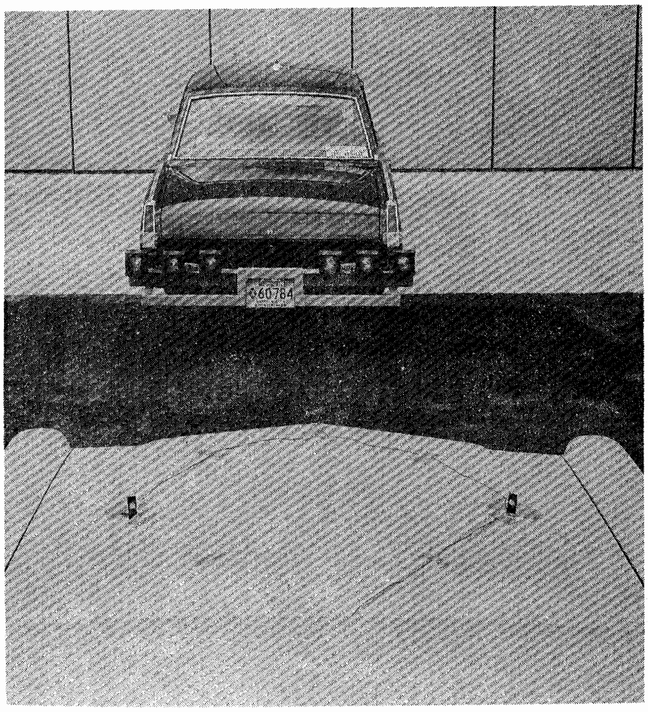

Figure 2. Lead vehicle indicating position of light alternatives.

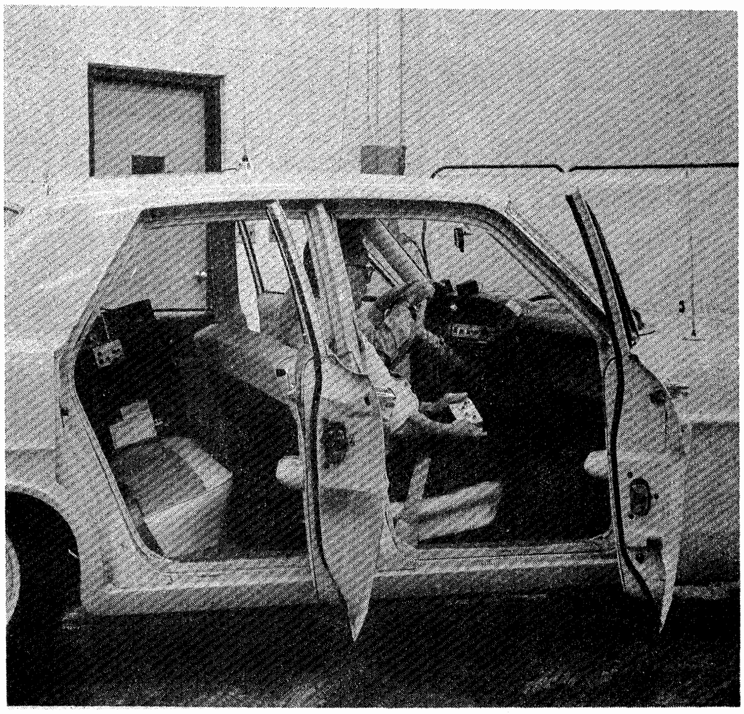

Figure 3. Following vehicle indicating instrumentation used by test subjects.

Previous tests were conducted by HSRI (Mortimer, 1969) on both city streets and a rural expressway. The present data were collected on urban streets in Ann Arbor.

The lighting systems that were evaluated are shown in Figure 4. System 1 represents the current concept found on most U.S. passenger cars. The experimental systems 2 and 3 used functional separation, and systems 4 and 5 functional separation with color coding. Tests were conducted with the intensity of the signals at 35 and 91 candlepower, with the presence light-signal intensity ratio being held constant at 1:13.

Mean reaction times, averaged across signal intensity, for each of the four signal modes and lighting systems are shown in Table 1. Statistically significant differences, detailed in the result of the Newman-Keuls tests, were found among the mean reaction times, generally showing that system 1 was poorest and system 5 the most effective by this criterion.

Distributions of the reaction times were, of course, also available from these studies. They are used in the subsequent analyses to be described to establish rear lighting system effectiveness using a criterion of crash probability.

MODEL DEVELOPMENT

METHODOLOGY

The evaluation of a change in the highway system component can be treated as a comparison between two highly related traffic subsystems; the first representing conditions before the component change and the second representing conditions after the change. The change in crash probability before and after the introduction of the component change can be expressed as follows, shown in Equation (1):

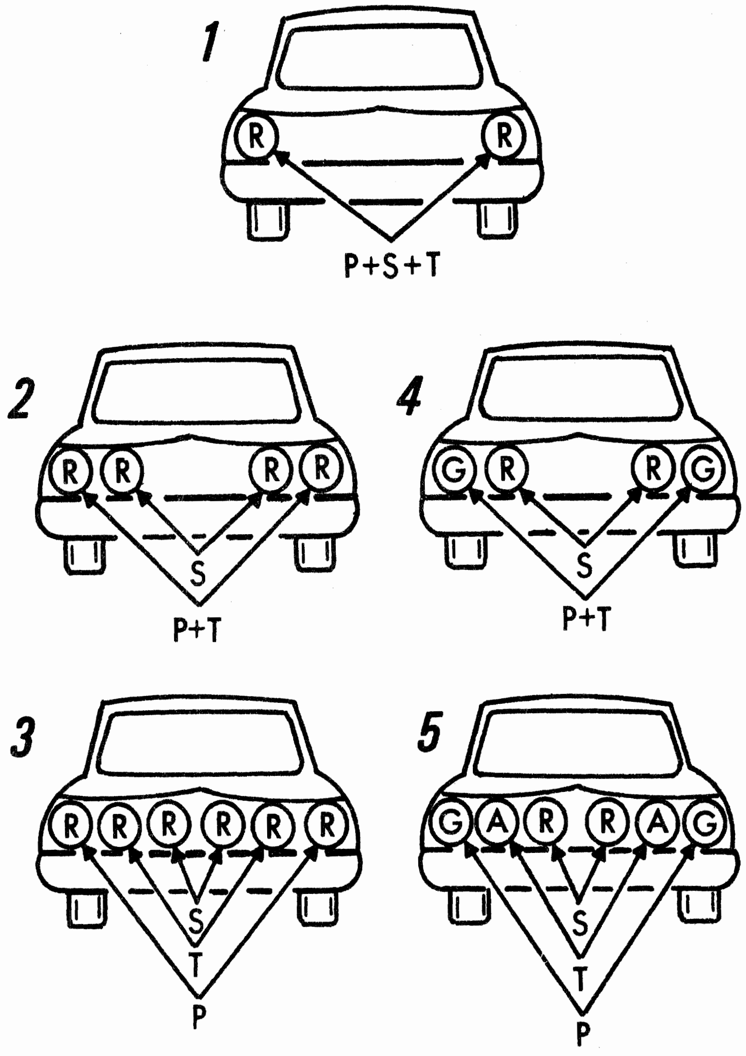

Figure 4. The lighting configurations. P=Presence (tail lights), S=Stop, T=Turn, R=Red, A=Amber, G=Green-Blue.

TABLE 1. GEOMETRIC MEAN REACTION TIME (SECONDS) FOR EACH SYSTEM AND SIGNAL MODE IN HIGH AND LOW INTENSITY CITY DRIVING TESTS, FOR 80 SUBJECTS.

	SYSTEM				
MODE	1	2	3	4	5
Turn	1.080	1.160	1.102	1.090	1.011
Stop	0.917	0.951	0.933	0.905	0.891
Turn→Stop[1]	0.985	0.865	0.915	0.812	0.811
Stop→Turn[1]	1.941	1.305	1.032	1.086	0.965
MEAN	1.231	1.070	0.996	0.973	0.919

<u>Individual Comparisons by Newman-Keuls Tests</u>:

1. Turn: 5 significantly[2] better than 4, 3, 2, 1
2. Stop: 5 significantly better than 2
3. Turn→Stop[1]: 5, 4, 2 significantly better than 3, 1
   5, 4 significantly better than 2
4. Stop→Turn[1]: 5, 4, 3, 2 significantly better than 1
   5 significantly better than 4, 3, 2
   4, 3 significantly better than 2

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[1] In Turn→Stop or Stop→Turn the reaction times shown are for the second signal only.

[2] Significant at $P \leqq .05$.

$$\Delta P = P_1 - P_0 \qquad (1)$$

ΔP - Overall change in the probability of crash; if this change is negative, an improvement has been made.

P_0 - The probability of a crash occurring within the traffic subsystem <u>before</u> a change.

P_1 - The probability of crash within the traffic subsystem <u>after</u> a change.

The traffic subsystem can be approximated as a set having N different discrete traffic situations as subsets or elements. Some examples of these subsets are:

1. A vehicle moving in an unrestricted state on a wet, concrete two-lane rural highway.
2. A car-following situation occurring on an urban, four-lane concrete expressway during rush hour.

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i The situations described in subset 2 above with the added condition that the lead vehicle suddenly makes an emergency stop.

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N An emergency stop on an urban, two-lane wet asphalt street.

Each of these subsets contains M_i elements or events defined by specific parameter values. For example, the following events would be contained as elements in subset 2 above:

1. Both vehicles moving at 50 mph.
2. Lead vehicle moving at 50 mph and the following vehicle moving at 55 mph.

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j Both vehicles moving at 60 mph with the pair located within a 20 vehicle platoon.

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M_i Lead vehicle moving at 50 mph and the following vehicle moving at 47 mph.

Since the traffic subsystem operated continuously it is necessary to impose a time dimension, t_{ij} ($j=1 \ldots M_i$; $i=1 \ldots N$) on each of these discrete events. This dimension, which will be specific for each event considered, covers the time from the defined beginning of the event under consideration until its defined end.

The subsets are identified by general parameter types while the events within the subsets are identified by specific values of the parameters. Distinction between general parameter types and specific parameter values is, of course, an important problem. For purposes of this analysis general parameter types are defined explicitly, by means of a constant, a functional relationship or a particular probability distribution. Specific parameter values are defined as the realization of a randomly selected event from the probability distribution defining a general parameter. The decision concerning what is a subset and what is an element within a subset is influenced by the objective and sensitivity of the analysis and by the available data. Examples are presented in this paper which indicate how subsets and events were defined for some typical problems.
Using the analysis described above, the probability of a crash occurring within the traffic subsystem can be expressed as:

$$P = \sum_{i=1}^{N} A_i \; P_i \qquad (2)$$

A_i - The percentage of the total traffic subsystem that constitutes a subset defined by situation i.

P_i - The probability of a crash occurring within subset i.

If subset i contains M_i discrete events, then:

$$P_i = \frac{C_i}{M_i} \qquad (3)$$

where C_i is the number of crashes occurring in subset i. The number of events, M_i, in any subset i will in general be countably infinite. M_i would be countable only if the subset were restricted to, for example, a particular intersection for a one or two week period. In general, the number of discrete events in any subset is independent of the number of discrete events in any other subset. The concept of dividing the total traffic subsystem is illustrated in Figure 5. If an improvement (i.e., a reduction in the number of crashes) can be achieved in subset i, an improvement to the total subsystem results. This follows directly from equation (2). However, since M_i and C_i are countably infinite the evaluation of P_i in the above form is not possible by conventional summation procedures.

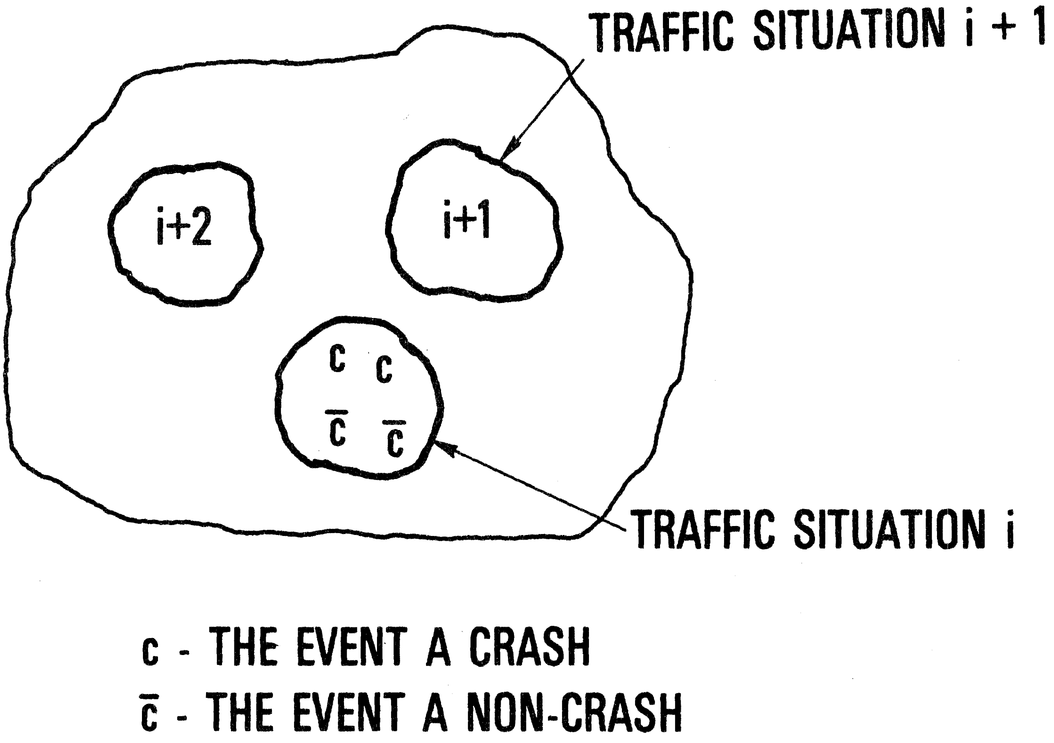

Figure 5. Set representation of an emergency traffic conflict within total traffic subsystem.

However, a mathematical model can be constructed for each of the subsets, i, defined by a particular traffic situation. By randomly selecting specific parameter values it is possible to compute a simulated realization of the crash vs no crash experiment. The events occurring within a subset can be represented in a model by particular parameter values. For example, a model of a car-following situation, in which the lead car makes a sudden stop, uses the laws of motion and the parameters listed below to define specific events:

1. Velocity of lead car (fps)
2. Velocity of following car relative to lead car (fps)
3. Braking acceleration for both cars (fps^2)
4. Headway (sec)
5. Perception and reaction time of following-car driver (sec)

Obviously other parameters could be used in addition to these. For any given set of parameter values it is possible to determine whether or not a crash will occur. A further sophistication would be to determine whether or not a crash of a given velocity will occur.

Within each subset, i, containing M_i events "ϕ_i" unique* event types can be defined ($\phi_i \leq M_i$). Each of these unique event types either result in a crash or they do not. The following convention identifies the result of each unique event type:

$$C_k = \left\{ \begin{array}{l} 0 \text{ if a crash does not occur} \\ 1 \text{ if a crash does occur} \end{array} \right\} K=1,\ldots\phi_i \qquad (4)$$

Since each unique event type is defined by r independent param-

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*A unique event type is one which is defined by a particular combination of the model parameters.

eters (in above example r=5), the probability of a particular unique event type, P_k, can be determined as follows:

$$P_i = \prod_{L=1}^{r} P_{KL} = P_{k1}.\ P_{k2}.\cdots.P_{kr} \tag{5}$$

P_{KL} - The probability that parameter L has the value required for event type K to occur (i.e., event K is defined by r parameters)

Thus, P_i, can be defined as:

$$P_i = \sum_{K=1}^{\phi} P_k\ C_k = \sum_{k=1}^{\phi_i} \left(\prod_{L=1}^{r} P_{kL} \right) C_k \tag{6}$$

The change in P_i, resulting from a modification in the traffic subsystem, is a measure of the effect of the change. Since ϕ_i is also very large it is not reasonable to compute P_i directly. However, a random sample of the events contained in subset i could be used to estimate the value of P_i. A simulated random sample of events can be obtained by randomly selecting values for each of the parameters, L, from their distribution in traffic situation i. Thus, if probability distributions for each parameter can be obtained, it will be possible to construct randomly selected elements of the set i. Using this sample the summation of the probability of each event type multiplied by C_k provides an estimate of P_i.

Many of the parameter distributions required as input have been developed through research on other highway problems. For example, Dawson and Chimini (1968) have developed a probability distribution of headways in single-lane traffic flow, and Tignor (1968) has determined the minimum stopping distances for a sample of cars selected from a busy highway.

In general, if a component change in the highway system can be expressed in terms of changes in the probability distribution of one or more of the parameters of a model, it can be evaluated by this method.

DESCRIPTION OF MODEL

The model is designed to represent a situation in which two vehicles are initially following each other at defined headway and velocities. The driver of vehicle A (the lead vehicle) suddenly applies the brakes, thus activating his brake light. The driver of vehicle B (the following vehicle) must perceive the brake-light signal and apply the brakes of his vehicle. The assumption that the following vehicle will brake was used because it is believed that most drivers will attempt to brake rather than turn when faced with a critical emergency. This is somewhat supported by a study in an automobile simulator conducted by Barret et al., (1968) in which only one out of eleven drivers reacted to a simulated emergency by turning. This driver was also an airplane pilot which might explain his particular reaction. The following possible occurrences can result from this emergency:

1. Vehicle B strikes vehicle A after vehicle B has begun braking.
    a. Vehicle A is moving
    b. Vehicle A is not moving
2. Vehicle B strikes vehicle A prior to the time vehicle B has begun braking.
    a. Vehicle A is moving
    b. Vehicle A is not moving
3. Vehicle B does not strike vehicle A

The model computes the time for various stages beginning with initial brake application through the point at which either a crash occurs or both vehicles stop. All times are computed using the basic laws of motion and selected parameter values. The model presently uses average brake deceleration values.

This is not considered to be a serious deficiency since the comparison is between different rear lighting configurations in the context of the same critical situation.

SYSTEM EVALUATION

The use of the model described above to evaluate different rear lighting configurations requires that perception time distributions be available for each configuration studied. In addition it is necessary to describe the emergency conflicts by means of probability distributions of other important parameters. The parameters used in this model have been defined previously. Through proper selection of the distributions it is possible to compare different lighting configurations within several defined emergencies. The question of which emergencies occur most frequently has not been completely answered. However, we have attempted to select a set of situations which occur frequently and which are affected significantly by driver reaction time to a rear lighting system. By making these comparisons over all of the most frequent emergencies we expect to obtain a robust comparison of the various lighting configurations.

The following sources of information have been used to define emergencies:

1. Signal perception time data from the experimental studies of automobile rear lighting configurations. These studies provide a time value for the period from brake application of lead vehicle to start of foot movement from accelerator to brake for the driver of the following vehicle. A separate value for moving the foot from accelerator to brake is used.
2. Traffic-flow studies conducted by Treiterer (1966) of Ohio State University have provided velocity, relative velocity between adjacent vehicles, and headway measure-

ments. He used photogrammetric techniques to obtain the measurements on an expressway near Columbus, Ohio, during an early morning rush hour.

3. A distribution of driver-vehicle braking capability was obtained from a study conducted by Tignor (1968) of the Bureau of Public Roads. He measured the stopping distance under emergency stopping conditions for a number of vehicles passing a particular point on a highway. His distribution of stopping distances was converted to a distribution of braking deceleration.
4. Speed distributions measured by the Michigan State Highway Department (1968) have been used to represent speeds on two-lane state highways.
5. A headway distribution model developed by Dawson and Chimini (1968) has been used to represent headways in single-lane traffic situations. This model, known as the Hyperlang Model, assumes that traffic flow is made up of constrained vehicles and unconstrained vehicles. It uses a weighted combination of an exponential distribution (unconstrained flow) and an Erlang distribution (constrained flow) to represent the highway situation. As the number of vehicles per hour increases the percentage of constrained-flow vehicles also increases. This model has been found to agree very well with data presented in the 1965 Highway Capacity Manual and with data obtained by Purdue University (1967).

CHOICE OF THE CRITERION

One measurement obtainable from the simulation model is the percentage of crashes occurring within each set of assumptions. However, we believe that it is also important to compare crash severity, since total loss due to highway crashes is the product of the number of crashes and the loss per crash. Therefore, reduction in crash severity is as important as reduction in number of crashes; i.e., an improvement that changes fatal crashes to nonfatal crashes is more important than an improvement that changes nonfatal crashes to noncrashes. The criterion chosen for comparing alternative systems is a cumulative frequency distribution of crashes occurring at or below a given velocity.

APPLICATION OF METHODOLOGY

THE EFFECTS OF FUNCTIONAL SEPARATION AND COLOR CODING, AND TYPE OF ROAD. Figures 6 through 9 compare the various rear lighting systems. Two modes are considered: The stop mode in which a lead car suddenly applies its brakes and the turn→stop mode in which the lead car is signaling a turn and suddenly begins an emergency stop. The cumulative frequency distribution curves indicate the percentage of crashes which occurred at the indicated velocity or at a lower velocity. The intersection of this cumulative distribution curve with the ordinate indicates the percentage of cases in which a crash did not occur (e.g., defined as a zero velocity crash). Therefore, the curve of a "better" rear lighting system would intersect the ordinate at "greater" percentage values and have a "steeper" slope. The optimal situation would be 100 percent of zero velocity crashes, indicated by a point in the upper left corner of the graph. For example, in Figure 6 the curve for the present system (system 1) indicates that approximately 51 percent of the crashes occurred at a velocity of zero feet per second or less, thus indicating no crash. Similarly, approximately 77 percent of the crashes occurred at 25 feet per second or less. This implies that in 26 percent (77 minus 51) of the cases a crash at a velocity between zero and 25 feet per second occurred using system 1.

Figure 6 represents the driving situation on the I-71 expressway near Columbus, Ohio, during a morning rush hour. Velocities and headways were obtained from the data supplied by Dr. J. Treiterer. Using that highway situation, which is characterized by uneven traffic flow, lower than normal expressway speed, and short headways, we have superimposed emergency car-following situations. Under these conditions system 5 has fewer crashes at all of the indicated relative velocities, including zero. For purposes of comparison it can be seen that system 1 had no crashes 51 percent of the time while system 5 had no crashes 62 percent of the time, thus indicating a reduction in crashes of 22 percent (11 over 51), given a defined emergency. The magnitude of difference is similar over all relative velocities of crash. Another possible measure of effectiveness is the improvement in the worst condition. In the emergency car-following conflict the worst condition would be a high velocity crash. Thus, the 99th percentile of the cumulative relative velocity at crash might be used as a measure of system effectiveness. Although this measure is subject to random variability it does provide an indication of the worst case for various situations. A more meaningful comparison can, of course, be made by comparing the entire distribution. For example, one might make such a comparison by over-laying the graphs on a transparent surface so that all curves project onto one grid system.

Figure 7 represents the driving situation on a rural two-lane road under crowded conditions. The velocity distributions used were obtained from the Michigan State Highway Department speed survey. The headways were obtained from the Hyperlang headway model. This evaluation represents a volume level of 1050 vehicles per hour per lane. In this case, system 1 has a zero relative velocity crash level of 40 percent as opposed to a zero relative velocity crash level of 50 percent for system 5. This represents an improvement of 25 percent.

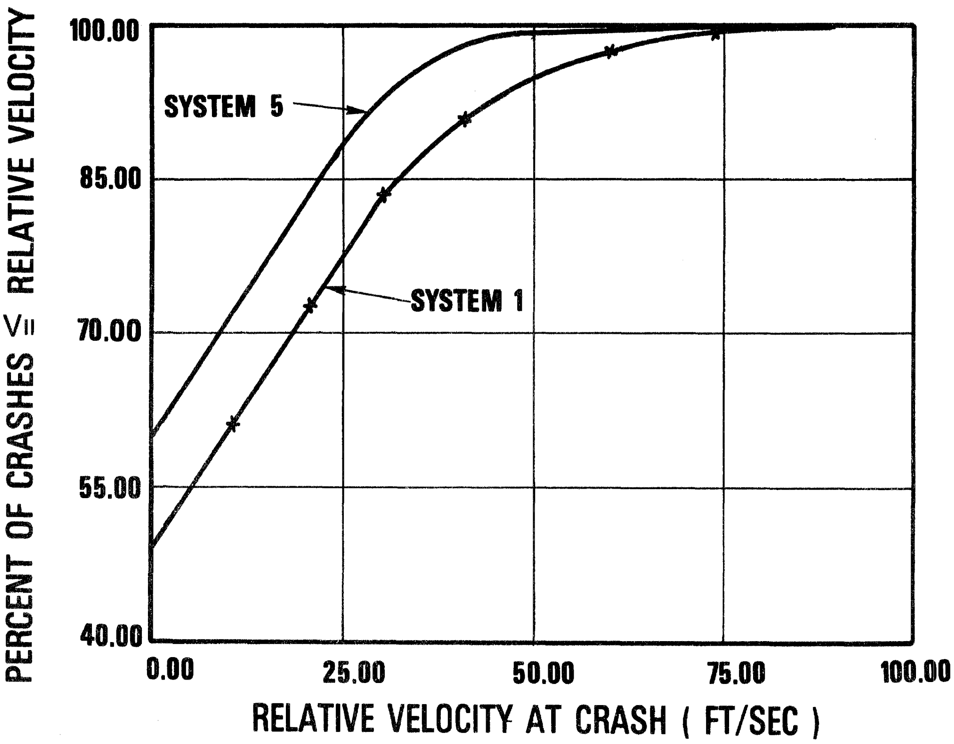

Figure 6. Crash probability for system 1 and 5 in turn-stop mode on an expressway.

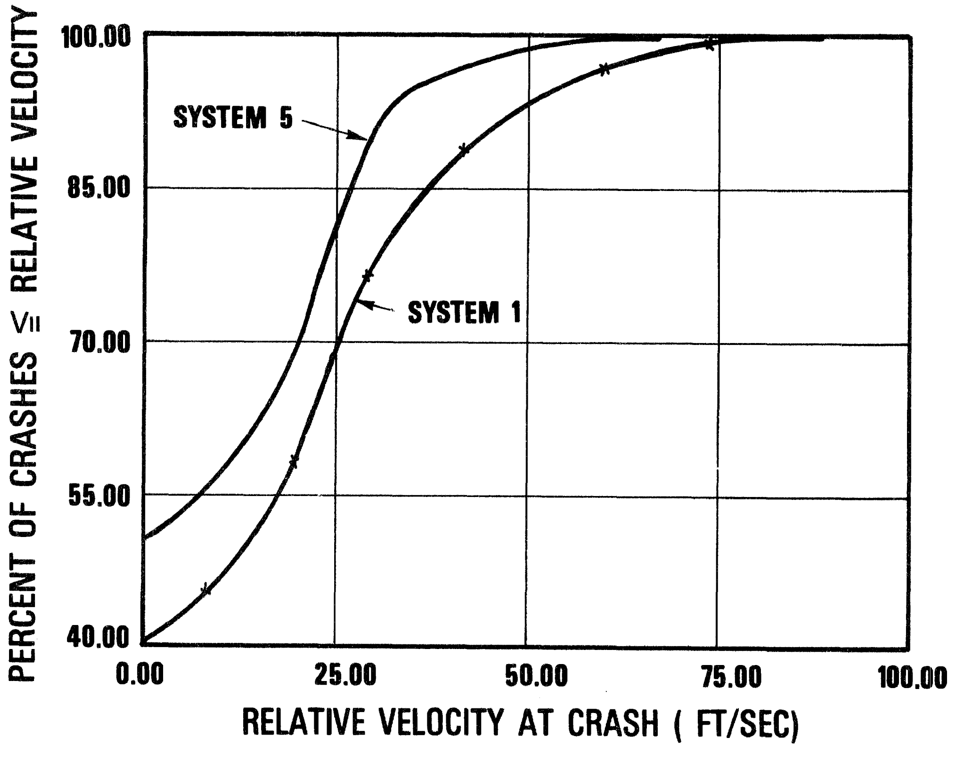

Figure 7. Crash probability for system 1 and system 5 in turn-stop mode on a two land rural highway.

By comparing Figures 6 and 7 it is also possible to observe the reduction in crash frequency and severity which result from using expressways instead of two-lane roads. In order to make these comparisons meaningful the headway and velocity distributions were adjusted to a common vehicles per hour per lane traffic volume.

THE EFFECT OF SIGNAL INTENSITY, FUNCTIONAL SEPARATION AND COLOR CODING

Figures 8 and 9 compare the effect of stop and turn signal intensities and system configurations. Figure 8 compares the present rear lighting configuration (system 1) with the signal at low intensity (35 cp) and an experimental configuration (system 5) at low and high (91 cp) intensities in the stop mode. At the lower intensity the differences between the configurations are negligible. The positive effect of increasing the intensity occurred for all lighting systems. This improvement, which occurred for a two-lane highway situation, also occurred for an expressway situation.

In contrast, Figure 9 indicates that in the turn→stop mode intensity has very little effect while functional separation of lamps and color coding are beneficial.

In summary, the results show that, using the experimentally obtained data in conjunction with the simulation model, safety is improved in the stop mode by increasing signal intensity, while light intensity has very little effect in the turn→stop mode. In that mode functional separation and color coding effectively reduce the incidence of crashes. The greater safety of expressways compared to two-lane roads was similarly apparent.

CONCLUSIONS

A methodology has been presented for evaluating the effect of changes to the highway environment on the number of crashes

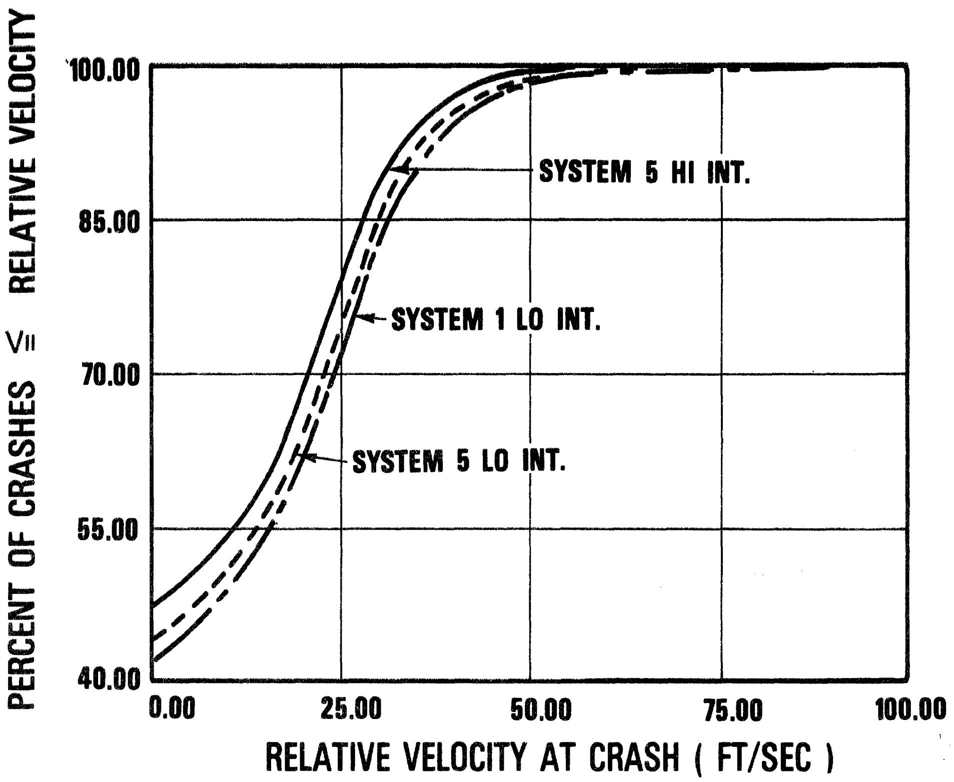

Figure 8. Crash probability for system 5, high and low intensity signals, and system 1, low intensity, in the stop mode on a two lane rural highway.

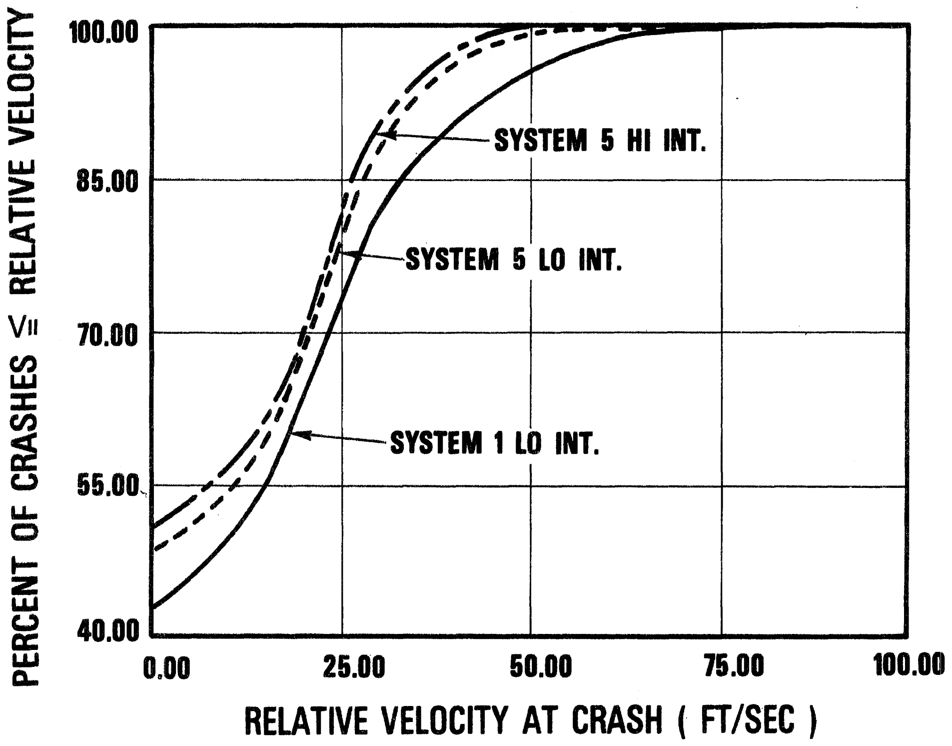

Figure 9. Crash probability for system 5, high and low intensity signals, and system 1, low intensity, in the turn stop mode on a two lane rural highway.

which occur. Specifically, an experimental vehicle rear lighting system was compared to one representing that found on most U.S. cars. For the subset of emergencies that were considered the change was shown to result in a significant reduction in number of crashes and in crash severity. The basis of the evaluation was a procedure for dividing the highway system into a number of discrete subsets and identifying those which are affected by the proposed change. An evaluation of the effect of the change on number of crashes is then performed within each of the identified subsets. If the changes result in a crash reduction within each subset then it follows directly that the entire system will experience a reduction in crashes.

There is, of course, still the question of how various subsets are represented in the total system. Thus, if a crash reduction is indicated for a subset which is a truly rare condition then the improvement will have little effect on the total system. At this point that problem can only be dealt with by applying good research judgement and by using the limited data available on exposure. As knowledge is gained concerning how drivers, vehicles and environments are represented in the total system it will become possible to define the occurrence of various subsets in the highway system. However, decisions concerning improvements are being made now with or without evaluation. We believe that this methodology can assist in the evaluation problem and, hence, contribute to better decisions.

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ACKNOWLEDGEMENTS

This study was conducted as part of contract FH-11-6936 with the U.S. Department of Transportation, National Highway Safety Bureau.