The Effects of Automotive Rear-Signal System Characteristics on Driving Performance

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This paper presents the results of several research projects concerned with the evaluation of the effects of automotive rear-signal system characteristics on driving performance. Variables considered in the evaluation included color, size, placement, location, and informational content of the signal systems. Experimental results indicate that almost any change from the current conventional system results in an improvement.

• EXTENSIVE RESEARCH INVESTIGATIONS on the effects of automotive rear-signal system characteristics on driving performance conducted by the Systems Research Group of the Department of Industrial Engineering at the Ohio State University are described and summarized. Sponsors of the research projects that are reported include the National Cooperative Highway Research Program, the Ohio Department of Highways, and the Federal Highway Administration and the National Highway Safety Bureau of the U. S. Department of Transportation. This research spanned a period of 5 years and not only was concerned with signal system design configurations and the conceptual basis for such designs but also included the problem of determining performance measures for evaluating alternative systems.

One of the areas of the traffic safety problem that rank high in accident frequency is the rear-end collision. Various studies claim that rear-end collisions account for 20 to 40 percent of all accidents. Although not adequately documented, it is believed that many of these collisions result from inadequate communication from the lead car to the following driver. The only method currently available for communicating between 2 vehicles is that of using the signal lights on the back of the lead vehicle. At the present time this communication system is capable of displaying very limited amounts of information. A list of the functions that the system can perform, or rather types of information that can be displayed with the current taillight configuration, includes only the following items: (a) braking information, on-off; (b) running information (absence of braking), on-off; (c) turning information, left-off-right; and (d) backing information, on-off.

Of these 4 functions it can be argued that the presentation of information concerning the braking behavior of the lead vehicle is the most important. Failure of the taillight system to transmit braking information might be a factor in the large number of rear-end accidents.

The type of taillight system currently used on automobiles is not an ideal communication system and often leads to confusion. Two types of errors can be identified with the present taillight system. The first kind of error occurs in the car-following situation where the separation distance between vehicles is less than 500 ft when the driver of the following vehicle fails to notice a change in the taillight signal of a lead vehicle.

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The second kind of error occurs in the approach or overtaking situation where the headway and relative velocity between the 2 vehicles are usually large. Here the driver of a vehicle suddenly encounters a vehicle in front of him and errs in judging whether the car is braking or maintaining speed. The first type of error can be considered an error in signal change detection, while the second type of error can be considered an error in signal magnitude estimation (because braking in the current system is signalled by an increase in intensity of the running light).

Brightness change for encoding information in a taillight system, which is currently used today, is a very poor choice. Doubling the absolute intensity of sound does not mean that the human subject will be able to perceive a doubling. In the case of brightness, J. C. Stevens and S. S. Stevens (12) and others have shown that the human requires large changes in brightness intensity to perceive differences. A tenfold increase in brightness yields about a twofold increase in perceived brightness for most individuals. In addition to using a coding mechanism to which the human is insensitive, the present system has many other faults. A red signal that means "stop" and also "running" causes confusion. Red signal lights also usually appear farther away than other colors viewed at the same distance (1). The major question, therefore, appears to be not whether a better rear-end signal system can be designed but which of the many available alternative systems is best. The Systems Research Group at the Ohio State University has conducted several research studies to find the answer to this problem.

Before describing the results of these studies, this paper will explore some of the problems that are inherent in research of this nature.

PROBLEMS ASSOCIATED WITH HUMAN FACTORS RESEARCH IN DRIVING

One problem associated with research on automobile taillights (or on any aspect of automobile driving) is that there exists an overabundance of experts in the field. Approximately 100 million critics subjectively judge the results of any research (at least those results that are implemented).

Another problem associated with this type of research is the selection of the methodological approach that is to be used in the research. Several approaches are available and include laboratory simulation, part task simulations, and studies conducted in the real world. All of the experiments performed by the Systems Research Group have been done in instrumented vehicles on actual Interstate highways and secondary roads. This approach does not allow the precise control over variables that might be available in a laboratory situation or in a partially simulated driving task. The results that are obtained on the highway do, however, have the distinct advantage of being readily interpreted into meaningful conclusions. The philosophical problems and stark practical uncertainties, which are present when extrapolations are attempted from laboratory simulation results into real-world contexts, are minimized when studies are conducted in the setting in which they are to be interpreted.

Another problem associated with research in vehicle rear-signal systems is the determination of a criterion. Given an alternate to the current system, how should it be evaluated in terms of the present or conventional system. It is clear that this question depends to some extent on measurement capabilities. Measurement problems include determining when the following-car driver detects the presence of a lead car and determining when the driver detects a mode change, for example, a change from running to braking. Two questions that point to other measurement problems are as follows:

1. How does a driver ascertain the rate of closure between his vehicle and the vehicle in front of him?
2. How can the confusability of a signal system be measured?

RESEARCH PHILOSOPHY

The research philosophy used by the Systems Research Group in conducting its investigations into the design of vehicle rear-light systems is a multifaceted philosophy. The complexity of this philosophy is dictated by the complexity of the rear-end signal

system design problems. Figure 1 shows a schematic diagram of some of the factors that must be considered in research into the design of automobile signal systems. Using the notation of the schematic, we might state the research objective as follows:

> Compare possible display configurations using the stated performance measures to determine which configuration is "best" suited to achieve the system functions in the different visual environments, and under different given situation variables and different human and component reliability factors.

Ideally all possible combinations of these factors would be examined in determining the best signal system display. At the present time, however, such an effort is not possible. It is, therefore, not currently possible to design the optimum or ultimate system. For that reason the Systems Research Group has adopted the principle of guided evolution in its research. This principle presumes that there should be logical order in the evolution of rear-end signal systems from the current conventional system to advanced optimum systems. The evaluation would be characterized by small, mutually

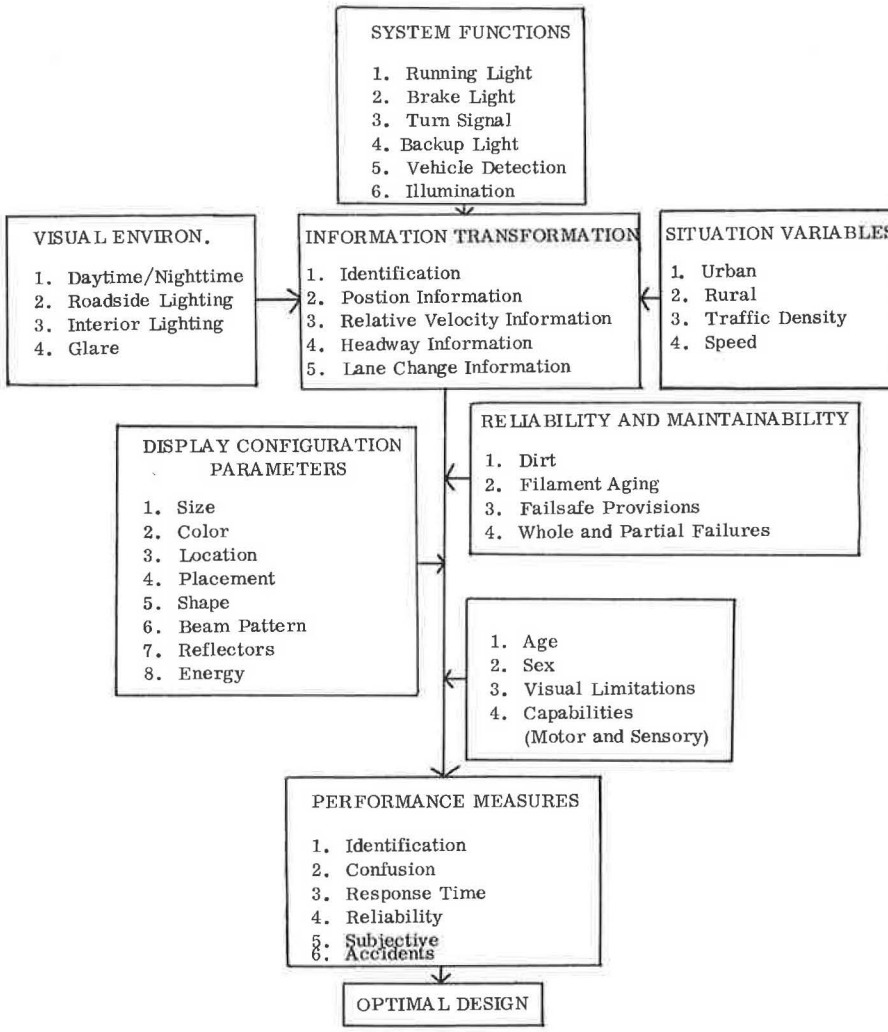

Figure 1. Factors in automobile signal system design.

compatible changes incorporating the latest in technological advances. Such small changes would have the advantage that the driving public might be more readily able to adapt to them than to major changes.

Any new system must be instantly understandable. Because each driver cannot personally be educated to system changes, the driver must have a natural response to the new information that is presented to him with whatever new presentation codes are used. For example, a purple signal has no obvious interpretation and hence its introduction into the highway scene could be disastrous because it might promote rather than minimize accidents. A system should also have redundant characteristics whenever possible, i.e., the use of 2 codes to provide the same information. Position and color, brightness and color, or position and brightness could be used to signal information so that if the first code is missed by the driver, either due to a visual abnormality or other system malfunction, the second code would yield the same message.

The Systems Research Group's philosophy centers around information transfer. This leads to the questions, What information should be presented to the driver? When should it be presented? How should it be presented? Of these, the most crucial issues involve what information is both necessary and possible to present to the following-car driver from such possibilities as position, presence of the vehicle, speed of the lead car, relative velocity of the 2 cars, and the relative acceleration of the 2 cars. This information is currently presented in the car-following situation by the static and dynamic physical position of the vehicles with respect to each other and with respect to the environment. The ability of the driver to obtain information from this natural display is not known completely, although Rockwell and Snider (10) have made some initial determinations of man's abilities to sense these kinds of information in some common car-following situations. In the design or selection of an alternate to the current taillight system, man's psychophysical capabilities should be considered because any signal system that is adopted for use on the vehicle should be capable of resulting in performance that is at least as good as the performance exhibited by the human without the signal system. Care should also be taken in evaluating automobile signal systems. This will ensure that a particular taillight design facilitating the transfer of 1 type of information pertinent to the driving task but impairing the transfer of other types of information is not adopted.

With respect to when signal system information should be presented to a following-car driver, it is helpful to consider a temporal model of the car-following phenomena. Given a situation in which a following car approaches a lead vehicle that is traveling at a slower speed, one can identify at any point in time a headway or a time to collision. If a collision is to be avoided, 6 events must occur within this time. These include (a) detection of the lead vehicle by the following-car driver; (b) determination of lead vehicle mode, such as running, braking, or turning; (c) estimation of rate of change information; (d) decision by the following-car driver concerning the appropriate response; (e) response on the part of the following-car driver in applying the decided on action; and (f) response on the part of the following vehicle. Each of these events consumes time. Too much time devoted to any one of these events will not leave sufficient time for the other events to take place and a collision could occur. Improvements in vehicle rear-light information coding systems can be expected to reduce the time required for mode determination, rate of change estimation, and decision-making.

VISUAL CHARACTERISTICS OF COLORED SIGNAL LIGHTS

Many proposed experimental signal systems incorporate lights of colors other than red. Some information concerning the visual characteristics of colored signal lights is reported in the literature.

When a light is just visible in the primary visual axis, it is nearly colorless. As the intensity of the light is increased or its distance from the observer shortened, red lights may be distinguished from lights of other colors, but lights of other colors still look alike. On further increase of intensity we distinguish green, amber, white, and blue in that order (13).

Studies in peripheral color vision have yielded different results. All parts of the retina do not have the same degree of sensitivity to color because of varying concen-

trations of cone cells in the periphery of the retina. In normal eyes the retina is sensitive to yellow over the largest area and to blue over one almost as large, to red over a still smaller area, and to green over the smallest (7).

Merrill J. Allen (1) has indicated that a lateral chromatic aberration of the eye called "chrome stereopis", present in two-thirds of the population, may have an effect on the depth perception of colored signals (1). This condition exists when the pupil is decentered nasally. The retina, therefore, receives only that part of the light passing through the edge of the lens. This part of the lens acts as a prism to separate the spectral colors on the retina. Because of this, reds appear farther away than they actually are, greens appear very nearly at their true location, and blues appear closer than they really are. Allen gives no indication of the severity of this phenomenon. On this basis, red would seem to be an illogical choice for a taillight because it may trick the driver into believing he has more headway than actually exists. Although amber was not considered in the previously mentioned study, there is reason to believe that it would appear somewhere between red and green because of its position in the spectrum.

The results of Allen's study may be given in the following matrix form:

Vision	Red	Amber	Green	Blue
Direct visibility	A	C	B	D
Peripheral visibility	C	A	D	B
Depth perception	D	C	A	B

In this tabulation, A indicates best performance and D indicates worst performance. Blue was rated above red and amber because it tends to appear closer than actuality; thus making the driver more conservative.

This matrix generally holds true for varying degrees of fog, clean air, daylight, and darkness. The absence of any change in the qualities caused by variations in ambient lighting may be attributed to the fact that no Purkinje shift can occur during the observation of signal lights at night. The eye is never really darkness-adapted under these conditions.

The principal effect of fog is to attenuate the light coming from a signal by scattering it. This is equivalent to reducing the intensity of the light itself, and this reduces the visual range of the signal both for detection and color recognition. In a true aqueous fog, all colors are scattered about equally so that their hue is not changed. A haze of smoke or dirt mainly reduces the intensity of a good blue or green signal and may make white and yellow lights appear somewhat reddish (13). It should be noted here that some researchers, notably Middleton (4) and McNicholas (3), believe that blue and green lights may be somewhat more spread or dispersed by fog than red or amber and therefore may appear closer. More intensive research may resolve this diversity of opinion.

RESULTS OF INITIAL SYSTEMS RESEARCH GROUP EXPERIMENTS

The Systems Research Group's first experiment in the area of rear-signal systems was partially directed toward the aim of testing new means of communication between vehicles via vehicle-borne taillight systems. In this experimentation sponsored by the National Cooperative Highway Research Program (11), 4 intervehicular signal systems—AID, Tri-light, NIL, and conventional signal systems—were compared. The display consisted of 5-in. square light units arranged, as shown in Figure 2. Conventional brake lights were displayed by the outer red lights. The Tri-light system used the vertical columns of red (brake pedal actuation), amber (no pedal actuation), and green (gas pedal actuation). The AID system employed the horizontal rows of red and green lights, actuated by vehicle acceleration, with the outer red signaling slight deceleration, the 2 outer reds a greater deceleration, and so on until all red lights were illuminated for a violent deceleration maneuver. The green lights functioned in a similar manner for acceleration. The NIL condition was one in which all lights were turned off and none was displayed during a vehicle maneuver. The following vehicle (driven by the subject) was equipped with a take-up reel and recorder to permit continuous recording of headway and relative velocity as well as vehicle velocity, pedal movements, and acceleration.

The analysis of the data obtained in this experiment indicated that both the AID and Tri-light systems resulted in decreased response times over the conventional system.

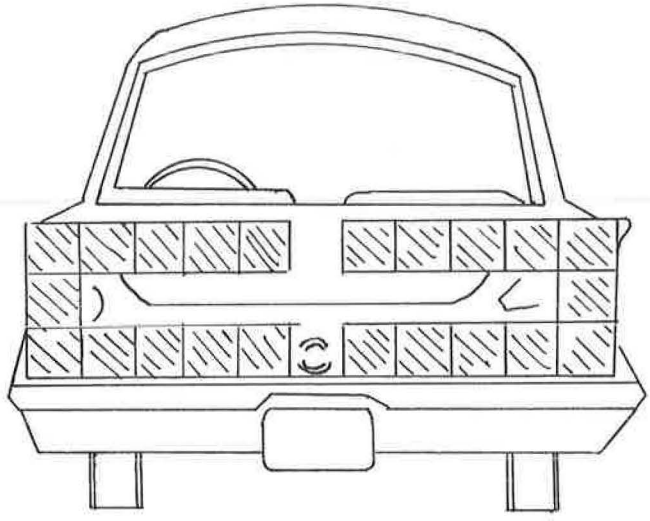

Figure 2. Arrangement of signal lights in previous experiments.

Response times under conventional and NIL systems (where drivers were left to detect decelerations by visual cues such as CANT and perceived relative velocity) were more than 3 times those obtained under the AID and Tri-light systems as shown in Figure 3. The greatest gains were obtained with the Tri-light system. Large differences between performance under conventional and that under AID or Tri-light clearly indicated the benefits obtainable from signaling small decelerations (e.g., coasting maneuvers by the lead car).

When performance under the 2 special systems (AID and Tri-light) was compared, it was found that the Tri-light system yielded slightly better performance during lead

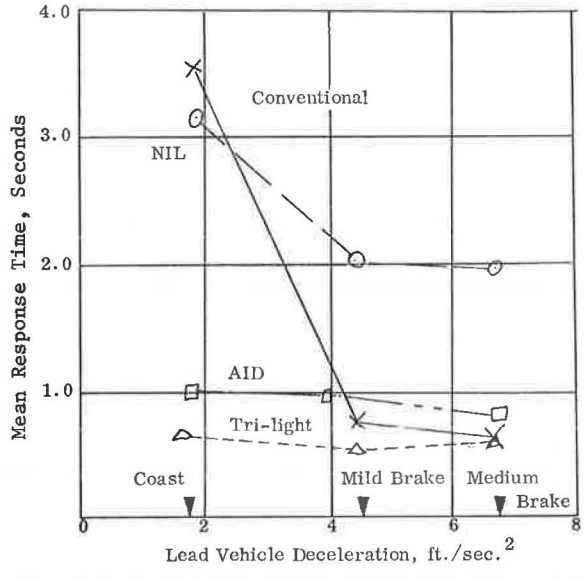

Figure 3. Experimental results.

vehicle deceleration and that both systems performed equally well during lead vehicle accelerations. This experiment was performed both at night and during the day. Essentially the same results were found for both periods of time.

DEVELOPMENT OF EXPERIMENTAL TESTING PROCEDURES

The experience of the Systems Research Group on this initial research project on vehicle rear-signal systems suggested some experimental procedures that were utilized in subsequent research projects. The testing procedures that evolved from the early research work of the Systems Research Group were designed to enable comparisons of different signal systems with respect to (a) performance in car-following situations; (b) performance in approach situations; (c) headway estimation performance; and (d) performance in coupling situations. Each of these performance tests will be described in more detail in the following.

EXPERIMENTS TO MEASURE PERFORMANCE IN CAR-FOLLOWING SITUATIONS

The experiments that were designed to measure performance in car-following situations were designed to measure those variables that could be associated with signal change detection errors and their relation to different signal systems. The major dependent variables considered in this experimentation included (a) reaction time, (b) headway changes, (c) relative velocity changes, (d) velocity changes, (e) brake pedal activity, and (f) gas pedal activity. The independent variables that were considered included the different signal systems.

The basic experimental procedure in the car-following situations required that the subject drive an instrumented vehicle at a fixed distance (usually 200 ft) behind a lead vehicle (usually traveling at a constant speed of 65 mph). The lead car then began a constant 10-sec deceleration that reduced the speed of the lead vehicle by 30 mph. This deceleration was signaled by the vehicle rear-signal system in a manner dependent on the type of signal system being utilized. After the 10-sec deceleration the lead vehicle began a 10-sec ramp acceleration to get the lead vehicle back to the original speed.

During the car-following experimentation, the following items of information were obtained for each maneuver (deceleration and acceleration of the lead vehicle):

1. Gas pedal response time—Time interval between initiation of the maneuver and the release of the gas pedal in the following vehicle;
2. Brake pedal response time—Time interval between initiation of the maneuver and the depression of the brake pedal in the following vehicle;
3. Gas pedal release interval—Time period that the subject's foot remained off the gas pedal;
4. Initial headway—Headway at the initiation of a maneuver;
5. Minimum relative velocity or maximum closing velocity—A negative quantity occurring during the period of closure;
6. Maximum relative velocity or maximum opening velocity—A positive quantity occurring during the acceleration period following the period of closure;
7. Percentage reduction in headway—A derived measure equal to the difference between the initial headway and the minimum headway divided by the initial headway; and
8. Acceleration response time—Period of time between the end of braking by the lead vehicle and depression of the gas pedal in the following vehicle.

It is recognized that drivers are more alert in an experiment of this kind than during normal freeway driving. This alertness was probably present for all trials and signal systems and, accordingly, did not affect direct comparison of signal-system performance. Absolute values such as response times, however, reflect the experimental conditions and generally are lower than one would expect under normal driving conditions void of this psychological set.

It is useful to divide system dynamics into 2 parts during a lead-vehicle maneuver. The first part begins with the deceleration of the lead vehicle and ends when zero relative velocity is regained. This period corresponds to the period of closure. The second

part includes the remainder of the maneuver terminating when the lead vehicle reaches its initial speed of 65 mph. In the first part of the maneuver, during lead-vehicle deceleration, interest is primarily directed toward 5 measures of car following. These include (a) gas pedal response time, (b) brake pedal response time, (c) minimum relative velocity or maximum closing velocity, (d) percentage reduction in headway, and (e) minimum headway.

In the second part of the maneuver attention is transferred to car-following performance during acceleration by the lead vehicle. This portion of the maneuver is possibly less important from a safety point of view, but is more important in terms of traffic flow. In accordance with the preceding during this portion of the maneuver 2 measures of car-following performance are considered important: (a) acceleration response time, and (b) maximum relative velocity.

Acceleration response time represents the time interval from the beginning of the lead vehicle's acceleration until the following-car driver steps on the gas pedal of his vehicle. It is interesting to note that the drivers were not specifically instructed to respond to the cessation of the brake light on the lead vehicle. In this respect this measure might be taken to be a more natural indication of the response time to various signals than the initial response times exhibited at the beginning of the lead vehicle's deceleration. Both types of response times indicate essentially the same things about the signal systems.

Maximum relative velocity during the lead vehicle's acceleration forms a partial measure of the following driver's performance in interpreting and following the lead vehicle's acceleration.

EXPERIMENTS TO MEASURE PERFORMANCE IN APPROACH SITUATIONS

This experimentation was designed to determine the relation of magnitude estimation (confusion) errors in the overtaking situation to different signal systems. The major dependent variables that were considered in this phase of the experiment included (a) reaction time, and (b) confusion errors (judgment of whether signal is braking or running). The independent variables that were considered included the different signal systems.

Prior to the start of this part of the experiment, the subject was given instructions similar to the following:

> We are now going to ask you to drive this car at a distance of 1,000 ft behind the lead car. After you are at 1,000 ft the lights on the rear of the lead car will go out. They will remain out for a time; then they will come back on. When they come on, we would like you to judge as quickly as possible whether the car is displaying a brake light or a running light.
>
> If you decide that the car is displaying a running light, depress the gas pedal slightly. If you decide that a brake light is on, take your foot from the gas pedal and touch the brake pedal without slowing down.

After the instructions were given, the driver was guided to a headway distance of 1,000 ft by the experimenter. The subject then followed the lead car at this distance. Instructions were issued when necessary so that the subjects could maintain this headway of 1,000 ft. During this phase the lead car taillights followed the pattern shown in Figure 4. Note that the subject was always presented with a running light prior to the turning off of the taillight system. The basic purpose for this design was to simulate the situation where confusion exists as to which light (BL or RL) is functioning.

EXPERIMENTS TO MEASURE HEADWAY ESTIMATION PERFORMANCE

This experiment was designed to determine the effects of taillight design parameters (e.g., size, color, intensity, or placement) on the ability of subjects to estimate distances.

The experimental procedure required that the subjects sit in the front seat of the instrumented vehicle on a private road in an unlighted area behind 2 other vehicles.

RL	NL	RL or BL	RL	NL	RL or BL

Time

RL = Running lights
BL = Brake lights
NL = No lights

Figure 4. Taillight patterns.

One of these other vehicles was a sedan equipped with 2 red taillights mounted in a position corresponding to the position of most current conventional taillights (i.e., the lower left and right of the back of the vehicle). The subjects were given the following instructions:

> As you can see, we have 2 vehicles in front of you. The vehicle on your right will remain parked with its red lights on. The vehicle on the left with different signal lights will drive slowly up to and past the other vehicle, then it will back up. We would like you to press the button that you hold in your hand when you think the 2 vehicles are exactly side by side. We would like you to do this both when the vehicle on the left is moving forward past the parked vehicle and when it is moving backward past the parked vehicle. Again press the button when you think the 2 vehicles are side by side and please hold the button down for a second or two.

The lead vehicle slowly drove forward to a point about 600 ft in front of the experimental vehicle, and then slowly backed up to a point about 200 ft in front of the experimental vehicle.

From the oscillograph traces obtained in this phase of the experimentation, the actual headway of the lead car, at the moment the subject thought the lead car was as far away as the parked vehicle, was obtained. The target distance (i.e., the distance from the subject vehicle to the parked vehicle, with which the vehicle with the experimental signal systems was being compared) was subtracted from the actual headway, and an error headway was obtained.

EXPERIMENTS TO MEASURE PERFORMANCE IN COUPLING SITUATIONS

In addition to the car-following situation where the separation distance between vehicles is usually small and the approach situation where separation distances are large but are decreasing, a third situation might be identified. This situation could be labeled as the coupling of the lead vehicle and the following vehicle. The coupling condition lies at the interface of the car-following condition and the approach condition. Primary measures of performance in the coupling situation were considered to be the rate of change of headway during coupling and the headway at which the following vehicle levels off behind the lead vehicle.

The experimental procedure that was used in this experimentation required that the subjects drive the instrumented vehicle at a speed of 65 mph several thousand feet behind the lead vehicle also going 65 mph. The lead vehicle then slowed to 35 mph. The closing behavior in terms of the headway changes between the 2 vehicles was measured every half second with a 16-mm motion picture camera.

Prior to the start of the experimentation, the subjects were given the following instructions:

> You will follow the lead car at 65 mph. The lead car will slow up. You will close up behind the lead car as if you were on a 2-lane highway and were not able to pass.

The film collected in this phase of the experiment was projected on a standard calibrated screen, and the distance between the signal lights was measured. These mea-

urements were then converted to headways via a computer program and plotted by the computer.

RESULTS OF CURRENT SYSTEMS RESEARCH GROUP EXPERIMENTS

The Systems Research Group's second research project in the area of rear-signal systems was sponsored by the Ohio Department of Highways and the Federal Highway Administration. It was designed to compare a proposed amber-red taillight system to the conventional taillight system. Of particular interest in this experimental design was (a) the susceptibility of the present taillight system to confusions between the running light and the brake light; and (b) the reaction time and response of drivers to signals of the present system as compared to signals of the new system under car-following conditions.

Two automobiles were used in this experiment. One of these cars was used as a lead car and was equipped with the experimental signal systems. The experimental signal system consisted of 2 circular taillights on each side of the car. When tests were being made with the conventional system, only the top lamp on either side of the car was employed. This lamp served both as a running lamp and as a brake light. Braking was signaled by an increased intensity of the lamp. As can be seen, this system is similar to that found on almost all American-made automobiles.

In other tests where the amber-red taillight system was being used, both lamps on either side of the car were employed. The lower lamp, which was equipped with an amber lens, served as a running light. The top lamp, with the red lens, remained off, except when the brake in the lead car was applied.

The testing procedure that was employed on this project utilized primarily the previously mentioned car-following and approach experiments.

In the car-following experiment the subject driver was instructed to follow the lead car at a distance of 200 ft. After the driver obtained a distance of 200 ft and followed the lead car for a time, the lead car began a ramp deceleration from 65 mph to 35 mph and then began a ramp acceleration back to 65 mph. The beginning of this maneuver (taillight actuation of the lead car) was recorded in the following vehicle. On preselected maneuvers different luminance ratios were used to signal the braking of the lead car. Each subject was presented with 5 replications of the maneuver under each of 8 luminance ratios with the conventional red-braking, red-running light system. In addition each subject was given 10 trials where the brake was signaled by the appearance of a red light in conjunction with an amber running light.

The results of this phase of the experiment are shown in Figure 5. As the luminance ratio (the ratio of brake light intensity to running light intensity) is increased up to the minimum ratio of 1:5, recommended by the Society of Automotive Engineers, performance improves. Increases beyond the 1:5 ratio did not yield significant improvements. The subject performance with the amber-red taillight was found to be about the same as the performance with the conventional system with a 1:5 ratio.

In the approach experimentation described earlier, the subject was randomly presented with 5 presentations of 8 different intensities of red lights, ranging from running lamp intensity to about 22 times running lamp intensity. After the subject was presented with these 40 trials, the experiment was repeated, but this time the subject was told that amber lights only would signal the running condition whereas an amber running light and red brake light would be the signal for a braking maneuver. From this part of the experiment the following measures were obtained:

1. The percentage of time that a taillight (which varied in intensity from 1:1 luminance to 1:22 luminance) was identified as a brake light or as a running light;
2. The response time for depression of the gas pedal when the signal light was identified as a running light;
3. The response time for release of the gas pedal when the signal light was identified as a brake light; and
4. The response time for the depression of the brake pedal when the signal light was identified as a brake light.

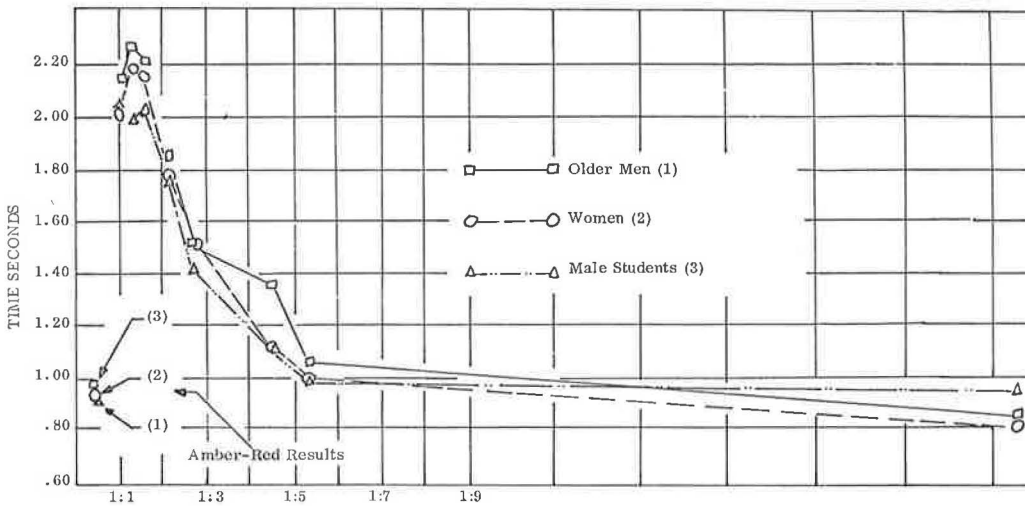

Figure 5. Running light to brake light intensity ratio.

The results of this study are given in Table 1. In general it was found that increases in the luminance ratio resulted in fewer confusion errors being made (i. e., brake lights being identified as running lights). The amber-red system noticeably improved performance with respect to decreasing the number of errors that were exhibited when an amber-red brake light was displayed. The response time measures failed to show any statistically significant differences across the various signal intensities.

EFFECT OF TAILLIGHT COLOR, LOCATION, PLACEMENT, AND SIZE ON DRIVING PERFORMANCE

The Systems Research Group's third research project, also sponsored by the Ohio Department of Highways and the Federal Highway Administration, was designed to expand the work done on past experiments to enable a more thorough evaluation of rear-end signal system characteristics in night driving. More specifically, the goals of this research were to (a) expand previous research work to include a thorough investigation of colors other than amber for running-light systems; (b) ascertain the effects of taillight location on driving performance; (c) determine the effects of taillight size on driving performance; (d) determine relationships among the 3 previously mentioned variables; (e) test for subject effects; and (f) ascertain the magnitude of the current automobile population with substandard taillight systems.

The testing procedure that was employed on this project consisted of all four of the experimental procedures described earlier. A total of 40 persons served as subjects in this experiment. These people came from 4 different groups, young men and young

TABLE 1

CONFUSION ERRORS—AMBER-RED VERSUS CONVENTIONAL SYSTEM

Category	Older Men	Male Students	Women
Percentage of running-light signals mistakenly called brake light			
Amber-red system	1.7	2.8	5.0
Conventional system (1:1)	3.2	12.7	7.0
Percentage of brake-light signals mistakenly called running light			
Amber-red system	0.0	0.9	2.0
Conventional system (1:5)	8.6	9.3	7.0

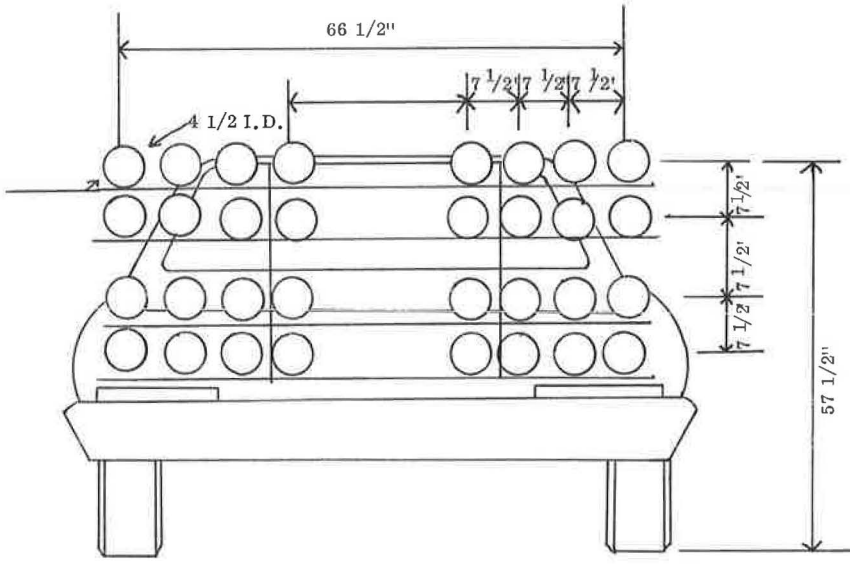

Figure 6. Experimental signal system.

women (under 25) and older men and older women (over 40). All road testing was done in instrumented vehicles (the same as those used previously) on Ohio freeways and secondary roads. The testing of the 40 subjects required 60 nights of successful experimentation and involved over 1,080 research man-hours (on the road) and over 16,000 research vehicle-miles.

	1	2	3	4
A	Red RB	Red RB	Amber	Green
B	Blue Green	Green	Red RB	Red RB
C	Red R	Amber	Amber	Green
D	Blue	Green	Blue Green	Red RB

Lamps on Left Side of Vehicle

Figure 7. Taillight configuration where R indicates that lights could be used as a running light and RB indicates that lights could be used as a running light or brake light.

Two automobiles were used in this experiment. The lead car was equipped with the experimental signal system (Figs. 6 and 7). The signal system consisted essentially of a 4-tiered rack on which the signal lamps could be placed. Lamps could be placed at any position on the rack from vertical and horizontal positions. Lamp lenses could be readily changed to allow different colored signals to be employed. Lamp sizes could be varied by the placement of sized filters over the colored lenses of the lamps. Lamp intensities could be controlled by the use of neutral density light filters in conjunction with the colored lenses.

When tests were being made with the conventional system, only 1 red lamp on either side of the vehicle was employed. This lamp served both as a running light and as a brake light. Braking was signaled by an increased intensity of the lamp. In other tests where the double-red system was being tested, 2 red lamps on both sides of the car were used. A single red lamp signaled the running condition of the vehicle, while braking was signaled by the addition of the second red light that was of higher intensity.

In experimentation with color-change taillight systems, 2 lamps on each side of the car were employed. A single lamp (of some color other than red) was used to signal the running condition of the vehicle while braking was signaled as in the double-red system by the addition of a red light that was of higher intensity than that of the running light.

CAR-FOLLOWING PERFORMANCE AS A FUNCTION OF TAILLIGHT COLOR, SIZE, LOCATION, AND PLACEMENT

The car-following experiment on the project was designed to determine the relation of signal change detection errors to different signal systems (i.e., conventional, double-red, and color change).

The subject driver was instructed to follow the lead car at a distance of 200 ft. After the driver obtained a distance of 200 ft and followed the lead car for a time, the lead car began a ramp deceleration from 65 mph to 35 mph and then began a ramp acceleration back to 65 mph. The beginning of this maneuver (taillight actuation of the lead car) was recorded in the following vehicle. On preselected maneuvers different signal systems were used to signal the braking of the lead car. Each subject was presented with 2 replications of the maneuver under each of 21 different signal systems. These 21 different signal systems are given in Table 2. The colors of the signal system conform where possible to specifications of the Commission Internationale de l'Eclairage.

In general, significant differences were noted with respect to gas pedal response time when the conventional systems were compared against color-change systems (Fig. 8). The other performance measures failed to distinguish differences among the systems.

CONFUSABILITY AS A FUNCTION OF TAILLIGHT COLOR, LOCATION, PLACEMENT, AND INTENSITY

In the approach experiments that were conducted on this project, the subjects were presented with 3 replications of each of the 21 different signal systems employed in phase 1 of the research. One of the replications consisted of presenting the signal in the running light mode. A second and third replication employed both the running light and the brake light with the brake light 2.5 and 5 times as intense as the running light respectively.

In general, it was found that the conventional system resulted in a larger number of errors when a running light or a low-intensity brake light was exhibited when compared to a color-change or a double-red system.

Gas pedal response times for the conventional system were also greater than for any other types of systems. The other response time performance measures failed to show any differences across the various signal systems tested.

EFFECT OF TAILLIGHT COLOR, SIZE, PLACEMENT, AND INTENSITY ON DISTANCE-ESTIMATION ABILITY OF SUBJECTS

This experiment was designed to determine the effects of taillight color, placement, size, and intensity on the ability of the subject to estimate distances. The experimental

TABLE 2

SIGNAL SYSTEMS TESTED IN PHASE 1

First Replication	Second Replication	System Type	First Replication	Second Replication	System Type
A1 red	A1 red	Conventional	D2 green	A1 red	Color change
B4 red	B4 red	Conventional	D1 blue	A1 red	Color change
B4 red	D4 red	Conventional	D2 green	A1 red	Color change
A1 red	A2 red	Double red	A4 green	A1 red	Color change
C1 red	A1 red	Double red	B2 green	A2 red	Color change
A1 red	B3 red	Double red	B2 green	B3 red	Color change
B3 red	B4 red	Double red	D3 blue-green	B3 red	Color change
A3 amber	A1 red	Color change	C3 amber	B3 red	Color change
A4 green	A2 red	Color change	A3 amber	A2 red	Color change
B2 green	B4 red	Color change	B2 green	B3 red	Color change
B1 blue-green	B3 red	Color change			

procedure required the subjects to sit in the front seat of the instrumented vehicle and to judge when the instrumented vehicle with the experimental signal system was adjacent to a vehicle that had red taillights in the normal (D1) position and was parked 400 ft from the instrumented vehicle.

In this experiment each of the 5 colors previously tested on the project (red, amber, green, blue, and blue-green) were tested in the A1, D1, and D4 positions of the taillight rack. In addition, small red lights in the D1 position were compared to larger red lights in the D1 position.

The data from this experiment indicated that colors have a highly significant effect on the subject's ability to estimate distances. Red was found to appear farthest away and blue or blue-green was found to appear closest. This is the ordering that would be expected due to the presence of the chrome stereopsis phenomenon mentioned previously.

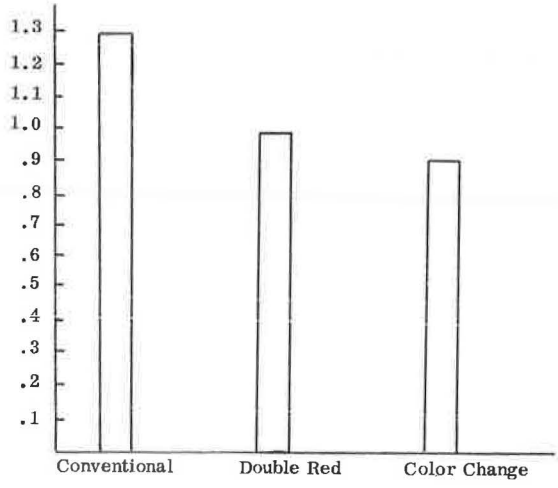

Figure 8. Gas pedal response time to lead-vehicle deceleration versus signal system. (Note: Graph combines data from 21 signal systems tested with 40 subjects and 80 replications per subject.)

Table 3 gives the order of the taillight colors on distance estimation. A Wilcoxon Matched Pairs signed rank test was used to test for this effect of color on distance estimation. When high-intensity red lights (braking intensity) in the high outside position were compared with low-intensity red lights in the same position, no significant differences were found.

When the low outside position was compared to the high outside position by using the previously mentioned test, lights in the high outside position were found to appear closer than lights in the low outside position. This effect was significant at the 0.001 level for both the opening and the closing headway conditions.

When small red lights were compared to large red lights in the D1 position, the small lights were found to appear farther away. This effect was found to be significant at the 0.05 level for the closing headway condition. No significant effects were found for the opening headway condition.

TABLE 3

HEADWAY ESTIMATION RESULTS

Ordering	Position A1		Position D1		Position D4	
	Opening Headway	Closing Headway	Opening Headway	Closing Headway	Opening Headway	Closing Headway
Appears farthest away						
1	Red	Red	Red	Red	Red	Red
2	Amber	Amber	Amber	Green	Amber	Red
3	Green	Green	Green	Amber	Green	Green
4	Blue-green	Blue-green	Blue	Blue-green	Blue	Blue
Appears closest						
5	Blue	Blue	Blue	Blue	Blue-green	Blue-green
Level of significance of ordering	0.001	0.01	0.001	0.001	0.001	0.001

EFFECTS OF TAILLIGHT COLOR, SIZE, AND PLACEMENT ON DRIVING BEHAVIOR OF SUBJECTS IN AN OVERTAKING SITUATION

This experiment was designed to determine the effects of taillight color, size, and placement on the driving behavior of subjects in an overtaking situation. The experimental procedure that was used required that the subjects drive the instrumented vehicle at a speed of 65 mph several thousand feet behind the lead vehicle that was also going 65 mph. The lead vehicle then slowed to 35 mph without giving a brake signal. The closing behavior in terms of headway changes between the 2 vehicles was measured with a 16-mm motion picture camera.

Examination of the data from this phase of the experiment indicated that taillight color, size, and placement had no effect on the subject's performance in the overtaking situation of this experiment.

FIELD STUDY OF AUTOMOBILE BRAKE LIGHT TO RUNNING LIGHT INTENSITY RATIOS

In addition to the 4 types of tests that were performed on this project and in view of the results found in previous research, it was decided to extensively sample the vehicle population of the state of Ohio to determine what percentage of the population of vehicles had substandard taillight systems (i.e., vehicles with less than 1:5 running-light-to-brake-light intensity ratio).

The data obtained from this portion of the research indicated that approximately 15 percent of the vehicles observed had inadequate taillight systems as shown in Figure 9. A large percentage of the cars with inadequate taillight systems had defective lights (i.e., broken or burnt-out lights).

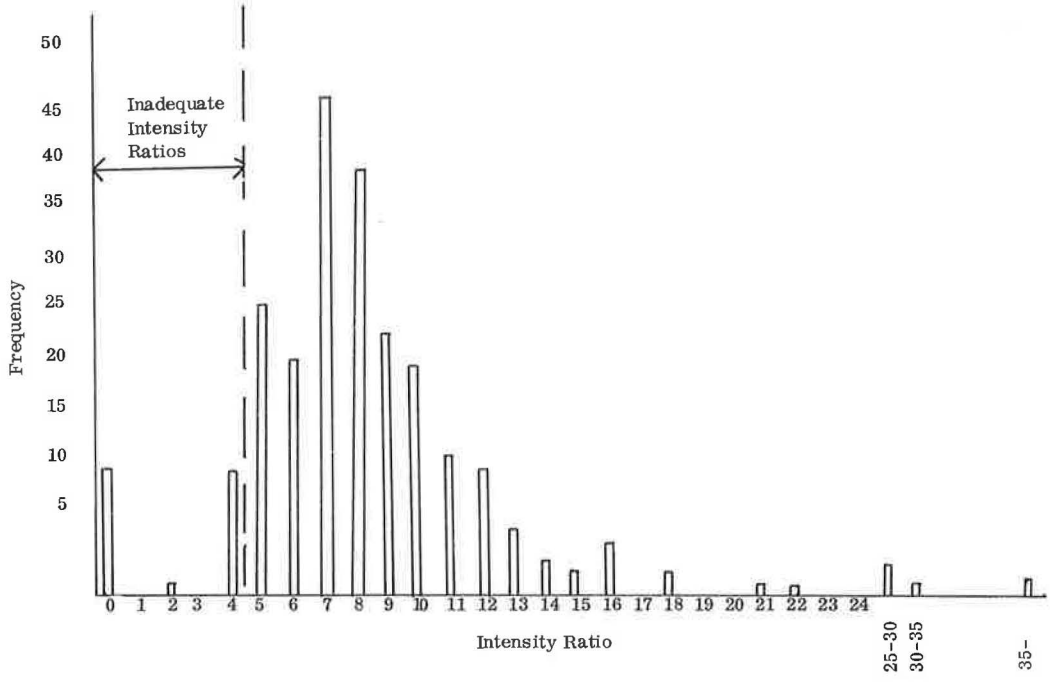

Figure 9. Intensity ratio versus frequency.

RECENT SYSTEMS RESEARCH GROUP STUDIES

In another experiment conducted by the Systems Research Group for the National Highway Safety Bureau, 4 taillight systems were tested. The systems included in addition to the conventional (C) system are as follows:

1. A Tri-light system (TL) similar to the one tested previously.
2. An acceleration Tri-light that presented a green light when the vehicle accelerated or when it decelerated very slightly, a yellow light when the vehicle decelerated mildly, and a red light for more extreme decelerations. Two acceleration systems were studied. They were sensitive (SAC) and moderate (AC) acceleration systems.
3. A headway-relative velocity (H-RV) command system that presented a green and a yellow light to the following-car driver if he followed at the correct distance (proportional to the following-car velocity), a green light if he was too far back, and a yellow light, a yellow light and a red light, or a red light as he became progressively closer.

These systems were tested in the 4 types of experimental tests described previously.

In analyzing the results of the experimentation on this project, performance measures obtained with the experimental systems were compared to the performance measures obtained with the conventional system. Two of the more sensitive performance measures are presented: gas pedal response time (GPRT) and headway variance. A ratio of these performance measures of the experimental systems to the performance measures of the conventional system was formed. These performance ratios permitted an easy determination of the effectiveness of the experimental systems. For these 2 performance measures, values less than one indicate an improvement over the conventional system. Figures 10, 11, 12, and 13 show the results.

One of the major results, shown in Figure 10, is that the Tri-light and acceleration systems produced larger headway variance than the conventional system under steady-state, car-following conditions only. These findings are in contrast to the smaller headway variance for the coasting and braking maneuvers while using the Tri-light and acceleration systems. This difference is explained in part by the steady-state, car-following condition using a large headway variance for one of the subjects. It is also possible that the apparent distance of the green light might affect the results.

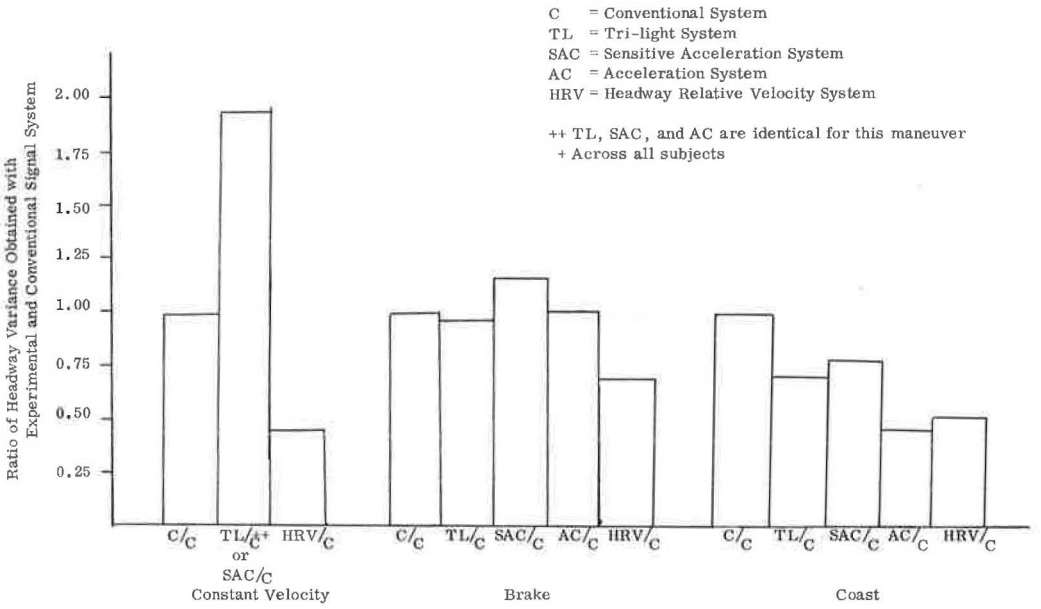

Figure 10. Ratio of headway obtained with experimental and conventional systems versus maneuver (night data).

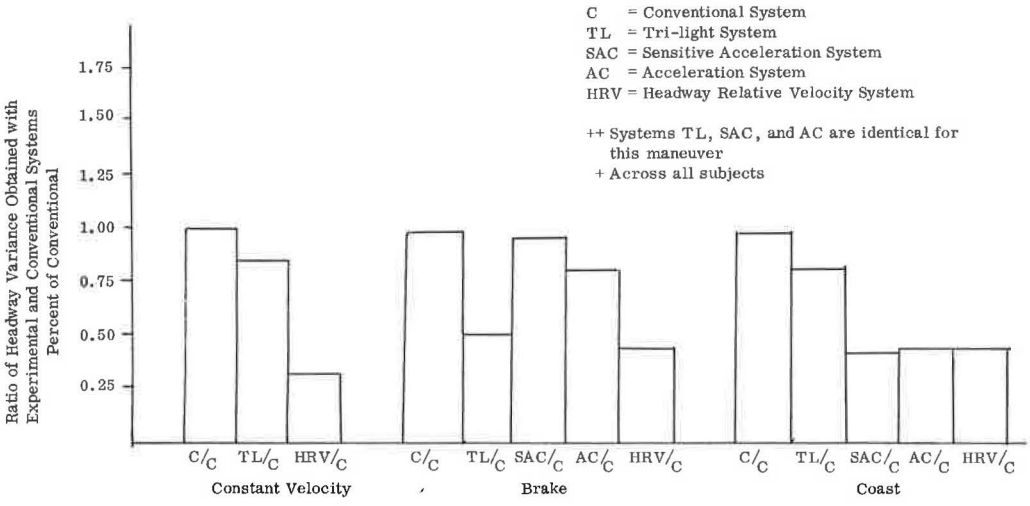

Figure 11. Ratio of headway obtained with experimental and conventional systems versus maneuver (day data).

The headway variance figures show that for both daytime and nighttime tests the H-RV system is the most effective system tested in terms of reduction of headway variance. The headway variance reduction ranges in value from a ratio of 0.69 of conventional system headway variance at night during the braking maneuver to a ratio of 0.325 of conventional system headway variance (H-Var) during the daytime for a constant velocity maneuver.

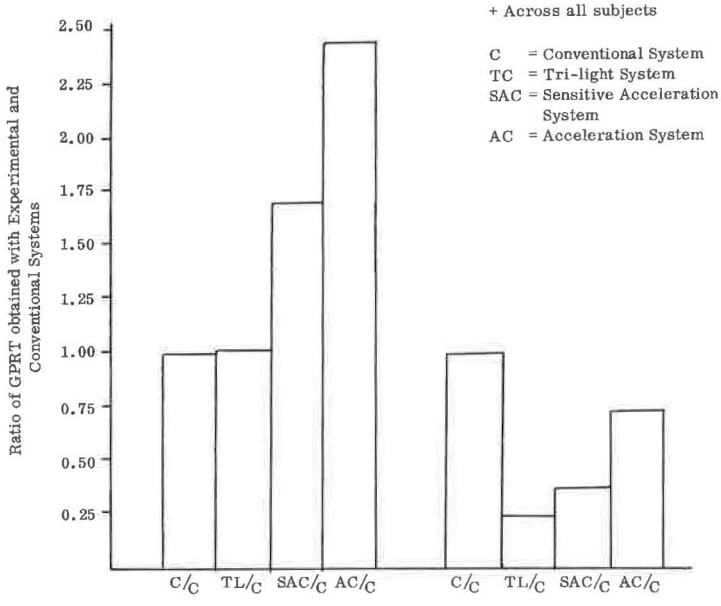

Figure 12. Ratio of gas pedal response time (GPRT) with experimental and conventional systems versus maneuver (night data).

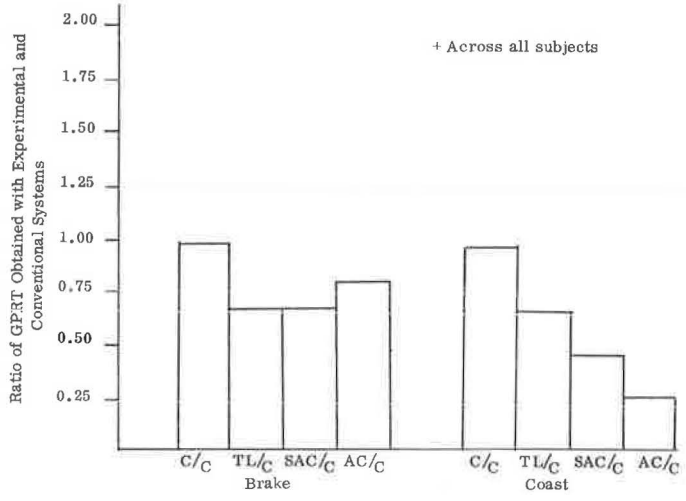

Figure 13. Ratio of gas pedal response time (GPRT) with experimental and conventional systems versus maneuver (day data).

Performance improvements were noted across all subjects. This suggests that technological efforts should be channeled into developing vehicle-based sensing systems that might be used to display the headway and relative velocity to the driver.

The other performance measure used as an aid in making a direct comparison of the systems was the gas pedal response time (GPRT). Figure 12 shows the comparison of the systems by maneuver for the GPRT. At night the conventional and Tri-light systems were almost identical with a ratio of 1.02 of conventional GPRT for the Tri-light. However, for a coast maneuver, the Tri-light system was superior to all others with a ratio of 0.21 of the conventional GPRT value. The mean GPRT for the Tri-light system on a coast maneuver was 0.75 sec as opposed to 3.5 sec for the conventional system.

These results are almost identical to those obtained by Rockwell and Safford in 1963, as shown in Figure 3. In this experimentation, systems were tested with different subjects by different researchers with different signal lamps and results still were nearly identical. During the daytime, as measured by GPRT, the Tri-light system is more effective than the conventional system. The braking maneuver resulted in a GPRT ratio of 0.68 of the conventional system's GPRT. The coast maneuver resulted in a GPRT ratio of 0.68 of the conventional system's GPRT.

CONFUSABILITY STUDY

The confusability study indicated the superiority of the tri-color system. It resulted in no errors made by following-car drivers in determining the mode of the lead car, indicating that the incorporation of colors other than red in a taillight system does not produce any detrimental results. This is in agreement with the studies previously mentioned in this paper.

TIME SERIES ANALYSIS

Use of time series analysis is a method of studying and comparing signal systems in the car-following mode by looking at the phase lag of the velocity profiles of the 2 vehicles, and specifically the cross correlation of the velocities of the 2 vehicles.

The data obtained in this experiment suggested that response lags of 1 to 1.5 sec for the conventional system were reduced to a third of this value by the use of the Tri-light. This is a natural result because the Tri-light system was designed to give the driver advance information and permit him to track the lead car more effectively.

In addition to testing the previously mentioned systems, the Systems Research Group also tested a "fusion light." The fusion light incorporated a lens with a distinctive pattern, portions of which would become visible at different distances. The use of a fusion light was found to result in reduced headway variance when compared with a conventional system with similar lamps but different lenses.

CONCLUSION

This paper has attempted to point out some of the philosophical and methodological problems associated with studying alternatives to the current automobile taillight. In addition, some of the visual problems associated with the presentation of colored lights to humans were mentioned.

The results of several research projects conducted by the Systems Research Group were presented. These results show that almost any change from the current conventional system results in an improvement. The results do not, however, point to an optimum system. It cannot be stated that the optimizing of a single aspect of a system holding all else constant will result in a better system. For example, the detectability of the current conventional system could be improved by increasing the intensity of the signal one hundred times. If this were done, further increases in intensity for purposes of signaling, braking, or turning would very likely suffer. This points out the fact that if an alternate to the current system is to be found, all aspects of system functions will have to be considered.

The extent to which the research results presented in this paper can be generalized to different driving situations cannot be stated absolutely. The fact that all of the research reported in this paper was conducted in "real" automobiles and on actual highways tends to make the results more readily acceptable than if they had been collected in the laboratory. It is also felt that the differences in the tested signal systems were to a certain extent marked by the fact that subjects in the experiment were alert to what was expected of them. Larger differences between systems might be expected if naive subjects (a wider spectrum of a driver's capability) were presented with the alternative systems.

The research that has been discussed here has shown that changes in the informational content and changes in the methods of presentation of the current taillight system results in improvements. Research efforts should be made to explore the aspects of automobile rear-signal systems not covered by this and other research material.

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