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AUTOMOBILE REAR LIGHTING SYSTEM MALFUNCTIONS: SURVEYS OF THEIR EXTENT AND DRIVING SIMULATOR STUDIES OF SOME OF THEIR EFFECTS

Rudolf G. Mortimer
Patricia A. Domas
Corwin D. Moore

Highway Safety Research Institute
University of Michigan
Ann Arbor, Mich. 48105

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320 New Center Building
Detroit, Mich. 48202

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16. Abstracts

Two types of surveys of passenger car and light truck rear lighting system malfunctions were made. The major objective of the surveys was to determine the relative frequency of malfunctions on vehicles with single and multiple compartment lamps. It was found that about 4% of vehicles with single compartment rear lamps had an inoperative presence or stop/turn lamp on one side of the vehicle. Less than 1% of vehicles with multiple compartment rear lamps had an inoperative presence lamp on one side, and about 2.5% had no stop/turn signal operating on one side. A survey of license plate lamp operation suggested that owners of vehicles with multiple compartment rear lamps maintain the lamps better, possibly leading to the above findings. Vehicle mileage was correlated with the total number of malfunctions scrutinized. The frequency with which turn signals were given by drivers at selected urban intersections showed that 23% failed to signal right turns and 12% failed to signal left turns.

The effects of major typical rear lighting system malfunctions on the ability of the driver to identify signals were then evaluated in two separate simulator studies to help determine the likely benefits of lamp redundancy vis-a-vis separation of lamps by function and other signal coding methods. Experiment I compared a conventional two-lamp, red system to two other systems with different degrees of functional separation and coding. In Experiment II three different systems involving various combinations of signal lamp redundancy and functional separation were evaluated. The malfunctions simulated were stop and turn lamp bulb failures and turn signals which do not flash.

In Experiment I, the conventional system's performance was significantly decreased by the malfunctions, especially by the stop lamp bulb failure on one side of the car. A second system, in which red stop lamps were separated from red turn/presence lamps, was impaired particularly in the stop signal mode when one stop lamp was inoperative, because such signals were often confused with turn signals or were missed. The remaining system, which used green-blue presence, yellow turn and red stop lamps, maintained drivers' performance in the malfunctioning conditions at a level not significantly different than when it was operating normally.

Redundant stop and/or turn signals in the systems tested in Experiment II helped reduce the number of signals that normally would be missed. However, one system with four red lamps for stop and two for turn signals led to more errors. A four-lamp, red system, the same as in Experiment I, produced similar results as before, with particular impairment in the stop signal when one stop lamp was inoperative. A six-lamp system with amber turn signals was also impaired in the stop signal with one lamp inoperative but not at a level significantly different than when operating normally. Errors and missed signals in these two systems were small. A fourth system with two inboard stop lamps and presence/stop/turn signals on the outboard lamps led to good overall performance with few errors and misses in all modes except the detection of turn signals with a previously initiated stop signal.

These findings support previous work, using normally operating systems, that has demonstrated improvements in system effectiveness by separating rear signal lamps by their function and color coding.

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OBJECTIVES

The objectives of the studies described in this report were:

1. To survey the frequency of various types of rear lighting system malfunctions on a sample of the population of automobiles and light trucks.

2. To discern differences in the types of malfunctions and their frequency between vehicles having rear lighting and signaling systems comprised of single lamps and those with multiple lamps or multiple compartment lamps, thereby showing the effect of redundant lamps.

3. To describe the effect on frequency and type of malfunction found in vehicles having some rear lamps separated by their signal function.

4. To evaluate the frequency of malfunctions in rear lighting systems as a function of vehicle accumulated mileage.

5. To evaluate the effects of some of the malfunctions upon the ability of drivers to identify the signals when given by various rear lighting and signaling systems in a dynamic car-following simulator.

6. To derive conclusions of the effectiveness of rear lighting systems having lamps which perform multiple functions, separate functions, and color coding of functions, and the effects of redundancy of lamps.

SUMMARY OF FINDINGS

Surveys of rear lighting system malfunctions showed a large variety of them to exist. Vehicles with multiple compartment or multiple rear lamps retained marking and signaling on each side of the vehicle more frequently (up to about 3%) than vehicles with one lamp on each side.

Simulator tests showed that inoperative lamps in both stop and turn modes, caused impairment in response times for all systems tested. Often, stop signals were confused with turn signals or missed completely. A failed bulb on one side of a car with single compartment rear lamps caused substantial deterioration in performance. Similarly, one bulb failure on a car with multi-compartment rear lamps led to increased response times, and in one such system also to an increased number of errors. The effect of the turn signal not flashing also caused an impairment in response times, but only to signals involving the turn mode.

Lamp redundancy was not effective in retaining system effectiveness, compared to separation of lamps by function, except in the turn signal if the flasher continues to operate with one bulb burnt out. The latter condition may require the use of variable load flashers to retain the turn signal function.

Six-lamp systems with different degrees of color coding were most effective in reducing reaction times, errors and missed signals. Systems using some type of functional separation without color coding, led to reduced reaction times and errors in some cases. The experimental data suggest that it is advantageous to separate the stop lamps from the presence-turn lamps and that systems employing color coding and functional separation are more effective than currently used conventional systems.

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SURVEYS OF VEHICLE REAR LIGHTING SYSTEM MALFUNCTIONS

INTRODUCTION

Motor vehicle lighting equipment malfunctions of some type are a common defect found at inspection lanes (e.g., McCutcheon and Sherman, 1968; Reinfurt and Pascarella, 1969; Hrebec, 1968). Malfunctions in marking and signaling systems are likely to restrict their ability to convey information to other motorists concerning the presence, orientation, braking action and intention to turn of the vehicles on which the lamps are mounted.

Several lighting systems, some differing from those currently used by color coding, functional separation and location of signals, and in other ways, have been evaluated in road tests (Mortimer, 1970) and simulator tests (Campbell and Mortimer, 1972). However, it is believed that the findings from such studies need to be extended in order to obtain information of their effectiveness when they are used with some commonly found marking or signaling lamp malfunction. In order to evaluate systems under conditions of degradation similar to those encountered on vehicles, information was needed on the specific marking and signaling system malfunctions that are extant.

Examination of data collected in inspection lanes showed that they are not reported in sufficient detail for the present purpose. Specifically, most vehicle lighting defects are grouped into general categories which do not distinguish between presence and signal lamps, or include grounding failures, flasher irregularities and switch malfunctions, etc. In addition, some disagreement exists as to what constitutes grounds for failure. For instance, on vehicles with a rear lighting array utilizing multiple lamps on each side performing identical functions, the failure of only one of those lamps is considered by some inspectors as acceptable, and by others as a cause for rejection.

Use of inspection station data also raises some issues concerned with sampling bias. Data collected at inspection lanes or in situations where drivers plan in advance to have the vehicle inspected, may not be typical of the performance of lighting components of vehicles in the population. Drivers would have an opportunity, and indeed the motivation, to have the problems corrected before-hand. In addition, the failure rates noted at random inspection lanes, such as used in Michigan, are also suspected of not being truly representative because older vehicles and those with collision damage or other obvious wear are more likely to be stopped for inspection.

Because of these deficiencies in the existing data on vehicle lighting malfunctions, additional surveys were conducted.

METHOD

Two surveys were made. The purpose of one was to obtain detailed information of rear lighting malfunctions on passenger cars and light trucks (cooperative survey) and the other (unobtrusive survey) was made to obtain gross data on a larger sample.

COOPERATIVE SURVEY

A total of 521 vehicles was closely examined to determine the functioning of all rear presence and signaling lamps. Since this work was done in the daytime, license plate lamp operation could not readily be checked. Also back-up lamps were not checked in either survey.

Other operational irregularities were recorded. If more than a merely light application of the service brake was necessary to cause the stop signal lamp to be illuminated, the stop signal switch was noted as being defective. A turn signal flash rate between 1.0 and 2.0 Hz, as averaged over a 10-second interval, and an on:off ratio of between about 1:2 and 3:1 were considered acceptable.

After all operational checks had been accomplished, the model year and mileage of each subject vehicle was recorded to the nearest one thousand miles.

The cooperative survey was conducted at Ann Arbor area gas stations, a drive-in window of a local bank, and in the HSRI employee parking lot. The active cooperation and participation of each vehicle's driver was necessary. Cooperation from the motorists contacted was excellent, with over 99% consenting to participate in the survey. As a service to participating motorists, any failures found were mentioned and appropriate corrective measures described.

UNOBTRUSIVE SURVEY

In the unobtrusive survey, vehicles were observed at various locations, during the day or at night, in order to make a count of the total number of vehicles and the number on which a rear lighting system malfunction could be readily noted.

The functioning of the rear presence lamps and the license plate lamps was noted during nighttime hours for vehicles moving away from an intersection or along a section of road where application of the service brakes was not expected to occur.

Vehicles were also observed during daylight hours as they approached intersections where a traffic control required them to stop. A moderate or high level of deceleration was presumed to have been accomplished by means of the service brake, and thus the stop signal lamps should have been lighted. Failure of any single or combination of lamps was noted.

Vehicles were observed in the daytime as they approached intersections where there was a high frequency of turning maneuvers, including T junctions, in which the use of turn signals would be expected.

A total of 10,809 vehicles was included in the unobtrusive survey. There was no contact with any of the drivers.

RESULTS

The findings from the two surveys will be treated separately.

COOPERATIVE SURVEY

PRESENCE LAMPS. Table 1 shows the results of the cooperative survey of rear presence lamp malfunctions. The table is divided according to the number of compartments on the vehicle (one on each side, or more than one on each side), and vehicles were classified according to the use of lamps having combined functions or separated by function, and by mileage in three categories.

Table 1 shows that 95.5% of vehicles with single compartment presence lamps were operating normally, compared with 89.4% of vehicles with multiple compartment rear presence lamps. However, all of the latter vehicles had at least one lamp working on each side to provide rear marking. Of the vehicles with single compartment rear presence lamps, 3.1% lacked marking on one side of the vehicle and 1.4% had lamps on both sides of the vehicle out entirely.

STOP AND TURN LAMPS. The results of the cooperative survey of malfunctioning stop and turn signals (Table 2) showed that the mean percent of such vehicles with combined signal functions was 96.1% and 91.3%, respectively, for single compartment and multiple compartment vehicles. Vehicles with separated signal functions all (100%) had normally operating turn signals, but a mean of 85.4% had normally operating stop signals. The table also shows that there were a mean of 2.2% of single compartment vehicles with combined signal functions in which one lamp was entirely malfunctioning, whereas there were no such cases in vehicles having multiple compartment lamps. Similarly, there were 4.4% of vehicles with separated signal functions having a stop signal lamp not operating on one side of the vehicle. There were no stop or turn signal lamps operating on 1.7% of single compartment vehicles having combined signal functions and a mean of 10.2% of stop signal lamps on vehicles with separated signal functions. None of the

TABLE 1. Percent of Vehicles with Various Rear Presence Lamp Malfunctions: Results of Cooperative Survey.

Malfunction	Vehicles with Single Compartment Presence Lamps												Vehicles with Multiple Compartment Presence Lamps			
	Vehicles with Combined Function Rear Signal Lamps				Vehicles with Separated Function Rear Signal Lamps				Average Across All Vehicles w/ Single Compartment Presence Lamps							
	Mileage (x 1000)				Mileage (x 1000)				Mileage (x 1000)				Mileage (x 1000)			
	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean
Both Sides Normal	95.9	94.9	97.1	95.9	100.0	90.2	100.0	94.2	97.0	93.5	97.5	95.5	97.0	89.9	77.6	89.4
One Side Partially Out, Other Side Normal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.0	9.3	20.4	9.8
Both Sides Partially Out Out	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.8	2.0	0.8
At Least One Lamp Working On Each Side	95.9	94.9	97.1	95.9	100.0	90.2	100.0	94.2	97.0	93.5	97.5	95.5	100.0	100.0	100.0	100.0
One Side Entirely Out, Other Side Normal	0	3.1	2.9	2.3	0	9.8	0	5.8	0	5.0	2.5	3.1	0	0	0	0
One Side Entirely Out, Other Side Partially Out	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0	0	0
Both Sides Entirely Out	4.1	2.0	0	1.8	0	0	0	0	3.0	1.5	0	1.4	0	0	0	0
Total Number of Vehicles	49	98	70	217	18	41	10	69	67	139	80	286	67	119	49	235

TABLE 2. Percent of Vehicles with Various Rear Signal Lamp Malfunctions: Results of Cooperative Survey.

Malfunction	Lamp Functions															
	Vehicles with Combined Signal Functions								Vehicles with Separated Signal Functions (All Single Compartment)							
	Single Compartment				Multiple Compartment				Turn Signals				Stop Signals			
	Mileage (x 1000)				Mileage (x 1000)				Mileage (x 1000)				Mileage (x 1000)			
	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean	0-20	20-60	+60	Mean
Condition of Bulbs[1]																
Both Sides Normal	96.1	95.4	97.4	96.1	100.0	93.6	72.7	91.3	100.0	100 0	100.0	100.0	77.8	87.5	90.0	85.4
One Side Partially Out, Other Side Normal	N/A	N/A	N/A	N/A	0	5.5	18.2	6.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Both Sides Partially Out	N/A	N/A	N/A	N/A	0	0	4.6	0.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
At Least One Lamp Working on Each Side	96.1	95.4	97.4	96.1	100.0	99.1	95.5	98.6	100.0	100.0	100.0	100.0	77.8	87.5	90.0	85.3
One Side Entirely Out, Other Side Normal	0	3.7	1.3	2.2	0	0	0	0	0	0	0	0	11.1	0	10.0	4.4
One Side Entirely Out, Other Side Partially Out	N/A	N/A	N/A	N/A	0	0.9	4.5	1.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Both Sides Entirely Out	3.9	0.9	1.3	1.7	0	0	0	0	0	0	0	0	11.1 (includes circuitry failure)	12.5	0	10.2
Condition of Other Circuitry																
Turn Signals on at Least One Side on Steady (not flashing)	2.0	0.9	0	0.9	0	4.6	2.3	2.7	0	2.5	0	1.5	N/A	N/A	N/A	N/A
Turn Signals on at Least One Side Flashing, but Improperly	0	2.8	4.0	2.6	0	4.6	9.1	4.1	0	2.5	10.0	2.9	N/A	N/A	N/A	N/A
Turn Signal Switch or Other Circuitry Failure	2.0	1.9	1.3	1.7	0	2.7	2.3	1.8	0	0	0	0	N/A	N/A	N/A	N/A
Stop Signal Switch or Other Circuitry Failure	0	0.9	5.3	2.1	0	3.6	0	1.8	N/A	N/A	N/A	N/A	11.1 (includes bulb failures)	12.5	0	11.5
Grounding Failure on at Least One Dual-Filament Bulb	0	2.8	1.3	1.7	0	0	0	0	0	0	0	0	0	0	0	0
Filament Reversal on at Least One Dual-Filament Bulb	0	0	2.7	0.9	0	0	2.3	0.5	0	0	0	0	0	0	0	0
Total																
Some Type of Rear Signal Lamp or Rear Presence Lamp Failure or Irregularity	7.8	13.1	17.3	13.3	3.1	26.4	47.7	23.7	22.2	27.5	30.0	26.5	same as for turn signals			
Total Number of Vehicles	51	107	75	233	65	110	44	219	18	40	10	68	same as for turn signals			

[1] "Condition of Bulbs" includes open filament, open wire to filament, or socket failure (except grounding failure on dual-filament bulbs) which cause bulb not to be illuminated when it should be.

vehicles with multiple compartment stop/turn signal lamps had both sides entirely out. Table 2 also shows contributing or additional types of malfunctions which were found on these vehicles, related to components other than bulbs.

UNOBTRUSIVE SURVEY

PRESENCE LAMPS. The results of the unobtrusive survey of rear presence lamp malfunctions is based on a total of 6,523 vehicles (Table 3), and shows that 96.35% of single compartment vehicles and 90.37% of multiple compartment vehicles had normally functioning rear presence lamps. It will also be seen that 99.01% of the multiple compartment vehicles had marking on each side of the vehicle, although 7.40% had one side partially out and an additional 1.24% had one malfunctioning compartment on each side. Further, 3.49% of the single compartment vehicles and 0.85% of the multiple compartment vehicles had one side entirely out, and 0.16% of single compartment vehicles and 0.14% of multiple compartment vehicles had no rear presence marking.

STOP LAMPS. The unobtrusive survey of stop signal malfunctions showed that 95.02% of single compartment and 90.05% of multiple compartment vehicles with combined signal functions were operating normally, and 96.15% of vehicles with separated signal functions were in normal condition (Table 4). The table also shows that 97.4% of the vehicles with multiple compartment stop lamps had at least one compartment working correctly on each side. There were 3.18% of vehicles with single compartments and 1.38% of vehicles with multiple compartments having combined signal functions, and 2.40% of vehicles with separated signal functions, which lacked a stop signal on one side of the vehicle. A complete lack of a stop signal was found in 1.80% and 1.22% of vehicles with combined functions, respectively, and 1.44% of vehicles having separated signal functions.

TURN SIGNALING FREQUENCY. The unobtrusive survey of rear turn signal operation obtained results that cannot be readily

TABLE 3. Percent of Vehicles with Various Rear Presence Lamp Malfunctions: Results of the Unobtrusive Survey.

Malfunction	Single Compartment Vehicles	Multiple Compartment Vehicles
Both Sides Normal	96.35	90.37
One Side Partially Out, Other Side Normal	N/A	7.40
Both Sides Partially Out	N/A	1.24
At Least One Lamp Working on Each Side	96.35	99.01
One Side Entirely Out, Other Side Normal	3.49	0.53
One Side Entirely Out, Other Side Partially Out	N/A	0.32
Both Sides Entirely Out	0.16	0.14
Total Number of Vehicles	3698	2825

TABLE 4. Percent of Vehicles with Various Stop Signal Malfunctions: Results of Unobtrusive Survey.

Malfunction	Vehicles with Combined Signal Functions		Vehicles with Separated Signal Functions
	Single Compartment	Multiple Compartment	Single Compartment
Condition of the Bulbs			
Both Sides Normal	95.02	90.05	96.15
One Side Partially Out, Other Side Normal	N/A	6.74	N/A
Both Sides Partially Out	N/A	0.61	N/A
At Least One Lamp Working on Each Side	95.02	97.40	96.15
One Side Entirely Out, Other Side Normal	3.18	0.61	2.40
One Side Entirely Out Other Side Partially Out	N/A	0.77	N/A
Both Sides Entirely Out (includes circuitry failure)	1.80	1.22	1.44
Condition of Circuitry			
Stop Signal Switch or Other Circuitry Failure (includes complete bulb failure)	1.80	1.22	1.44
Grounding Failure on at Least One Dual-Filament Bulb	0.22	0	0.48
Total Number	1385	653	208

translated into lamp malfunctions because of the confounding with actual use of the turn signal on the part of the driver. Turn signal operation was observed at nine intersections and a count was made of the total number of vehicles making left or right turns and the number of those vehicles for which it could be inferred that a turn signal had been given by the driver. The latter could be inferred because: the signal could be observed, the lamp on one side was lighted but not flashing when both stop lamps had been previously observed, or after the stop signal had been observed the lamp on one side went out. These observations were made only for vehicles in which stop and turn lamps were combined, since equivalent measures could not be reliably taken for vehicles having lamps separated by function. Table 5 shows the percent of vehicles observed for which it was inferred that a turn signal was given, at each of eight intersections, at five of which a separate turn lane was provided. It will be noted that the percent of drivers who signaled was a function of the intersection involved, with 1.8%-36.1% of drivers not signaling at these sites. Overall, based upon 2,090 observations of turning vehicles, 396 did not signal, representing 18.9% of the vehicles. Not shown in the table is the additional finding that 12.3% of left-turning vehicles did not signal while 22.7% of right-turning vehicles did not signal.

LICENSE PLATE LAMPS. As a part of the survey of presence lamp failures, a count was also made of the number of single and multiple compartment rear presence lamp vehicles whose license plate lamps were not working. This was done in an attempt to obtain some additional insights into the possibility that differences arising from the frequency of malfunctions between single compartment and multiple compartment rear presence/signal lamp vehicles may be due in part to the differences in maintenance practices of the owners of these types of vehicles. The license plate survey showed (Table 6) that 17.7% of vehicles with single compartment rear presence lamps, compared with 7.4% of vehicles with multiple compartment rear presence lamps, had malfunctioning license plate lamps.

TABLE 5. Turn Signal Use by Drivers at Some Urban Intersections.

Site No.	Separate Turn Lane	No. Not Signaled	Number Observed	% Not Signaled
1	No	10	61	16.4
2	Yes	80	351	22.8
3	No	13	239	5.4
4	Yes	108	408	26.5
5	Yes	56	155	36.1
6	Yes	1	56	1.8
7	No	13	199	6.5
8	Yes	115	621	18.5
Total		396	2090	18.9

TABLE 6. Frequency of Vehicles with License Plate Lamp Failures: Results of Unobtrusive Survey .

Description	Vehicles with single compartment rear presence lamps	Vehicles with multiple compartment rear presence lamps	Total
Total Number of Vehicles Observed in Subset	2044	1628	3672
Percent with Failure	17.66%	7.37%	13.10%

DISCUSSION

The two surveys that were carried out in this study obtained similar results in terms of the percent of rear lighting system malfunctions observed. For example, for vehicles with single compartment presence lamps the cooperative survey showed that 95.5% were operating normally, which compares favorably with the findings of the unobtrusive survey that 96.35% were normal. Similarly, 89.4% of vehicles with multiple compartment rear presence lamps (Table 1) were found to be normal in the cooperative survey, which compares favorably with the 90.37% found normal in the unobtrusive survey. The cooperative survey of stop and turn signals (Table 2) found that 96.1% of vehicles with single compartment rear signal lamps were normal, as compared with 95.02% found in the unobtrusive survey (Table 4). The analogous values for vehicles with multiple compartment lamps were 91.3% in the cooperative survey and 90.05% in the unobtrusive survey of stop signal malfunctions. The only aspect of the two studies where a difference was found, concerns the frequency of normally operating stop signal lamps in vehicles with separated stop and turn lamps in the cooperative survey (mean 85.4%) and in the unobtrusive survey (96.15%). It should be noted that the data for vehicles with separated signal functions are generally the least reliable, because they are based on the fewest number of observed vehicles in both surveys.

The major findings of the survey studies are the values obtained concerning the percent of vehicles in which presence and signal lamp operation malfunctions can be expected to occur in a sample of vehicles surveyed on the highway. About 4% of vehicles with single compartment lamps can be expected to have an inoperative presence or signal lamp on one side of the vehicle, with less than 1% having inoperative presence lamps and about 2% inoperative stop/turn lamps on both sides of the vehicle.

By comparison, less than 1% of vehicles equipped with multiple compartment rear presence lamps had marking on only one side and about 2.5% had stop/turn signals operative on only one side. Less than 1% were entirely without presence marking and about 1% of vehicles with multiple compartment rear signal lamps had inoperative stop/turn lamps on both sides of the vehicle.

As already mentioned the findings concerning vehicles with separated signal functions are based on a relatively small sample in both surveys. But the cooperative survey found that 10.2% of such vehicles had inoperative stop signal lamps. This conclusion was not supported by the finding of the unobtrusive survey in which only 1.44% of this type of failure was found on these vehicles. It is considered important to determine which of these survey results is more representative of vehicles in the population. It may be supposed that, if the stop signal malfunction rate is high on vehicles with separated signal functions, consideration should be given to a malfunction indicator for the stop lamps.

Overall, the results indicate that vehicles with single compartment presence and signal lamps tend to be in "normal" operating condition more frequently than vehicles with multiple compartment lamps. However, the results also show that vehicles with multiple compartment rear lamps have at least one operating compartment on each side of the vehicle, more frequently than vehicles with single compartment lamps, thereby providing a potential overall benefit in retaining presence and signal lamp effectiveness.

The possible conclusion that owners of vehicles with multiple compartment rear lamps maintain the lighting system in somewhat better condition than owners of single compartment rear lamps, is reinforced by the survey of license plate lamps, which showed that there were almost twice as many license plate lamp failures on vehicles with single compartment rear lamps than those with multiple compartment rear lamps. This aspect of vehicle maintenance influencing the findings of this study, may be, in part, a reflection of the fact that vehicles with multiple compartment rear presence lamps are normally those in the middle-upper price brackets.

The findings of the cooperative survey of signal lamp malfunctions (Table 2) provides indications of problems associated with the bulbs and with circuitry, turn signal flashers, and stop lamp switches. This information may be of assistance in pinpointing certain types of rear signaling system failures.

There was no clear effect of accumulated mileage upon the frequency of specific malfunctions. However, when the number of bulbs and other component malfunctions that were found in the cooperative survey of stop/turn lamps were summed, it was found (Table 2) that they increased with increasing mileage. Also, the vehicles with more compartments or lamps had more total malfunctions, which is not surprising because those vehicles have more components in the rear lighting system. Thus, vehicle age seems to have a relation with total number of system malfunctions.

The use drivers made of turn signals was greatly affected by characteristics of the intersections where observations were made. Drivers apparently perceive the need to signal left turns more than right. The findings are similar to those of Zoltan (1963), although the overall signaling rate was 60% in his observations made in Columbus, Ohio compared to 81% found in Ann Arbor. That drivers neglect to use turn signals on urban streets and on expressways (Zuercher, et al., 1968) can be readily observed.

The implications of the results of these studies for design of vehicle rear lighting systems may also be important. Systems that employ separate functions for signal lamps require more lamps than those in which functions are combined. It would be important to consider the effects upon signal system performance of malfunctions, typical of those found in these surveys, upon the ability of following drivers to identify and respond to signals given by systems that incorporate signal lamp redundancy, such as found in multiple compartment, combined signal function systems compared with those not having this form of redundancy, such as is the case where signals are separated according to function or where single compartment lamps are used in which functions are combined. The studies to be described in the next sections of this report are concerned with evaluations of the effects of common signal malfunctions upon various rear lighting and signaling systems.

It is believed that the results of the survey may be useful in providing information of rear lighting system malfunctions described in terms that are more specific than those usually reported by agencies concerned with motor vehicle inspection. The extent of certain failures, such as those concerned with the turn or stop signal switch, are documented in this report. Such information may be useful to vehicle and component manufacturers, to agencies concerned with enforcement or inspection, the service-related trades and vehicle owners. Each of these segments of the population can be involved in reducing the frequency of lighting system malfunctions.

SIMULATOR EVALUATIONS

INTRODUCTION

The surveys showed that about 4% of vehicles with single compartment rear lamps had an inoperative stop/turn lamp, up to 9% of automobiles with multiple compartments had a rear signal lamp compartment failure, and up to 26.5% of automobiles (with separated functions) had some form of malfunction or irregularity in the operation of their rear signal lamps. The effects of such malfunctions could influence rear-end collisions if it is demonstrated that such malfunctions impair the performance of drivers. The present experiments investigated the effects of rear lighting system malfunctions on the ability of drivers to identify signals.

Some of the lighting configurations used here have been extensively evaluated in previous simulator (Campbell and Mortimer, 1972) and night driving tests (Mortimer, 1969; 1970), for various intensities of signal lamps and signal-presence lamp intensity ratios. (For the sake of uniformity the same system numbers are used in this report as used previously [Mortimer, 1969]). In those previous studies the effects of common system malfunctions were not determined. However, malfunctions are certainly an important consideration affecting the ability of a rear lighting system to convey information to a following driver in a consistent manner.

Six different rear lighting configurations, operating normally and with malfunctions, were evaluated in two separate experiments. The first experiment compared the conventional two-lamp, red system (System 1) to two other systems with different degrees of functional separation and color-coding (Systems 3 and 8). Experiment II tested three different systems involving various combinations of signal lamp redundancy and functional separation. All systems will be fully described later.

Many signal lamp malfunctions were found to be common in the surveys (Tables 2, 4) and those simulated in the present experiments constitute a representative subset. Probably the most common malfunction in lighting systems is due to an open filament in a bulb resulting in loss of a signal in that lamp compartment. For example, if one stop lamp filament is open on a vehicle with two single compartment lamps on the rear, only the functioning lamp on the other side will be lighted when the brake pedal is depressed. Such an indication could be confused with a turn signal, particularly if the driver should be applying the brakes intermittently.

If a front turn signal filament is open, the rear turn signal filament on the same side will probably remain on without flashing when a turn signal is given, since most cars are equipped with constant-load flashers. None of the turn lamps will flash if the flasher contacts remain in the closed position, but they will emit a steady light. If the flasher contacts remain in the open position, there will be no turn lamps lighted.

These are some of the more common malfunctions, although many others occur, and the same symptoms described above can be caused in a variety of other ways. Dependent on the operational design of the rear lighting system, such malfunctions can cause signals to lose their alerting qualities. The reactions of drivers to such signals and their interpretations were studied in these experiments.

EXPERIMENT I

REAR LIGHTING CONFIGURATIONS

Three rear lighting configurations, as shown in Figure 1, were evaluated. System 1, the two-lamp system, represents that which is current practice on U.S. automobiles and used two red lamps, each of which provide presence (tail), stop, and turn signals. System 3 is a four-lamp system, in which the red presence and turn lamp signals are given by lamps separate from those displaying the stop signal. System 8, the six-lamp, 3-color system, uses a different color for each signal with complete functional separation.

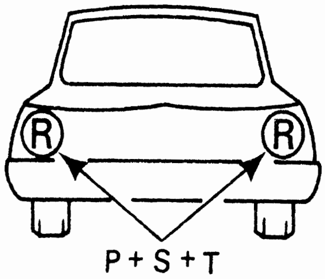
METHOD

SUBJECTS. Twenty-three (23) men and women served as paid subjects. The sample was drawn from HSRI employees and University of Michigan students who held valid operator's licenses and had normal color vision.

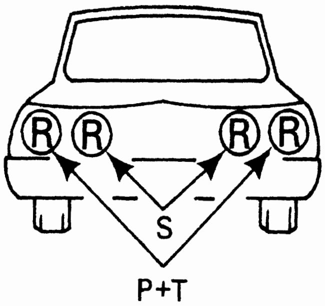
PROCEDURE. The simulator has been fully described previously (Campbell and Mortimer, 1972). All features of the simulator were not used in this study. Control of the rear lighting signals originated from the experimenter's console, with each system being viewed by the subject for about five minutes, in each normal and malfunctioning mode.

In the malfunctioning mode the signals of the rear lighting systems were altered to represent what would be seen on a real car if it had defects such as a burned out stop lamp bulb, a turn flasher in which the contacts remain closed or a front turn bulb filament is open so that the rear lamp does not flash. The combination of the three normal configurations and the two malfunctions that were simulated, generated the nine systems used in the experiment. Table 7 contains a description of each system and its corresponding malfunctions. In each system, edges of adjacent lamps were separated by 4.5 inches (simulated), and presence lamps

SYSTEM 1
TWO-LAMP, RED



SYSTEM 3
FOUR-LAMP, RED



SYSTEM 8
SIX-LAMP, 3 COLOR

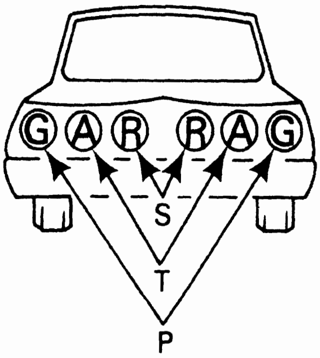


Figure 1. The rear lighting and signaling displays of Systems 1, 3 and 8.

were operated at an equivalent intensity of 7 cd and stop and turn lamps at 91 cd. The ambient light level was set to simulate dusk, the roadway illumination being 10 foot-candles, which was low enough to make the presence lights clearly visible.

The lead car was positioned 180 feet (simulated) ahead of the subject's car, and both vehicles remained stationary throughout the experiment. This made the use of the accelerator and brake pedals unnecessary.

The subjects used two, hand-operated switches to respond to turn signals, and a foot-operated switch to respond to stop signals. They were asked to respond to all signals as quickly as possible after identification, to correct any mistakes by pressing the proper switch afterwards, and to guess whenever they were unsure of the identity of a signal.

Subjects responded to eleven signals within each system: stop (S), left and right turn (T), left and right turn followed by stop (T→S), and stop followed by left and right turn (S→T). For example, a subject's reaction time to a stop signal which was followed by a turn signal was recorded under signal mode, $\underline{S}\rightarrow T$. His response to the turn in the same combination would be recorded under signal mode, $S\rightarrow\underline{T}$. The order in which the lighting systems were presented was counterbalanced across subjects, while the ordering of signals presented within each system was randomized.

Each subject was given one practice trial using the conventional, two-lamp, red system. The experimental trials began with one of the three lighting systems operating normally. On the following blocks of trials, one type of malfunction for that configuration was presented at a time until the system had been used to present signals in all the malfunction modes. This procedure was repeated for the other systems until all had been displayed to the subject in normally operating condition and in the malfunctioning conditions.

RESULTS

The data collected included reaction times to a specific signal or combination, signal identification errors, and signals missed. Separate analyses were performed on each of these dependent variables.

REACTION TIME ANALYSIS. The geometric mean reaction times, in seconds, to signals in each of the nine systems are shown in Table 7. When a subject failed to respond to a signal within ten seconds, it was recorded as missed, and ten seconds was used as the reaction time in the analysis. In Table 7, for example, an entry of ten seconds indicates that all subjects failed to respond to the specified signal.

Analysis of variance of the reaction time data showed that there were significant effects due to signal modes, systems, and the modes x systems interaction. Newman-Keuls tests on systems in each signal mode showed significant differences between various combinations of systems within each signal mode.

Comparisons Within Systems. Figure 2 shows that, for the two-lamp system, mean reaction times are increased in the malfunctioning conditions. Table 8 shows the results of Newman-Keuls tests on signal modes in System 1. With one stop lamp bulb burned out (System 1.1) there were significant increases in mean reaction times to all the signals compared to the system operating normally, and for the same system with the turn flasher staying in the on position except in mode S→T. The turn flasher remaining in the on position (System 1.2) resulted in significantly longer mean reaction times than for the normal system only in signal modes involving the turn signal.

Figure 3 shows the mean reaction times in the signal modes for System 3. Table 9 shows that, in the stop mode, a stop lamp filament failure (System 3.1) resulted in significantly longer mean reaction times to stop signals than for the other conditions, and increased the response time to the turn signal in the T→S

TABLE 7. Geometric Mean Reaction Times to Signal Modes Presented by Three Rear Lighting Systems, Operating Normally or Under the Specified Malfunctions.

Description		Signal Mode					
System	Malfunction	S	T	T→S	T→S	S→T	S→T
1. Two-Lamp, Red							
1.0	Normal	0.729	0.775	0.742	1.23	0.844	1.67
1.1	Left Stop/Turn filament burned out	2.69	3.84	3.72	5.23	2.14	4.56
1.2	Flasher remains in ON position	0.885	2.13	1.69	1.24	0.908	10.0*
3. Four-Lamp, Red							
3.0	Normal	0.764	0.686	0.686	0.674	0.752	0.703
3.1	Left Stop filament burned out	1.78	0.886	0.958	0.956	1.31	0.912
3.2	Flasher remains in ON position	0.847	0.752	0.816	0.672	0.929	0.713
8. Six-Lamp, 3-Color							
8.0	Normal	0.766	0.595	0.654	0.627	0.781	0.606
8.1	Left Stop filament burned out	1.12	0.624	0.668	0.691	0.961	0.635
8.2	Flasher remains in ON position	0.853	0.589	0.613	0.534	0.834	0.571

*Reaction time to missed signals recorded as 10.0 sec.

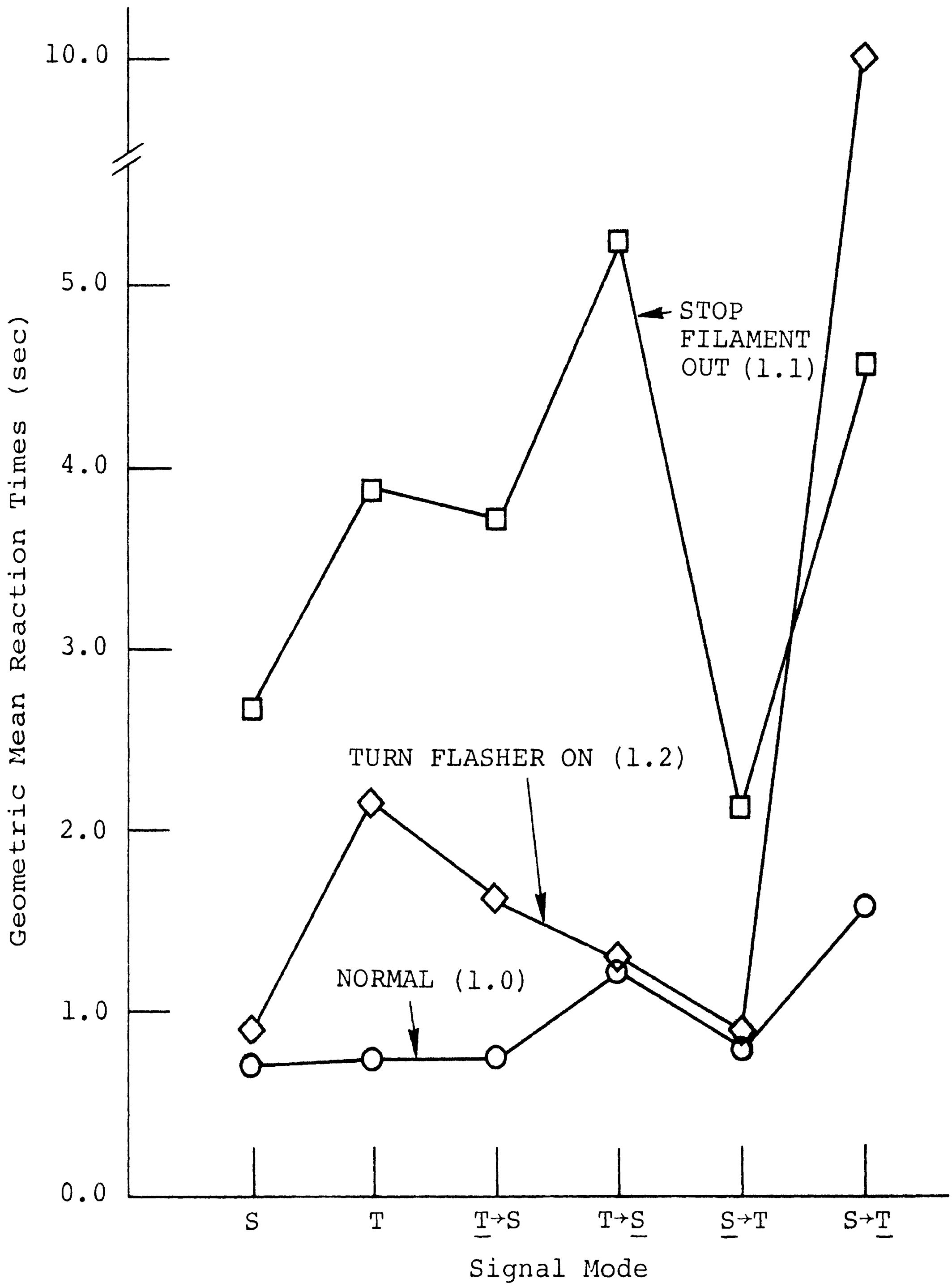


Figure 2. Two-lamp, red system. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

Note: Lines connecting points are intended only to facilitate identification of performance within a system. Slopes of the lines are not meaningful in the usual sense of suggesting a continuous function.

TABLE 8. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 1 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	1.0, 1.2	"	1.1
Turn	1.0	"	1.1, 1.2
	1.2	"	1.1
$\underline{T}\rightarrow S$	1.0	"	1.1, 1.2
	1.2	"	1.1
$T\rightarrow \underline{S}$	1.0, 1.2	"	1.1
$\underline{S}\rightarrow T$	1.0, 1.2	"	1.1
$S\rightarrow \underline{T}$	1.0	"	1.1, 1.2
	1.1	"	1.2

TABLE 9. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 3 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	3.0, 3.2	"	3.1
Turn	None	"	–
$\underline{T}\rightarrow S$	3.0	"	3.1
$T\rightarrow \underline{S}$	3.0, 3.2	"	3.1
$\underline{S}\rightarrow T$	3.0, 3.2	"	3.1
$S\rightarrow \underline{T}$	None	"	–

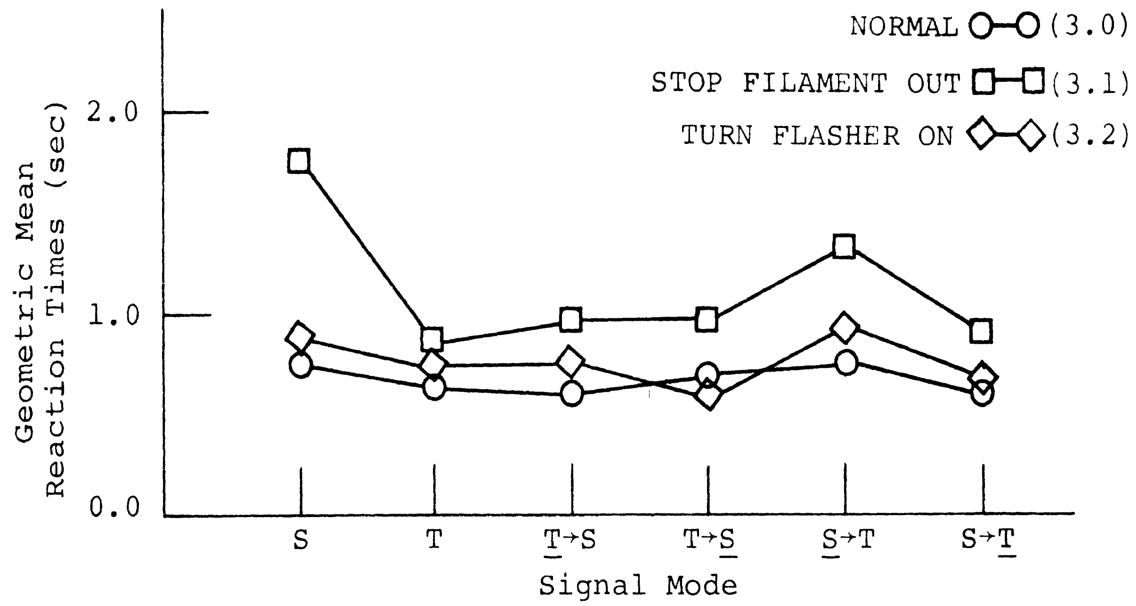


Figure 3. Four-lamp, red system. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

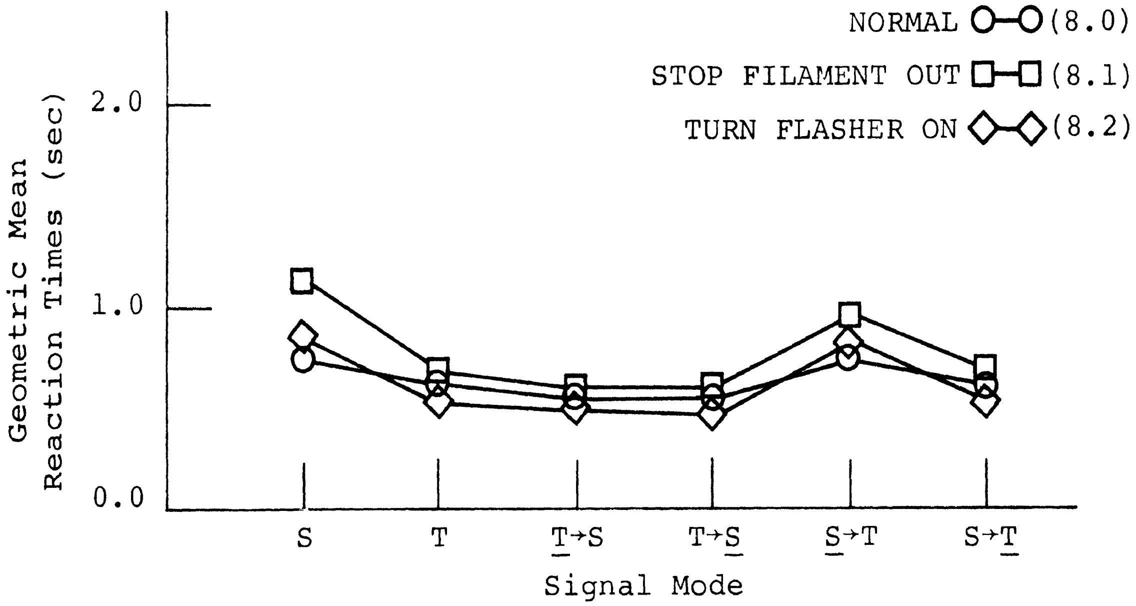


Figure 4. Six-lamp, three color system. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

mode compared to the normal condition. There were no significant increases in mean reaction times due to the turn flasher staying in the on position (System 3.2).

Figure 4 shows the analogous results for System 8. In the stop and S→T modes the stop lamp malfunction (System 8.1) increased the mean reaction times compared to the system operating normally (Table 10). In the stop and T→S modes the mean response times to the system with the turn flasher malfunction (System 8.2) were significantly less than with the stop lamp malfunction. There were no other significant effects on mean response times.

Comparisons Between Systems. Figure 5 shows the mean reaction times of each system in normal condition, in each signal mode. Table 11 shows that mean reaction times in T→S and S→T modes for systems 8.0 and 3.0 were significantly lower than System 1.0, and mean response times to the turn signal were lower with system 8 than 1.

Figure 6 shows the effects of one stop lamp filament open, in which the mean reaction times to all signals of System 1.1 were significantly longer than the other systems (Table 12) and System 3.1 was less effective than System 8.1 in the stop mode.

The effect on systems of the flasher contacts remaining in the on position is shown in Figure 7. Systems 8.2 and 3.2 did not differ significantly (Table 13), but were more effective than System 1.2 in the turn, T→S, T→S, and S→T modes.

ERROR ANALYSIS. The number of errors in identifying signals are shown in Table 14 as a percent of the signals presented in each mode, whether singly or in combination, for each system. For example, Table 14 shows that in System 1.0 the turn signal was incorrectly identified as a stop signal on 4.3% of presentations as the only signal, whereas in System 1.2 the same error was made to 54.3% of turn signals. The marginal row totals of Table 14 are shown in Table 15, which indicates the percent of errors

TABLE 10. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 8 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	8.0, 8.2	"	8.1
Turn	None	"	—
$T \to S$	None	"	—
$T \to \underline{S}$	8.2	"	8.1
$\underline{S} \to T$	8.0	"	8.1
$S \to \underline{T}$	None	"	—

TABLE 11. Significant Differences Between Systems (1.0, 3.0, 8.0) in Normal Operation.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	None	"	—
Turn	8.0	"	1.0
$\underline{T} \to S$	None	"	—
$T \to \underline{S}$	3.0, 8.0	"	1.0
$\underline{S} \to T$	None	"	—
$S \to \underline{T}$	3.0, 8.0	"	1.0

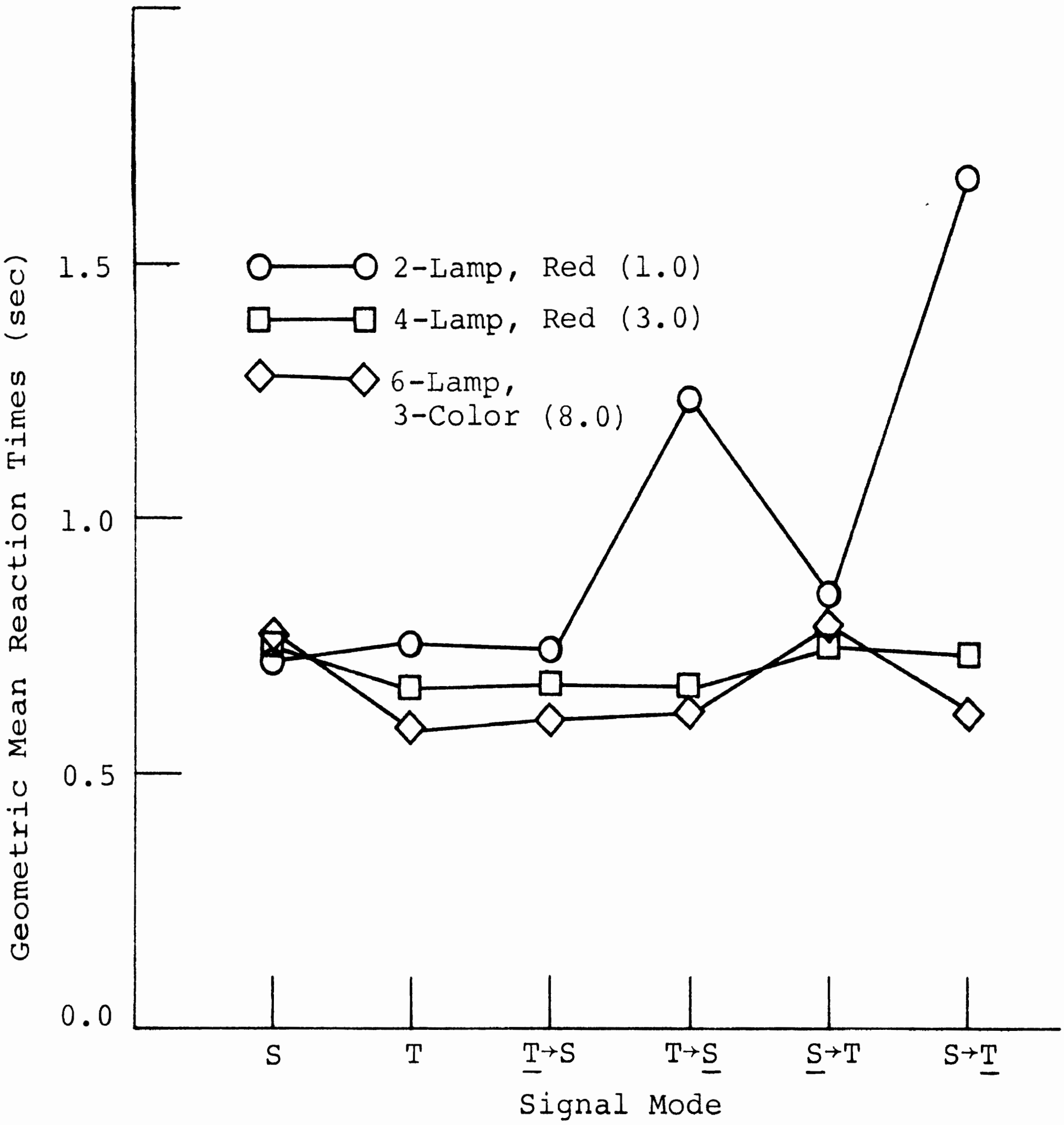


Figure 5. Comparison of three rear lighting systems in normal operating condition

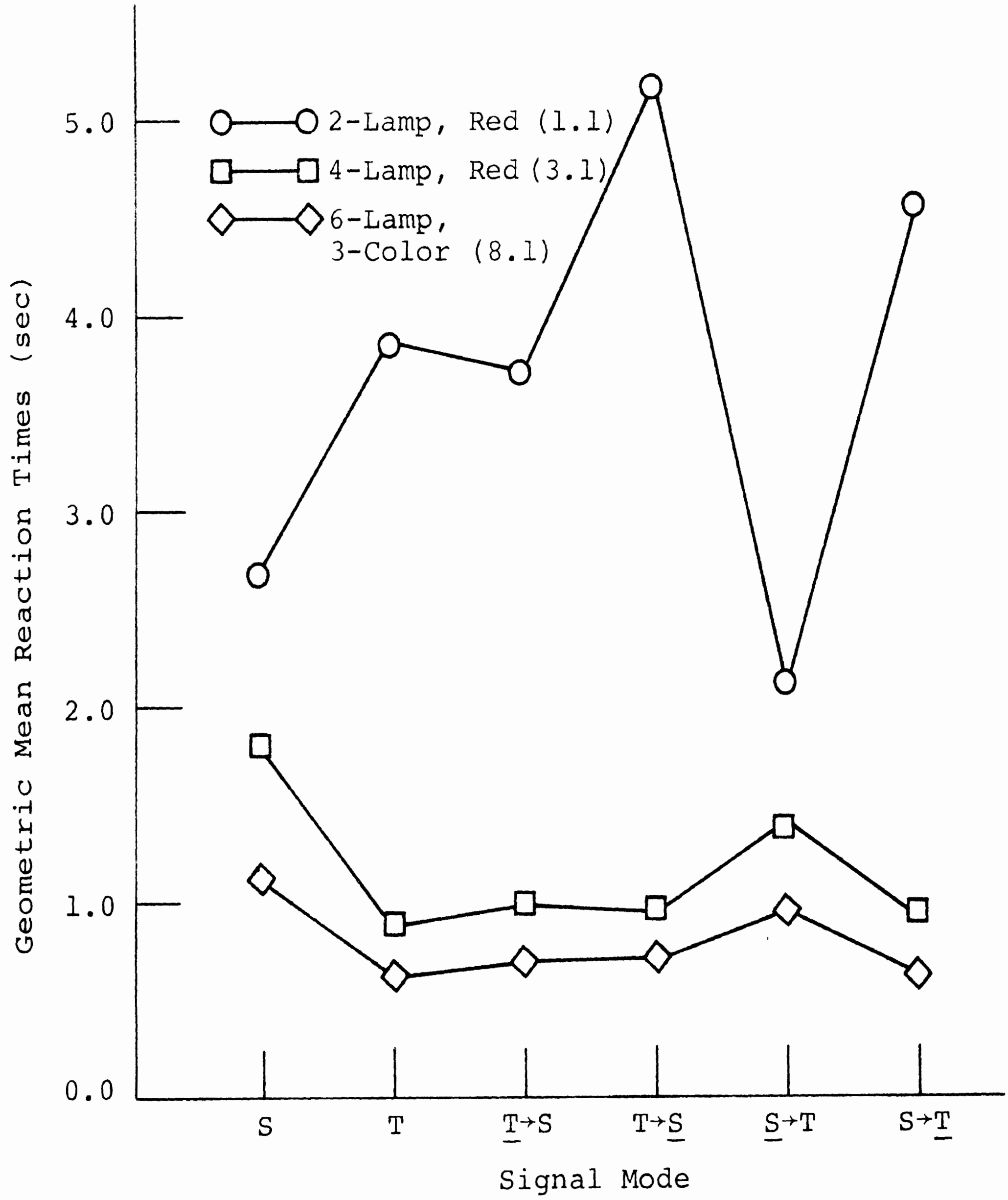


Figure 6. Comparison of three rear lighting systems with left stop lamp malfunction.

TABLE 12. Significant Differences Between Systems (1.1, 3.1, 8.1) With One Stop Lamp Malfunctioning.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	3.1, 8.1 8.1	"	1.1 3.1
Turn	3.1, 8.1	"	1.1
$\underline{T} \rightarrow S$	3.1, 8.1	"	1.1
$T \rightarrow \underline{S}$	3.1, 8.1	"	1.1
$\underline{S} \rightarrow T$	3.1, 8.1	"	1.1
$S \rightarrow \underline{T}$	3.1, 8.1	"	1.1

TABLE 13. Significant Differences Between Systems (1.2, 3.2, 8.2) With the Turn Signal not Flashing.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
Stop	None	"	—
Turn	3.2, 8.2	"	1.2
$\underline{T} \rightarrow S$	3.2, 8.2	"	1.2
$T \rightarrow \underline{S}$	3.2, 8.2	"	1.2
$\underline{S} \rightarrow T$	None	"	—
$S \rightarrow \underline{T}$	3.2, 8.2	"	1.2

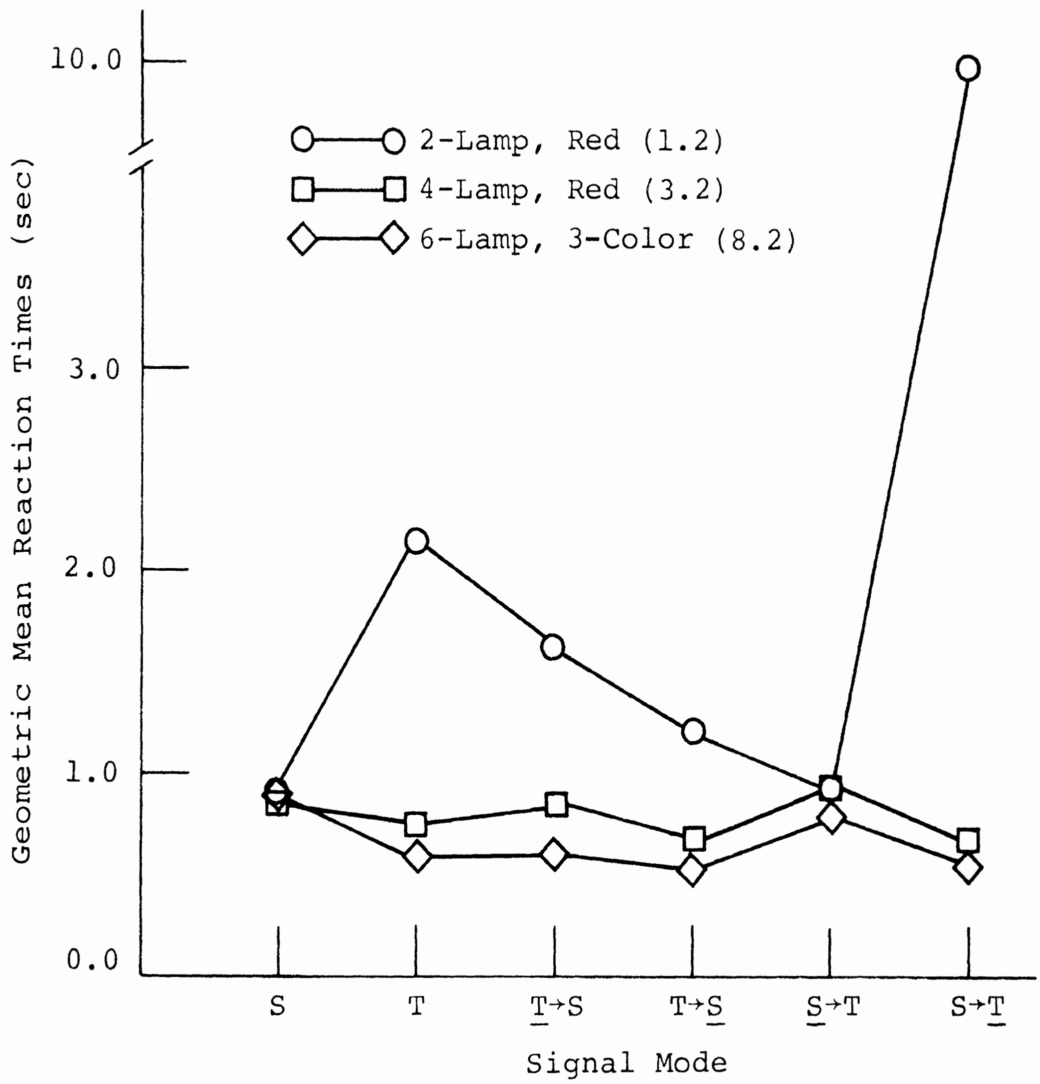


Figure 7. Comparison of three rear lighting systems with turn flasher in "on" position.

TABLE 14. Percent and Type of Errors Made to Stop and Turn Signals When Displayed Singly or in Combination, by Each System.

ERROR TYPE (R-RIGHT TURN, L-LEFT TURN, S-STOP)

SIGNAL PRESENTED (S-STOP, T-TURN, → DENOTES FOLLOWED BY)

1.0

	R	L	S
S			
T			4.3
S→T			
T→S	2.2	5.4	2.2

3.6

1.1

	R	L	S
S	39.1		
T			8.7
S→T	15.2		
T→S	12.0		6.5

20.4

1.2

	R	L	S
S			
T			54.3
S→T			
T→S	3.3	2.2	19.6

19.9

3.0

	R	L	S
S		8.7	
T			4.3
S→T			
T→S			1.1

3.6

3.1

	R	L	S
S	43.5	4.3	
T			8.7
S→T	6.5	1.1	
T→S	3.3		1.1

17.2

3.2

	R	L	S
S		4.3	
T			10.9
S→T			
T→S			1.1

4.1

8.0

	R	L	S
S		8.7	
T			
S→T	1.1		
T→S		1.1	2.2

3.3

8.1

	R	L	S
S	21.7		
T			
S→T	1.1		1.1
T→S	1.1		

6.3

8.2

	R	L	S
S		4.3	
T			
S→T			
T→S			

1.1

TABLE 15. Percent of Errors and Missed Signals in Each System and Signal Mode.

System	Malfunction	% Errors					% Missed				
		Signal Mode					Signal Mode				
		Stop	Turn	S→T	T→S	Mean	Stop	Turn	S→T	T→S	Mean
1. Two-Lamp, Red											
1.0	None	0	4.3	0	9.8	3.6	0	0	0	4.3	1.1
1.1	Stop filament out	39.1	8.7	15.2	18.5	20.4	26.1	50.0	38.1	54.3	42.1
1.2	Turn flasher on	0	54.3	0	25.1	19.9	0	32.6	50.0	19.5	25.5
3. Four-Lamp, Red											
3.0	None	8.7	4.3	0	1.1	3.6	0	0	0	0	0
3.1	Stop filament out	47.8	8.7	7.6	4.4	17.2	17.4	0	0	1.1	4.6
3.2	Turn flasher on	4.3	10.9	0	1.1	4.1	0	2.2	2.2	1.1	1.4
8. Six-Lamp, 3-Color											
8.0	None	8.7	0	1.1	3.3	3.3	0	0	0	1.1	0.3
8.1	Stop filament out	21.7	0	2.2	1.1	6.3	0	0	0	0	0
8.2	Turn flasher on	4.3	0	0	0	1.1	0	0	0	0	0

made in each signal mode of a system, and the overall percent of errors for each system, without identifying the nature of the errors such as was done in Table 14.

Analysis of variance of these errors showed that there were significant effects due to signal modes, systems, and the signal modes x systems interaction. Newman-Keuls tests on the signal modes x systems interaction are shown in Table 16.

For the normally operating systems there were no significant differences in the percent of errors in any signal mode. The overall error rate was 3.6%, 3.6% and 3.3% for Systems 1.0, 3.0 and 8.0, respectively.

When there was a stop lamp filament malfunction, Systems 1.1 and 3.1 incurred significantly more errors in the stop signal mode (39.1% and 47.8%, respectively), than System 8.1 (21.7%). There were no significant differences in the percent of errors to the other signal modes for this malfunction, but fewest errors were made to signals of System 8.1. Overall, the error rate was 20.4% for System 1.1, for System 3.1 it was 17.2%, and for System 8.1 it was 6.3%.

The malfunction in which the turn signal remained on without flashing produced no differences in percent errors for stop and S→T modes; but in the turn and T→S modes Systems 3.2 and 8.2 produced significantly fewer errors than System 1.2. That this system was most impaired in effectiveness is shown in Table 15 by the overall error rate of 19.9% for it, compared to 4.1% and 1.1%, respectively, for Systems 3.2 and 8.2.

MISSED SIGNAL ANALYSIS. The percent of signals that were missed in each signal mode and system, in terms of the specific signal missed, are shown in Table 17. The row marginals of this table are shown in Table 15, which also shows the overall percent of signals missed for each system.

TABLE 16. Significant ($p \leq .01$) Differences Between Systems in Percent Errors in Each Signal Mode.

In Signal Mode	Systems	Had Significantly Fewer Errors	Than Systems
Stop	1.0, 1.2	"	1.1
	3.0, 3.2 8.0, 8.1, 8.2	"	3.1
	1.0, 1.2		8.1
Turn	1.0, 1.1 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.2
Stop→Turn	None	-	-
Turn→Stop	3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.2

TABLE 17, Percent of Stop and Turn Signals Missed, When Displayed Singly or in Combination, by Each System.

SIGNAL TYPE MISSED (R-RIGHT TURN, L-LEFT TURN, S-STOP)

SIGNAL PRESENTED (S-STOP, T-TURN, → DENOTES FOLLOWED BY)

1.0

	R	L	S
S			
T			
S→T			
T→S			4.3

1.1

1.1

	R	L	S
S			26.1
T		50.0	
S→T	2.2	25.0	10.9
T→S		21.7	32.6

42.1

1.2

	R	L	S
S			
T	13.0	19.6	
S→T	25.0	25.0	
T→S	4.3	7.6	7.6

25.5

3.0

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

3.1

	R	L	S
S			17.4
T			
S→T			
T→S			1.1

4.6

3.2

	R	L	S
S			
T	2.2		
S→T		2.2	
T→S		1.1	

1.4

8.0

	R	L	S
S			
T			
S→T			
T→S			1.1

0.3

8.1

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

8.2

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

Analysis of variance of the percent of missed signals showed that significant effects were due to the signal modes, systems, and the signal modes x systems interaction.

A Newman-Keuls test on this interaction (Table 18) showed that there were no significant differences between normal systems in any signal mode. Most missed signals were in the T→S mode of System 1.0. Overall, the missed signal rate was 1.1% for System 1.0, 0% for System 3.0 and 0.3% for System 8.0.

For the left stop lamp malfunction condition, System 8.1 incurred significantly fewer (0%) missed signals than Systems 3.1 (17.4%) and 1.1 (26.1%), in the stop mode. Both Systems 8.1 and 3.1 produced significantly fewer errors than System 1.1 in all other signal modes for this malfunction. Overall, there were no signals missed in System 8.1, 4.6% in System 3.1, and 42.1% in System 1.1.

The malfunction in which the turn signal remained on resulted in a significantly greater percent of missed signals in System 1.2 than 3.2 or 8.2 in all modes except the stop signal. Overall, there were 25.5% of signals missed in System 1.2, 1.4% in System 3.2, and none in System 8.2.

DISCUSSION

In normally operating condition the three rear lighting configurations produced comparable response times to signals given alone or as the first in a combination, although mean response time to the amber turn signal of System 8.0 was significantly less than for the red signal of System 1.0. Response times to the second signal in a combination were significantly longer in the conventional system. Thus, the functional separation of the signal lamps in the four-lamp, red system and six-lamp, 3-color system (8.0) was an advantage in responding to these signals, as found in prior studies (Mortimer, 1969; 1970).

TABLE 18. Significant ($p \leq .01$) Differences Between Systems in Percent Missed Signals in Each Signal Mode.

In Signal Mode	Systems	Had Significantly Fewer Missed Signals	Than Systems
Stop	1.0, 1.2 3.0, 3.2 8.0, 8.1, 8.2	"	1.1, 3.1 3.1
Turn	1.0, 1.2 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.1
	1.0 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.2
Stop→Turn	1.0 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.1, 1.2
Turn→Stop	1.0, 1.2 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.1
	1.0 3.0, 3.1, 3.2 8.0, 8.1, 8.2	"	1.2

An inoperative stop lamp on one side of the car with the conventional system produced an increase in response times in all signal modes compared to the system operating normally, and to that system with the turn signal not flashing, except in one mode. Thus, a failed bulb one side of a car with single compartment rear lamps caused a substantial deterioration in the ability of subjects to detect signals. The effect of the turn signal not flashing also caused an impairment in response times, but only to signals involving the turn mode (Table 8).

The analysis of errors in identification of signals showed that, when a left stop filament was inoperative in the conventional system, stop signals were frequently (39.1%) misinterpreted as right turn signals. The same system with the turn signal not flashing increased the number of errors in the turn (54.3%) and T→S (19.6%) modes, because the turn signal was confused with the stop signal.

Both malfunction conditions resulted in significantly greater percents of missed signals in the conventional system. The left stop lamp failure increased missed signals in all signal modes, and the turn signal not flashing in all modes involving the turn signal, compared to the normally operating conventional system. Clearly, therefore, the malfunctions studied greatly reduced the effectiveness of signals of the conventional system to convey information.

For the rear lighting system in which red stop lamps are separate from lamps providing red turn and presence indications, there were detrimental effects on response times to stop signals presented alone or when preceded or followed by the turn signal if one stop lamp was inoperative, compared to the system operating normally. In this system, the turn signal not flashing did not significantly increase response times to signals.

The inoperative left stop lamp in System 3.1 also led to a substantially greater percent of errors (47.8%) in misinterpreting stop signals as turn signals, and in missed stop signals (17.4%), compared to errors (3.7%) and missed signals (0%) of the normally operating system. The turn signal malfunction in this system did not lead to significant increases in errors or missed signals.

These findings show that separation of stop lamps from combined turn/presence lamps provided an overall improvement in system effectiveness compared to the conventional system. However, the failure of one stop lamp led to increased response times and a large proportion of errors and missed signals to stop signals.

The performance of the three-color system was significantly impaired by the stop lamp malfunction, which increased mean response times to the stop signal presented alone or when preceding the turn signal. The finding that the System 8.2 produced a significantly lower mean response time in the T→S mode than System 8.1, suggests that, because the turn signal was not flashing in System 8.2, it produced less interference with the detection of the stop signal than was the case in the system operating normally, because the mean response time for the latter (8.0) was not significantly less than System 8.1.

The major impairment found for the three-color system was in the left stop lamp malfunction which resulted in 21.7% of stop signals being confused with right turn signals. While this is undesirable, it would be expected that, following longer exposure to vehicles equipped with the amber turn signal of this system than occurred in this study, more drivers would learn that a red signal can denote only a stop signal. They would be aided in this task by the green-blue presence lamps which would signify that the vehicle is using this type of rear lighting system. In fact, the data show that all these errors were corrected quickly (Table 7) by the subjects, because the signals were not missed (Table 17).

The same learning effect would not be as likely to occur in response to a stop lamp malfunction of system 3, which uses red lamps for all functions, and could, therefore, be confused with a conventional system using multiple compartment lamps.

In a previous driving study (Mortimer, 1970) in which Systems 1.0, 3.0 and 8.0 were included, it was found that the overall error rate was 5.2%, 2.8% and 2.0%, respectively; and the missed signal rate was 3.9%, 1.9% and 0.7%, respectively. The overall system error rates compare moderately well with those obtained in this test (Table 15), but the miss rate in the field test was higher, particularly for Systems 1.0 and 3.0. This may have been due to the lower information processing load placed on the subjects, in the simulator test, who were not carrying out a side-task or controlling a vehicle as was the case in the expressway driving test. The comparison suggests that the percent of missed signals, especially of Systems 1 and 3, found in this simulator study may be underestimates of road performance.

The findings of this study reinforce those obtained in earlier tests, conducted on systems in correctly operating conditions, in which functional separation of lamps and color coding of functions have been found to lead to improvements in aspects of the performance of a driver in a following vehicle. This study has added information on the effects of two commonly noted rear signal system malfunctions upon the detection and interpretation of signals. As with normally operating systems, the concepts of functional separation and color coding of functions each led to considerable improvements, compared to the conventional system, in retaining integrity of the signals.

EXPERIMENT II

REAR LIGHTING CONFIGURATIONS

A similar experiment was performed to investigate the effects of malfunctions in three additional rear lighting systems. A fourth system, System 3 from Experiment I, was included as a control (see Figure 8). Systems 9, 10, and 11 incorporated new combinations of lamps displaying stop and/or turn signals. In System 9, four lamps were activated when a stop signal was given, and two lamps when a turn was given. Similarly, in System 10, four lamps were used to display a stop signal; however, the turn signal activated a single lamp, as in a conventional rear lighting system. System 11, a six-lamp system with complete functional separation, used amber for turn signals and red for presence and stop. Presence and stop lamps in System 11 were in the same relation as in System 3, with the amber turn located above the presence lamp.

METHOD

SUBJECTS. Fourteen (14) men and women served as paid subjects. The sample was drawn from University of Michigan students who held valid operator's licenses and had normal color vision.

PROCEDURE. The basic procedure was the same as in Experiment I. Rear lighting signals were presented to the subjects in the simulator with control of the signals originating from the experimenter's console. The lead car was positioned 180 feet (simulated) ahead of the subject's car and remained stationary with respect to the subject's car throughout the experiment. However, part of the subject's task was to maintain various speeds (30, 40, 50, or 60 mph) while responding to the signals given by the lead car.

The malfunctions included in this experiment were a burned out stop and/or turn bulb in the outboard or inboard location, and a turn flasher which does not flash and leaves the lamp in

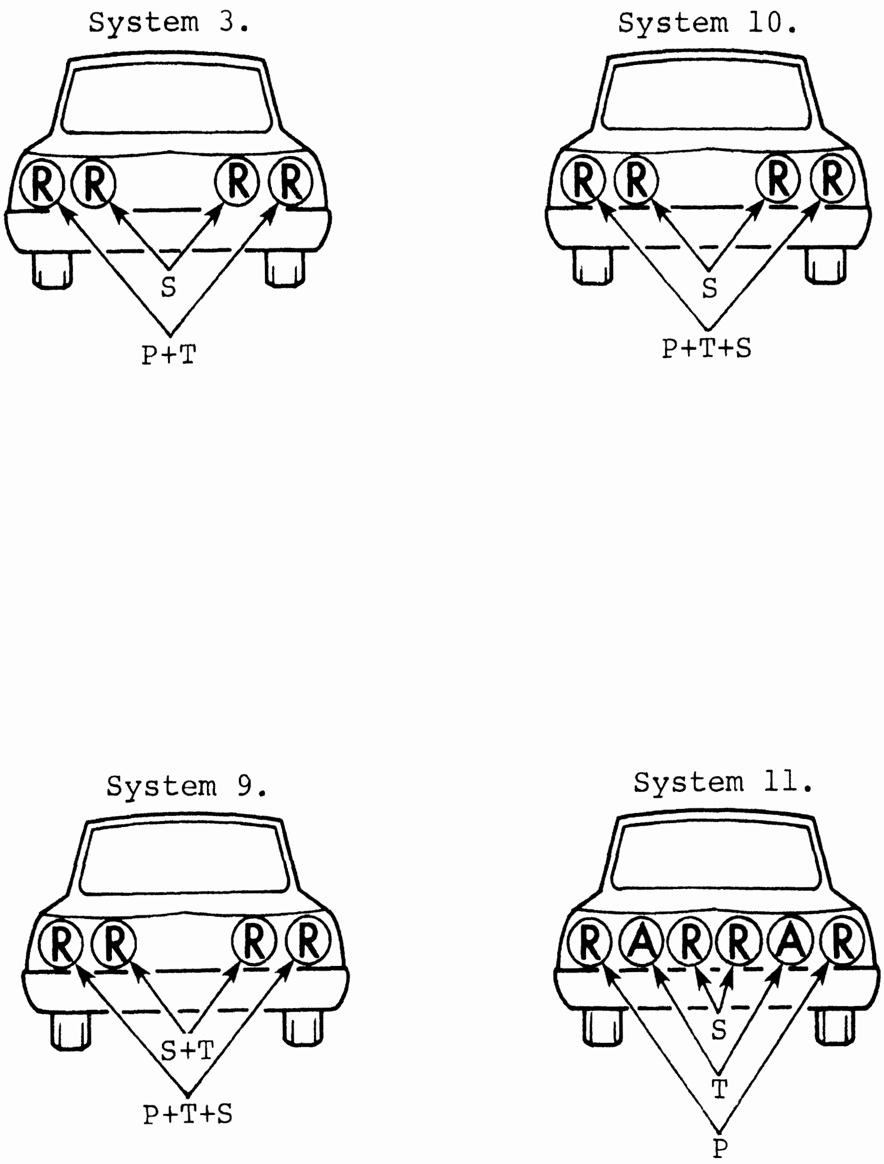


Figure 8. Rear lighting configurations evaluated in the second experiment. (P-presence, S-stop, T-turn, R-red, A-amber)

the "on" position. The four systems operated in the normal and malfunctioning conditions that were simulated, generated the sixteen systems used in the experiment. Table 19 contains a description of each system and its corresponding malfunctions.

In Systems 3, 10, and 11 presence lamps were operated at an intensity of 7 cd and stop and turn lamps at 91 cd. The output of the presence lamps in System 9 was reduced to 4 cd and stop and turn lamps to 57 cd each to simulate a system with multiple compartment lamps. The ambient lighting was 10 foot-candles, as in Experiment I.

Each subject was given one practice trial driving the simulator and responding to signals in System 3. The experimental trials began with one of the four lighting systems operating normally, followed by each of the three malfunctions in a predetermined random order. The order in which the lighting systems were presented was counterbalanced across subjects, while the speed assigned on a given trial was randomized.

RESULTS

The data collected included reaction times to a specific signal or combination, signal identification errors, and signals missed. Ratings of signal effectiveness for each system were also obtained. Separate analyses were performed on each measure.

REACTION TIME ANALYSIS. Geometric mean reaction times, in seconds, to signals in each of the sixteen systems are displayed in Table 19. As noted, when a subject failed to respond to a signal within ten seconds, it was recorded as missed, and ten seconds was used as the reaction time in the analysis.

Analysis of variance of the reaction time data showed that there were significant effects due to signal modes, systems, and the modes X systems interactions. Newman-Keuls tests were performed to pinpoint significant differences between systems within each signal mode.

TABLE 19. Geometric Mean Reaction Times to Signal Modes Presented by Four Rear Lighting Systems, Operating Normally or Under the Specified Malfunctions.

Description		Signal Mode					
System	Malfunction	$\underline{S}$	$\underline{T}$	$\underline{T}\to S$	$T\to\underline{S}$	$\underline{S}\to T$	$S\to\underline{T}$
3.0	Normal	0.891	0.802	0.740	0.830	0.915	0.946
3.1	Left inboard stop filament out	2.20	0.984	0.853	0.986	1.63	1.12
3.2	Flasher remains in ON position	0.965	0.857	0.785	0.844	0.944	1.49
3.3	Outboard right turn filament out	0.966	2.94	3.08	0.821	0.916	3.51
9.0	Normal	1.0	0.898	0.963	1.17	0.967	1.69
9.1	Left inboard stop/ turn filament out	2.81	1.31	1.64	2.05	1.60	2.24
9.2	Flasher remains in ON position	1.02	2.19	2.01	1.13	1.03	10.0*
9.3	Outboard right stop/ turn filament out	0.963	1.14	1.08	0.978	1.04	2.01
10.0	Normal	0.843	0.707	0.834	0.769	0.893	1.82
10.1	Right inboard stop filament out	1.17	0.808	0.835	0.931	1.10	1.88
10.2	Flasher remains in ON position	0.871	0.802	0.678	0.721	0.861	10.0*
10.3	Outboard left stop/ turn filament out	0.939	2.62	2.30	0.873	0.896	4.31
11.0	Normal	0.949	0.718	0.725	0.737	0.939	0.785
11.1	Right inboard stop filament out	1.42	0.720	0.745	0.935	1.22	0.717
11.2	Flasher remains in ON position	0.988	0.774	0.734	0.749	0.904	0.761
11.3	Outboard left turn filament out	0.931	2.25	2.34	0.845	0.934	2.25

*Reaction time to missed signals recorded as 10.0 sec.

Comparisons Within Systems. In System 3, mean reaction times increased in some malfunctioning conditions as shown in Figure 9. Results of Newman-Keuls tests on signal modes in System 3 are shown in Table 20. With the inboard stop filament burned out (System 3.1) there were significant increases in mean reaction times over all other conditions in the stop and S→T signal modes. With a turn filament out (System 3.3), performance times were significantly longer in the turn, T→S and S→T modes. The turn flasher in the on position (System 3.2) resulted in significantly longer mean reaction times than for the normal system only in the signal mode, S→T.

Figure 10 shows the mean reaction times in the signal modes for System 9. The Newman-Keuls tests in Table 21 show that an inboard stop/turn lamp malfunction (System 9.1) led to significantly longer reaction times when compared to the other systems in the stop and T→S modes. A turn flasher in the on position (System 9.2) resulted in significantly longer reaction times over the other systems in the turn and S→T modes. Both Systems 9.1 and 9.2 led to significantly longer reaction times over Systems 9.0 (normal) and 9.3 (outboard stop/turn lamp malfunction) in the T→S mode.

In System 10, as displayed in Figure 11, the variability of responses to the malfunctioning conditions appears to have decreased. Table 22 shows that an inboard stop lamp malfunction (System 10.1) led to significantly worse performance only in the stop mode. A turn flasher in the on position (System 10.2) resulted in significantly longer reaction times in only one mode, S→T. In the turn, T→S, and S→T modes, an outboard stop/turn lamp malfunction led to significantly longer reaction times.

Similarily, Figure 12 shows only a small amount of variability between reaction times of System 11 in normal and malfunctioning modes. In the turn, T→S, and S→T modes, an outboard turn lamp malfunction (System 11.3) resulted in significantly longer reaction times than

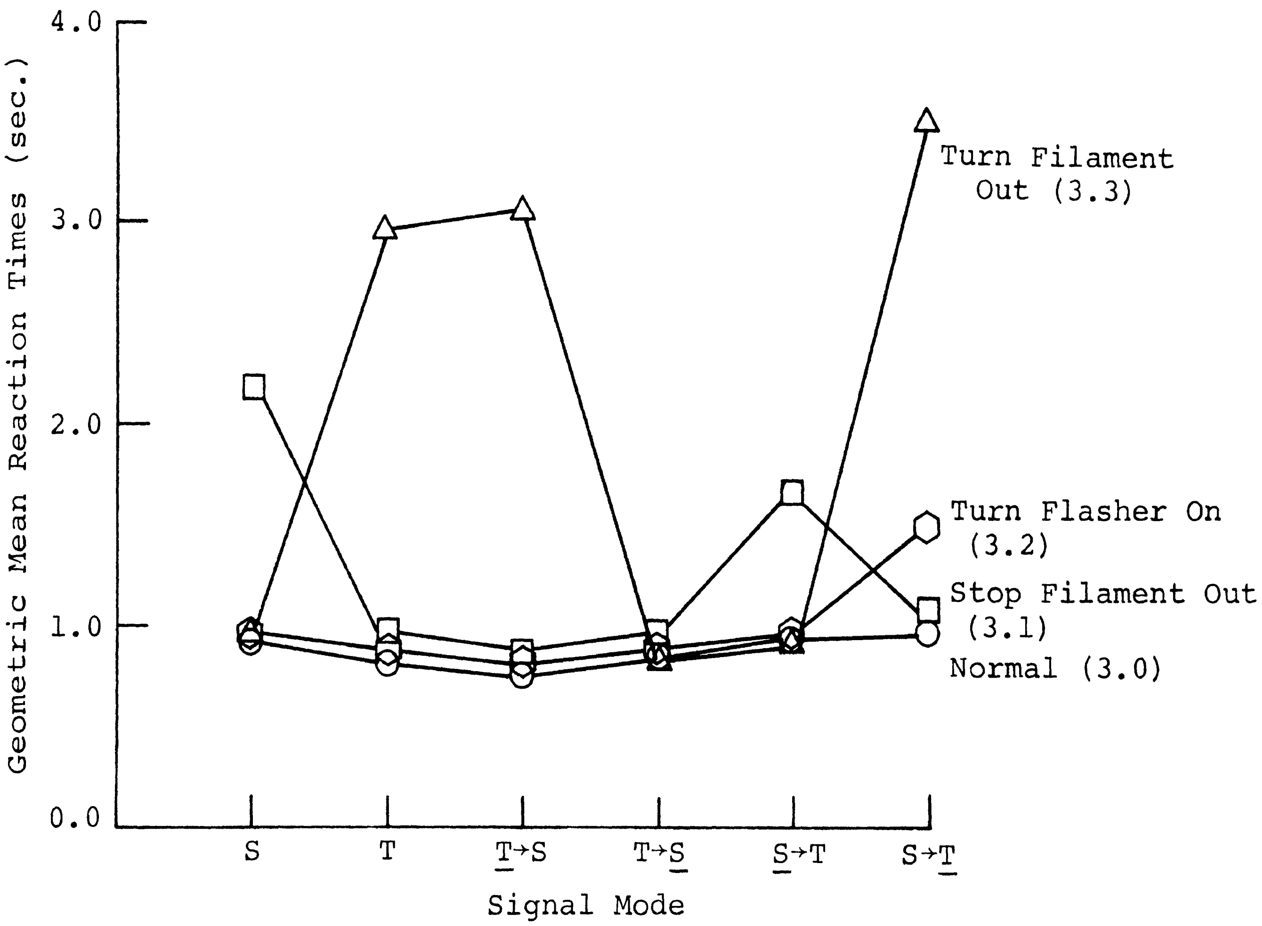


Figure 9. System 3. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

TABLE 20. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 3 in Each Signal Mode.

Signal Mode	System (s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	3.0, 3.2, 3.3	"	3.1
T	3.0, 3.1, 3.2	"	3.3
$\underline{T}\to S$	3.0, 3.1, 3.2	"	3.3
$T\to \underline{S}$	None	"	Other
$\underline{S}\to T$	3.0, 3.2, 3.3	"	3.1
$S\to \underline{T}$	3.0, 3.1, 3.2	"	3.3
	3.0	"	3.2

TABLE 21. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 9 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	9.0, 9.2, 9.3	"	9.1
T	9.0, 9.1, 9.3	"	9.2
$\underline{T}\to S$	9.0, 9.3	"	9.1, 9.2
$T\to \underline{S}$	9.0, 9.2, 9.3	"	9.1
$\underline{S}\to T$	None	"	Other
$S\to \underline{T}$	9.0, 9.1, 9.3	"	9.2

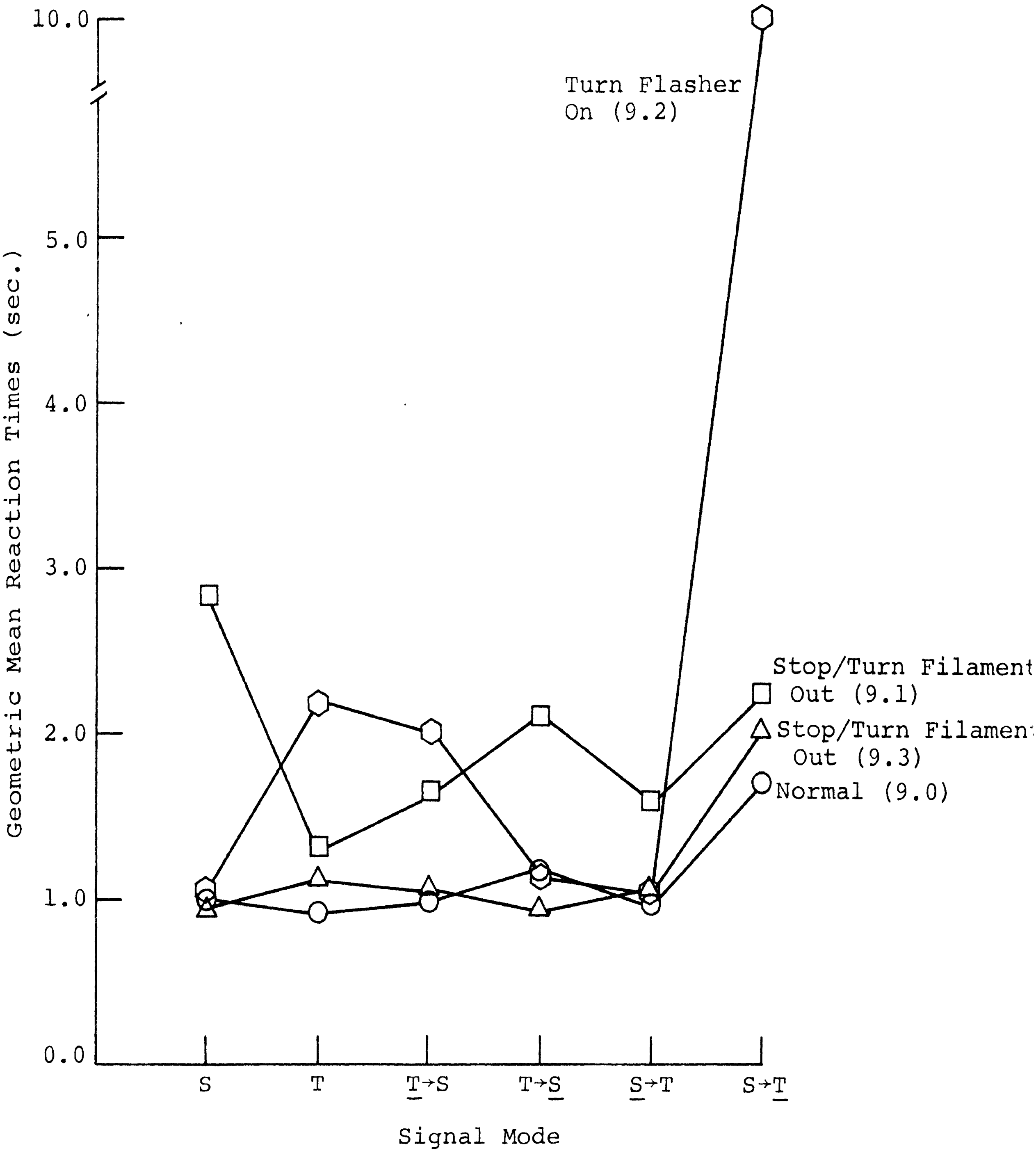


Figure 10. System 9. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

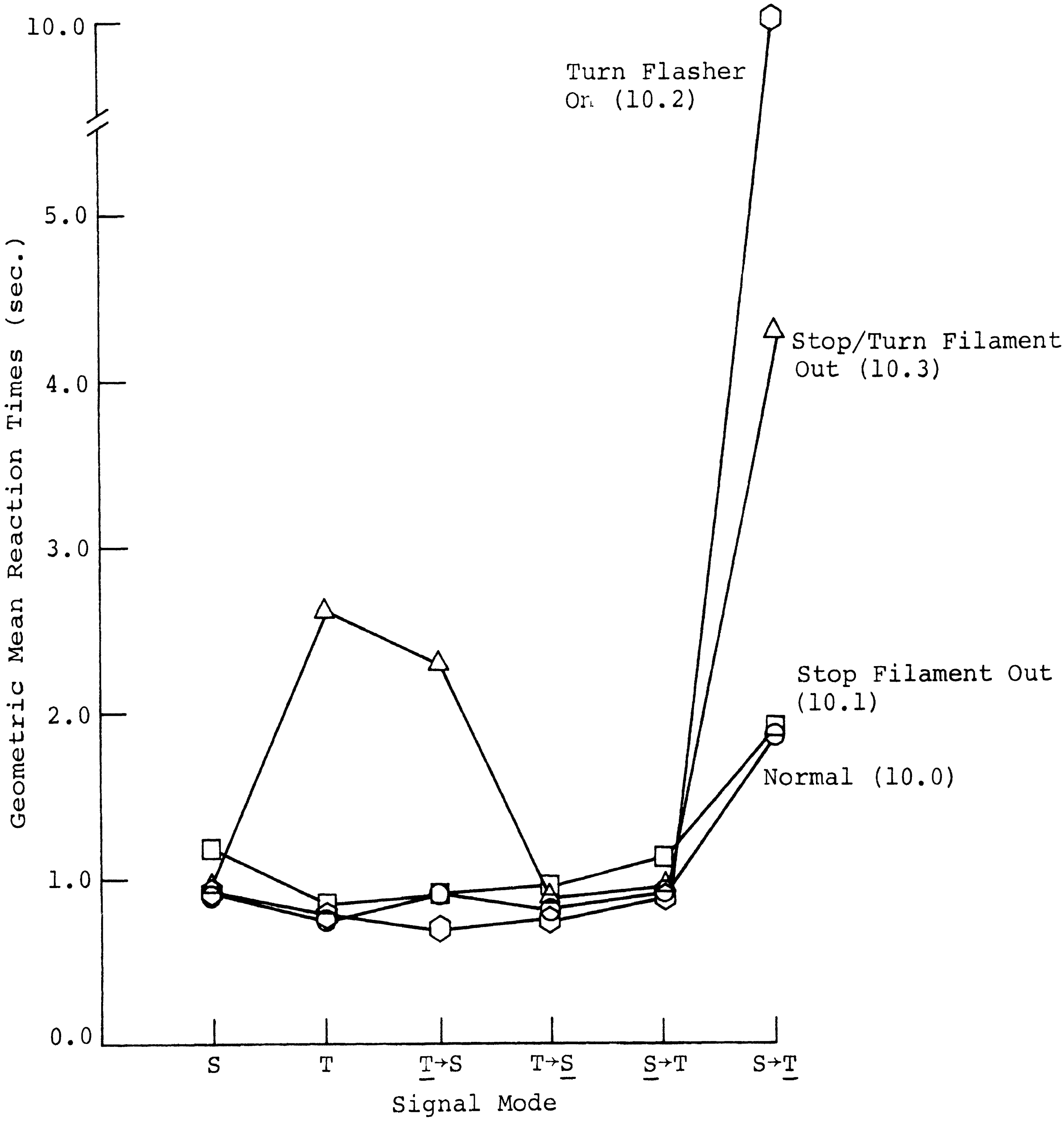


Figure 11. System 10. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

TABLE 22. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 10 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	10.0, 10.2	"	10.1
T	10.0, 10.1, 10.2	"	10.3
$\underline{T}\rightarrow S$	10.0, 10.1, 10.2	"	10.3
$T\rightarrow \underline{S}$	None	"	Other
$\underline{S}\rightarrow T$	None	"	Other
$S\rightarrow \underline{T}$	10.0, 10.1	"	10.2, 10.3
	10.3	"	10.2

TABLE 23. Significant Differences ($p \leq .01$) in Mean Reaction Times for Normal and Malfunctioning Conditions of System 11 in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	11.0, 11.2, 11.3	"	11.1
T	11.0, 11.1, 11.2	"	11.3
$\underline{T}\rightarrow S$	11.0, 11.1, 11.2	"	11.3
$T\rightarrow \underline{S}$	None	"	Other
$\underline{S}\rightarrow T$	None	"	Other
$S\rightarrow \underline{T}$	11.0, 11.1, 11.2	"	11.3

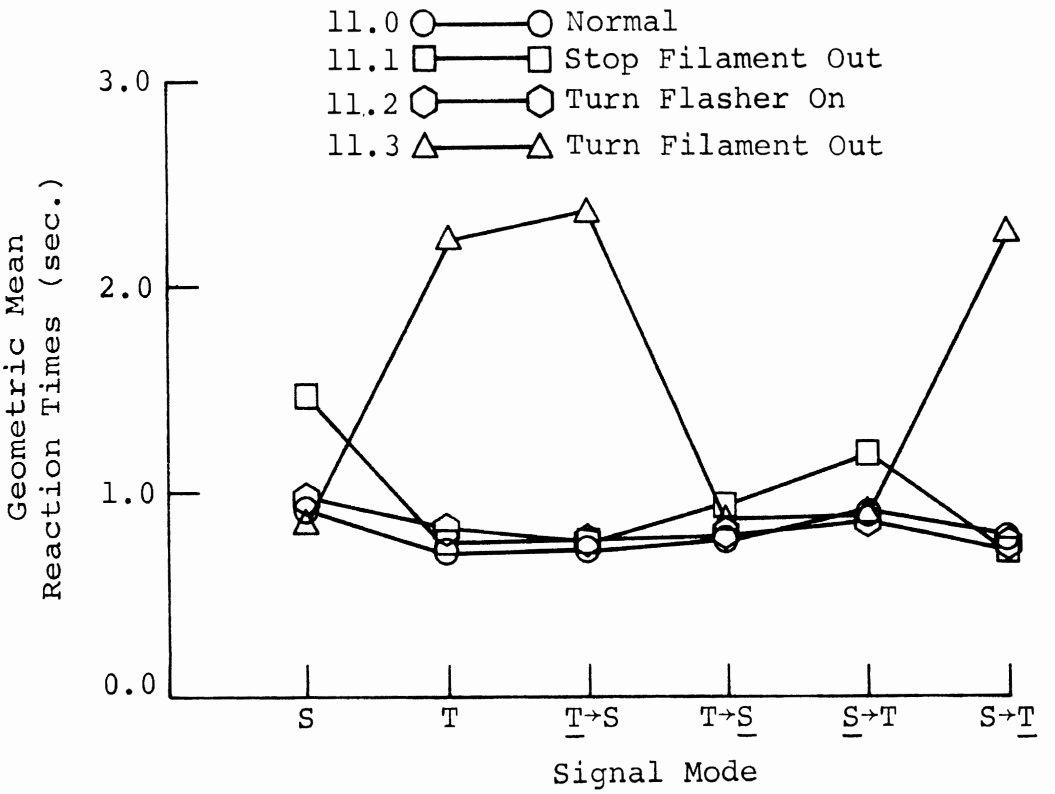


Figure 12. System 11. Geometric mean reaction times plotted as a function of signal mode, in normal and malfunctioning systems.

the other systems (Table 23). When an inboard stop lamp malfunctioned (System 11.1), reaction times were significantly longer than the other systems in the stop mode.

Comparisons Between Systems. Mean reaction times to each signal mode and system operating normally are displayed in Figure 13. System 9 led to significantly longer reaction times in the T→S mode (Table 24). In the S→T mode, Systems 9 and 10 both resulted in significantly longer reaction times. Systems 3 and 11 have the advantage of a turn signal lamp separated from the stop which most likely explains this difference.

Figure 14 shows the effects of an inboard stop lamp malfunction in Systems 3, 10 and 11; and in System 9 the effects of a combined stop/turn lamp malfunction. Although the stop signal display was similar, System 11.1, a six-lamp system with functional separation was more effective than System 3.1 (Table 25). The use of amber for the turn signal in System 11 apparently led to fewer stop/turn confusions than in System 3. System 9.1 led to significantly poorer performance than Systems 10.1 and 11.1. System 10, as mentioned in the introduction, had a higher total intensity than System 9, with four stop lamps on. This may explain the performance advantage in System 10.

The effects of a turn flasher in the on position are shown in Figure 15. Significant differences were found in the turn and T→S modes between System 9.2 and the others, with System 9.2 producing significantly longer reaction times (Table 26). In the S→T mode, Systems 9.2 and 10.2 resulted in significantly longer reaction times than Systems 3.2 and 11.2; and in addition, System 3.2 was significantly worse than System 11.2.

Figure 16 displays mean reaction times to signal modes in systems with an outboard stop/turn filament out. Significant differences were only found in signal modes involving a turn (Table 27). In the turn and T→S modes, System 9.3 produced signi-

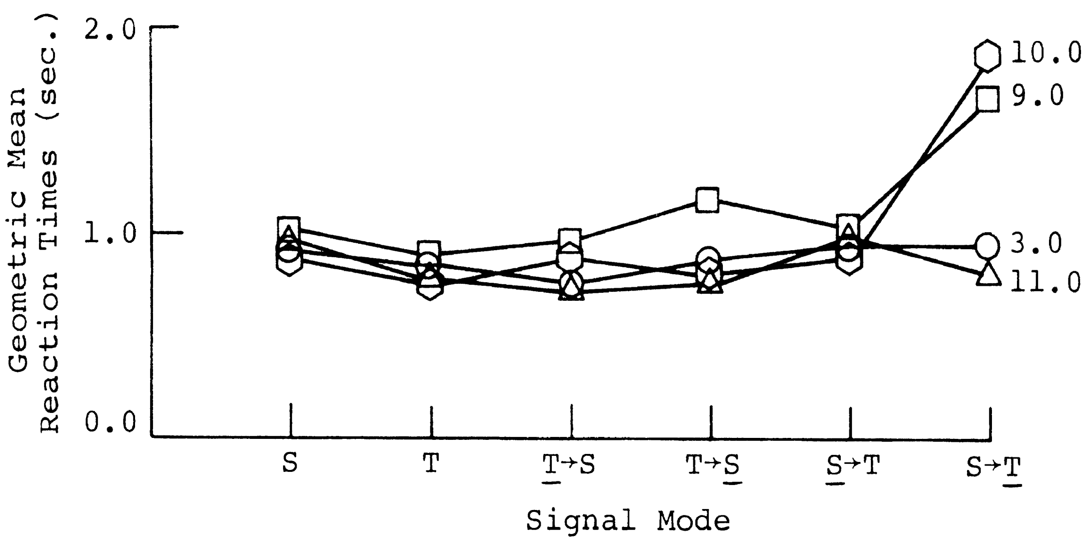


Figure 13. Geometric mean reaction times plotted as a function of signal mode, in normal systems.

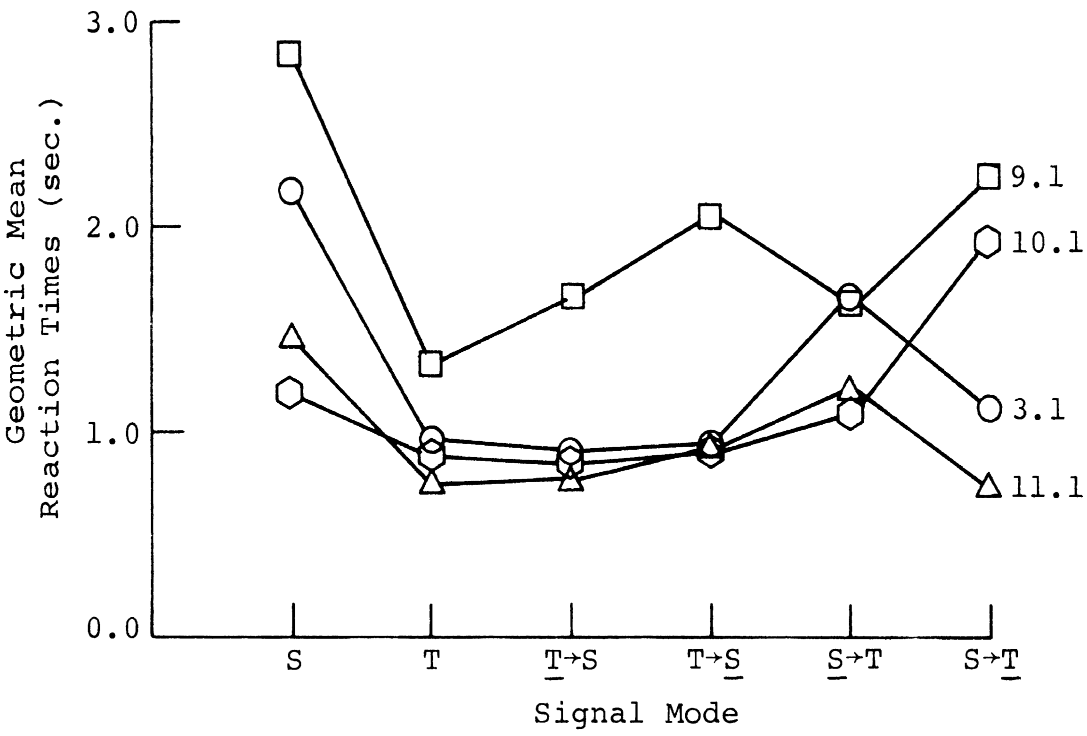


Figure 14. Geometric mean reaction times plotted as a function of signal mode, in systems with inboard stop/turn filament malfunction.

TABLE 24. Significant Differences ($p \leq .01$) in Mean Reaction Times Between Systems Under Normal Operation in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	None	"	Other
T	None	"	Other
$\underline{T} \rightarrow S$	None	"	Other
$T \rightarrow \underline{S}$	3.0, 10.0, 11.0	"	9.0
$\underline{S} \rightarrow T$	None	"	Other
$S \rightarrow \underline{T}$	3.0, 11.0	"	9.0, 10.0

TABLE 25. Significant Differences ($p \leq .01$) in Mean Reaction Times Between Systems With Inboard Stop/Turn Filament Out in Each Signal Mode.

Signal Mode		Resulted in Significantly Shorter Reaction Times	Than System(s)
S	10.1, 11.1	"	3.1, 9.1
T	10.1, 11.1	"	9.1
$\underline{T} \rightarrow S$	3.1, 10.1, 11.1	"	9.1
$T \rightarrow \underline{S}$	3.1, 10.1, 11.1	"	9.1
$\underline{S} \rightarrow T$	None	"	Other
$S \rightarrow \underline{T}$	3.1, 11.1	"	9.1, 10.1
	11.1	"	3.1

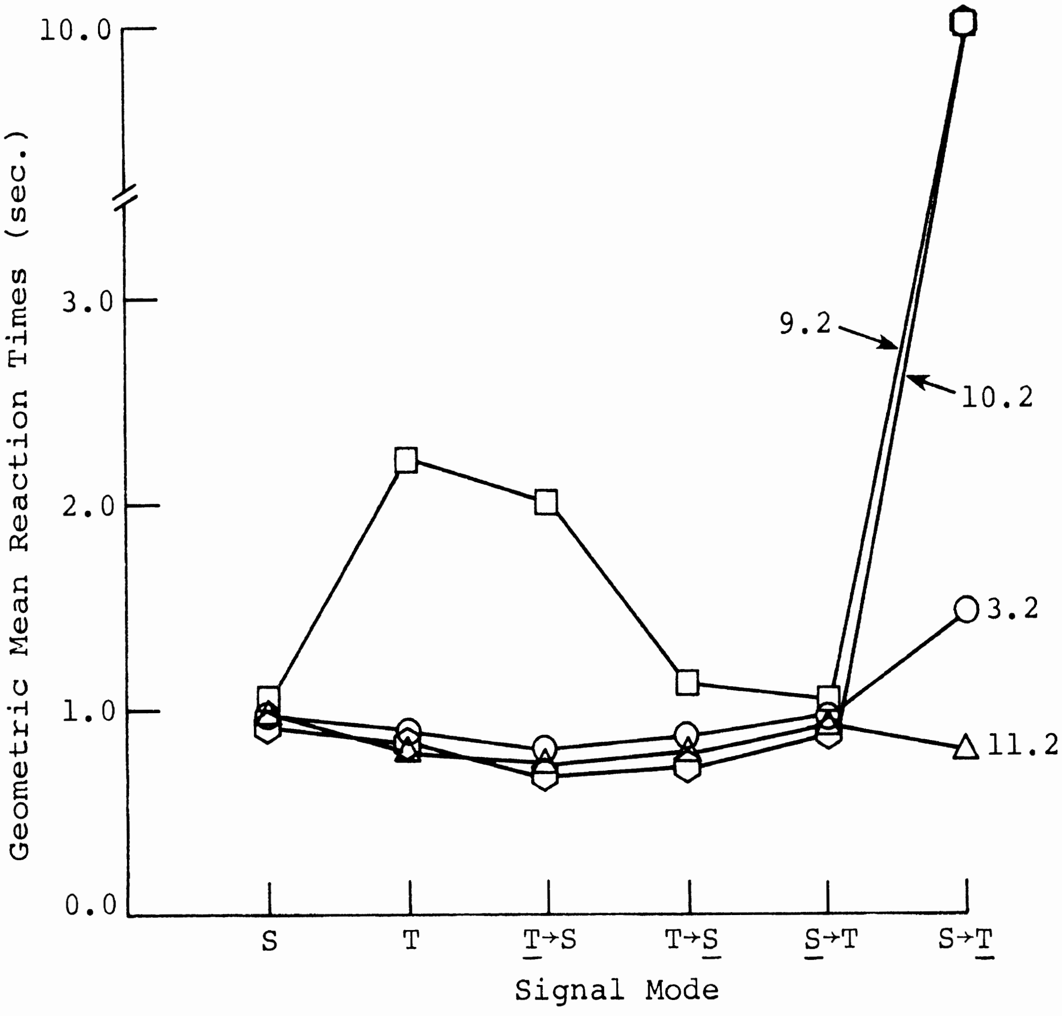


Figure 15. Geometric mean reaction times plotted as a function of signal mode, in systems with turn flasher in the on position.

TABLE 26. Significant Differences ($p \leq .01$) in Mean Reaction Times Between Systems With Turn Flasher On in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	None	"	Other
T	3.2, 10.2, 11.2	"	9.2
$\underline{T}\rightarrow S$	3.2, 10.2, 11.2	"	9.2
$T\rightarrow \underline{S}$	None	"	Other
$\underline{S}\rightarrow T$	None	"	Other
$S\rightarrow \underline{T}$	3.2, 11.2	"	9.2, 10.2
	11.2	"	3.2

TABLE 27. Significant Differences ($p \leq .01$) in Mean Reaction Times Between Systems With Outboard Stop/Turn Filament Out in Each Signal Mode.

Signal Mode	System(s)	Resulted in Significantly Shorter Reaction Times	Than System(s)
S	None	"	Other
T	9.3	"	3.3, 10.3, 11.3
$\underline{T}\rightarrow S$	9.3	"	3.3, 10.3, 11.3
$T\rightarrow \underline{S}$	None	"	Other
$\underline{S}\rightarrow T$	None	"	Other
$S\rightarrow \underline{T}$	9.3, 11.3	"	3.3, 10.3

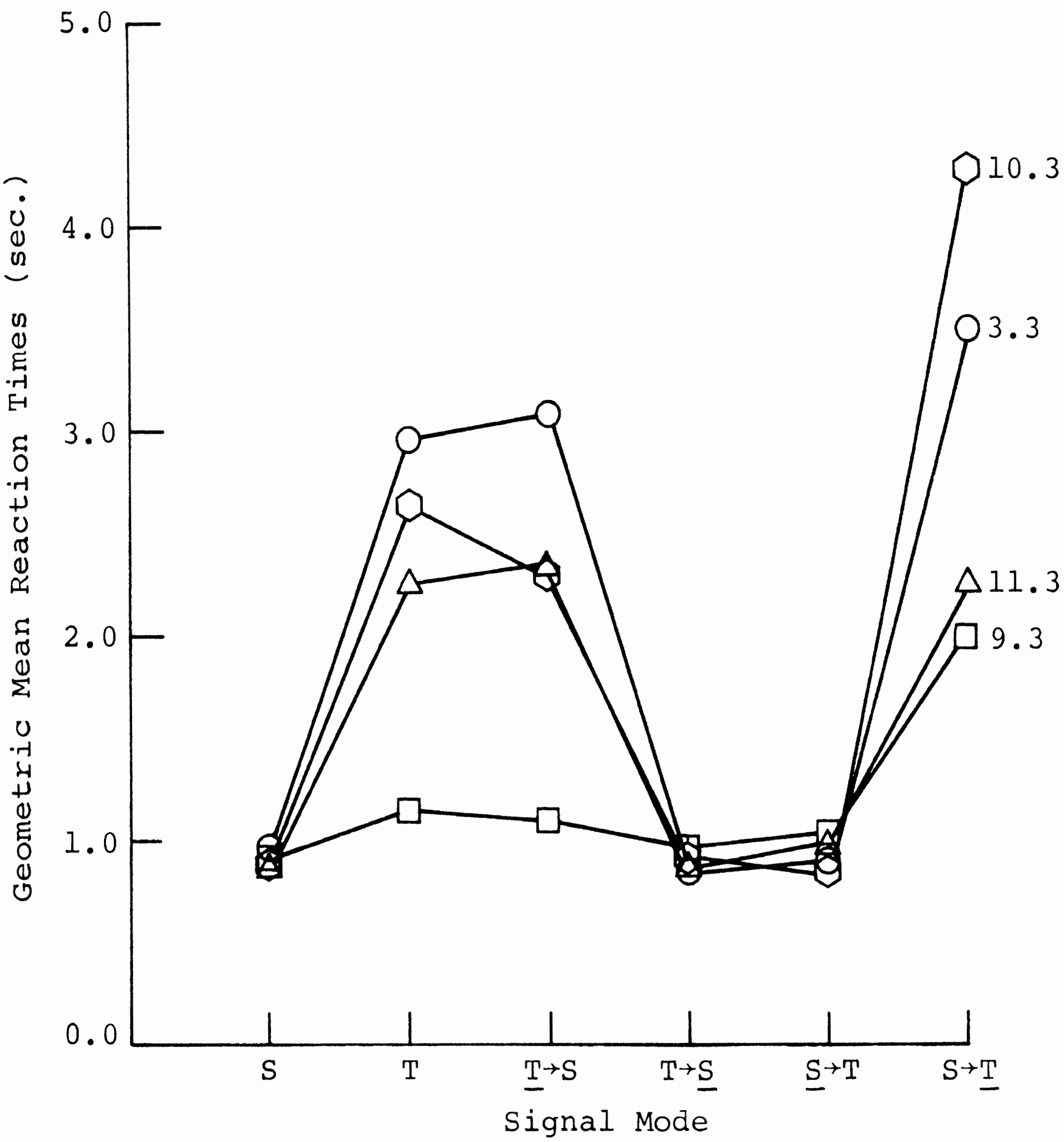


Figure 16. Geometric mean reaction times plotted as a function of signal mode, in systems with outboard stop/turn filament out.

ficantly shorter reaction times than the other three systems. In the S→T mode, Systems 9.3 and 11.3 were significantly better than Systems 3.3 and 10.3.

ERROR ANALYSIS. Table 28 shows the number of errors in identifying signals as a percent of the signals presented in each mode, whether singly or in combination, for each system. The marginal row totals of Table 28 are shown in Table 29, which indicates the percent of errors mode in each signal mode of a system, and the overall percent of errors for each system, without identifying the nature of the errors as done in Table 28.

Analysis of variance of these errors showed that there were significant effects due to signal modes, systems, and the signal modes X systems interaction. Newman-Keuls tests on the signal modes X systems interaction are shown in Table 30.

When systems were operating normally there were no significant differences in percent of errors in any signal mode. Overall error rates were 3.6%, 0.9%, 0.4%, and 0.9% for Systems 3.0, 9.0, 10.0, and 11.0, respectively.

For systems with an inboard stop and/or turn lamp malfunction, System 9.1 produced significantly more errors in the stop mode (42.9%) than Systems 10.1 and 11.1 (0% and 14.3%, respectively). Also in the stop mode, System 3.1 produced significantly more errors (28.6%) than System 10.1 (0%). The overall error rate for System 3.1 was 9.8%; System 9.1, 14.3%; System 10.1, 1.8%; and System 11.1, 4.0%.

When the turn flasher remained in the on position, System 9.2 produced significantly more errors (42.9%) in the turn mode than Systems 3.2, 10.2, and 11.2 (3.6%, 3.6% and 10.7%, respectively).

Within System 3, an inboard stop lamp malfunction produced significantly more errors than the normal and two other malfunctioning systems. In System 9, in the stop mode, System 9.1 produced

TABLE 28. Percent and Type of Errors Made to Stop and Turn Signals when Displayed Singly or in Combination, by Each Subject.

ERROR TYPE (R-RIGHT TURN, L-LEFT TURN, S-STOP)

SIGNAL PRESENTED (S-STOP, T-TURN, → DENOTES FOLLOWED BY)

3.0

	R	L	S
S			
T			10.7
S→T	1.8		
T→S			1.8

3.6

3.1

	R	L	S
S	28.6		
T			7.1
S→T	3.6		
T→S			

9.8

3.2

	R	L	S
S			
T			3.6
S→T			
T→S			1.8

1.3

3.3

	R	L	S
S			
T			
S→T	1.8		
T→S			1.8

0.9

9.0

	R	L	S
S			
T			
S→T		1.8	
T→S			1.8

0.9

9.1

	R	L	S
S	42.9		
T			3.6
S→T	3.6		
T→S			7.1

14.3

9.2

	R	L	S
S			
T	3.6		39.3
S→T			
T→S	1.8	1.8	12.5

14.8

9.3

	R	L	S
S			
T			
S→T		1.8	
T→S			

0.4

10.0

	R	L	S
S			
T			
S→T			
T→S			1.8

0.4

10.1

	R	L	S
S			
T			3.6
S→T			
T→S	1.8		1.8

1.8

10.2

	R	L	S
S			
T			3.6
S→T			
T→S			

0.9

10.3

	R	L	S
S			
T	3.6		
S→T			
T→S			

0.9

11.0

	R	L	S
S			
T			3.6
S→T			
T→S			

0.9

11.1

	R	L	S
S		14.3	
T			
S→T		1.8	
T→S			

4.0

11.2

	R	L	S
S			
T			10.7
S→T	1.8		
T→S			1.8

3.6

11.3

	R	L	S
S			
T			
S→T		1.8	
T→S			

0.4

TABLE 29. Percent of Errors and Missed Signals in Each System and Signal Mode.

System	Malfunction	% Errors: Signal Mode: Stop	Turn	S→T	T→S	Mean	% Misses: Signal Mode: Stop	Turn	S→T	T→S	Mean
3.0	Normal	0	10.7	1.8	1.8	3.6	0	3.6	1.8	0	1.3
3.1	Left inboard stop filament out	28.6	7.1	3.6	0	9.8	14.3	0	0	0	3.6
3.2	Flasher remains in ON position	0	3.6	0	1.8	1.3	0	3.6	7.1	0	2.7
3.3	Outboard right turn filament out	0	0	1.8	1.8	0.9	0	50.0	26.8	25.0	25.4
9.0	Normal	0	0	1.8	1.8	0.9	0	0	0	0	0
9.1	Left inboard stop/ turn filament out	42.9	3.6	3.6	7.1	14.3	35.7	0	5.4	12.5	13.4
9.2	Flasher remains in ON position	0	42.9	0	16.1	14.8	0	28.6	50.0	14.3	23.2
9.3	Outboard right stop/ turn filament out	0	0	1.8	0	0.4	0	0	1.8	0	0.4
10.0	Normal	0	0	0	1.8	0.4	0	0	0	0	0
10.1	Right inboard stop filament out	0	3.6	0	3.6	1.8	0	0	0	0	0
10.2	Flasher remains in ON position	0	3.6	0	0	0.9	0	3.6	50.0	0	13.4
10.3	Outboard left stop/ turn filament out	0	3.6	0	0	0.9	0	50.0	25.0	25.0	25.0
11.0	Normal	0	3.6	0	0	0.9	0	0	0	0	0
11.1	Right inboard stop filament out	14.3	0	1.8	0	4.0	7.1	0	0	0	1.8
11.2	Flasher remains in ON position	0	10.7	1.8	1.8	3.6	0	0	1.8	0	0.4
11.3	Outboard left turn filament out	0	0	1.8	0	0.4	0	50.0	25.0	25.0	25.0

TABLE 30. Significant ($p \leq .01$) Differences Between Systems in Percent Errors in Each Signal Mode.

In Signal Mode	System(s)	Had Significantly Fewer Errors	Than System(s)
Stop	3.0, 3.2, 3.3, 10.1	"	3.1
	9.0, 9.2, 9.3, 10.1, 11.1	"	9.1
Turn	3.2, 9.0, 9.1, 9.3, 10.2, 11.2	"	9.2
Stop→Turn	None	"	Other
Turn→Stop	None	"	Other

significantly more errors than the system operating normally or the other malfunctions. In the turn mode, System 9.2 produced significantly more errors than the normal and other malfunctioning systems. There were no significant differences found within Systems 10 and 11.

MISSED SIGNAL ANALYSIS. The percent of signals missed in each signal mode and system are displayed in Table 31. Marginal row totals are shown in Table 29 along with the overall percent of signals missed in each system. Analysis of variance of the percent of missed signals showed that significant effects were due to the signal modes, systems, and the signal modes X systems interaction.

The results of Newman-Keuls tests on the interactions are displayed in Table 32. There were no significant differences between normal systems in any signal mode. Overall the missed signal rate was 1.3% for System 3.0, and 0% for Systems 9.0, 10.0, and 11.0.

For the inboard stop/turn lamp malfunction, System 9.1 incurred significantly more missed signals (35.7%) than Systems 3.1 (14.3%), 10.1 (0%) and 11.1 (7.1%) in the stop mode, Within Systems 3 and 9, this malfunction (Systems 3.1 and 9.1) caused a significant performance decrement when compared to the normal and other malfunctioning systems in the stop mode.

When the turn signal remained in the on position System 9.2 produced significantly more misses than Systems 3.2 and 11.2 in the Turn (28.6%, 3.6%, 0%, respectively) and S→T (50%, 7.17%, 1.8%, respectively) modes. In the turn mode only System 9.2 (28.6%) produced significantly more misses than System 10.2 (3.6%). Most missed signals in the S→T mode were turn signals which were masked by stop signals. Systems 3 and 11 had an advantage with the turn signal functionally separated from the stop, and the use of amber in System 11.

Within System 9, in the turn and S→T modes, System 9.2 produced significantly more missed signals. Within System 10, in

TABLE 31. Percent of Stop and Turn Signals Missed, when Displayed Singly or in Combination, by Each System.

SIGNAL TYPE MISSED (R-RIGHT TURN, L-LEFT TURN, S-STOP)

SIGNAL PRESENTED (S-STOP, T-TURN, → DENOTES FOLLOWED BY)

3.0

	R	L	S
S			
T		3.6	
S→T		1.8	
T→S			

1.3

3.1

	R	L	S
S			14.3
T			
S→T			
T→S			

3.6

3.2

	R	L	S
S			
T		3.6	
S→T	1.8	5.3	
T→S			

2.7

3.3

	R	L	S
S			
T	50.0		
S→T	25.0	1.8	
T→S	25.0		

25

9.0

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

9.1

	R	L	S
S			35.7
T			
S→T		3.6	1.8
T→S			12.5

13.4

9.2

	R	L	S
S			
T	14.3	14.3	
S→T	25.0	25.0	
T→S	5.4	7.1	1.8

23.2

9.3

	R	L	S
S			
T			
S→T	1.8		
T→S			

0.4

10.0

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

10.1

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

10.2

	R	L	S
S			
T		3.6	
S→T	25.0	25.0	
T→S			

13.4

10.3

	R	L	S
S			
T		50.0	
S→T		25.0	
T→S		25.0	

25.0

11.0

	R	L	S
S			
T			
S→T			
T→S			

NONE

0.0

11.1

	R	L	S
S			7.1
T			
S→T			
T→S			

1.8

11.2

	R	L	S
S			
T			
S→T		1.8	
T→S			

0.4

11.3

	R	L	S
S			
T		50.0	
S→T		25.0	
T→S		25.0	

25.0

TABLE 32. Significant ($p \leq .01$) Differences Between Systems in Percent of Signals Missed in Each Signal Mode.

In Signal Mode	System(s)	Had Significantly Fewer Misses	Than System(s)
Stop	3.1, 9.0, 9.2, 9.3, 10.1, 11.1	"	9.1
	3.0, 3.2, 3.3	"	3.1
Turn	3.0, 3.1, 3.2, 9.3	"	3.3
	3.2, 9.0, 9.1, 9.3, 10.2, 11.2	"	9.2
	9.3, 10.0, 10.1, 10.2	"	10.3
	9.3, 11.0, 11.1, 11.2	"	11.3
Stop→Turn	3.0, 3.1, 3.2, 9.3	"	3.3
	3.2, 9.0, 9.1, 9.3, 11.2	"	9.2
	3.2, 10.0, 10.1, 10.3, 11.2	"	10.2
	9.3, 10.0, 10.1	"	10.3
	9.3, 11.0, 11.1, 11.2	"	11.3
Turn→Stop	3.0, 3.1, 3.2, 9.3	"	3.3
	9.3, 10.0, 10.1, 10.2	"	10.3
	9.3, 11.0, 11.1, 11.2	"	11.3

the S→T mode, System 10.2 incurred significantly more missed signals than the normal and other malfunctioning systems.

In the turn, S→T, and T→S modes an outboard stop/turn lamp malfunction resulted in a significantly smaller percent of missed signals in System 9.3 (0.4% overall) than Systems 3.3, 10.3, and 11.3 (25.4%, 25.0%, and 25.0% overall), respectively.

SUBJECTIVE RATING ANALYSIS. Mean ratings of stop and turn signal effectiveness for each system are shown in Table 33. The results of an analysis of variance of the ratings showed that there was a significant system X mode interaction. The Newman-Keuls tests on the system X signal mode interactions are displayed in Table 34. In the turn mode, for the systems under normal operation, System 11.0 was rated as significantly more effective than the three other normal systems. Systems with a turn flasher in the on position were always rated significantly less effective than the normal and other malfunctioning conditions, but System 11.2 was rated more effective than the other systems with this turn flasher malfunction. When an inboard stop/turn lamp malfunctioned, System 11.1 was rated as significantly better than Systems 3.1, 9.1, and 10.1. This same difference was found between System 11.3 and Systems 3.3, 9.3, and 10.3.

In the stop mode, all systems with an inboard stop/turn lamp malfunction (Systems 3.1, 9.1, 10.1 and 11.1) were rated significantly less effective.

DISCUSSION

When compared to the normal systems, the malfunctions evaluated in this experiment significantly increased reaction times to rear lighting signals in either the turn, stop, or combination modes. In the modes involving a stop signal, reaction times to systems with a stop lamp out were significantly longer than for the normal systems. When the lamp that was out was both stop and

TABLE 33. Subjective Ratings of Turn and Stop Signal Effectiveness in Each System, Operating Normally or Under the Specified Malfunctions (5=most effective, 1=least effective).

System	Malfunction	Signal	
		Turn	Stop
3.0	Normal	2.7	3.5
3.1	Left inboard stop filament out	2.6	1.6
3.2	Turn flasher on	1.2	3.5
3.3	Outboard right turn filament out	2.6	3.6
9.0	None	2.9	3.6
9.1	Left inboard stop/ turn filament out	2.5	2.4
9.2	Turn flasher on	1.4	3.1
9.3	Outboard right stop/ turn filament out	3.2	3.1
10.0	None	3.0	3.9
10.1	Right inboard stop filament out	2.7	2.4
10.2	Turn flasher on	1.7	3.6
10.3	Outboard left stop/ turn filament out	2.7	3.6
11.0	None	4.6	3.9
11.1	Right inboard stop filament out	4.6	2.1
11.2	Turn flasher on	3.6	3.9
11.3	Outboard left turn filament out	4.6	3.9

TABLE 34. Significant ($p \leq .01$) Differences Between Systems in Ratings of Stop and Turn Signals.

Signal	System(s)	Were Rated Significantly More Effective	Than System(s)
Turn	3.0, 3.1, 3.3, 11.2	"	3.2
	9.0, 9.1, 9.3, 11.2	"	9.2
	10.0, 10.1, 10.3, 11.2	"	10.2
	11.0	"	3.0, 9.0, 10.0, 11.2
	11.1	"	3.1, 9.1, 10.1, 11.2
	11.3	"	3.3, 9.3, 10.3, 11.2
Stop	3.0, 3.2, 3.3	"	3.1
	9.0, 9.2, 9.3	"	9.1
	10.0, 10.2, 10.3	"	10.1
	10.0, 11.2, 11.3	"	11.1

turn, an increase in reaction times also occurred in the turn modes. The inherent advantage of Systems 3 and 11, which have stop and turn functionally separate, is compromised by the confusion of one stop lamp on with a turn signal before it flashes. In Systems 9 and 10, two additional stop lamps were added inboard; however, one stop lamp burned out still led to significantly longer reaction times.

When a turn flasher remains in the on position, Systems 3 and 11 again have an advantage. In those systems, this malfunction did not impair performance, whereas in Systems 9 and 10 this malfunction produced significantly longer reaction times.

Under normal operations in the S→T modes, a comparison between systems shows that Systems 3.0 and 11.0 led to significantly shorter reaction times than Systems 9.0 and 10.0. These latter systems have the same disadvantage of the conventional system; that is, the turn comes on over the stop and is not detected until it cycles to "off." The advantage of Systems 3.0 and 11.0 is a functionally-separated turn signal lamp whose intensity increases when the signal is given. In the T→S mode Systems 3.0, 10.0, and 11.0 were significantly better than System 9.0. Two turn lamps flashing seemed to hinder the detection of a stop signal given later.

When comparing systems with an inboard stop/turn lamp malfunction, System 9.1 is significantly worse than Systems 10.1 and 11.1 in all modes except S→T. A significant difference between Systems 9.1 and 3.1 was evident in the stop and S→T modes. Both Systems 9 and 10 had four lamps on in the normal stop mode. The shorter reaction times and fewer errors in System 10 may be due to the higher total intensity output of the four lamps. It is interesting to note that System 11 with two stop lamps was as effective as System 10 in almost all modes and significantly more effective in the S→T mode. The errors in System 11.1 were not significantly different from those in 10.1. However, the stop signal in System 11.1 was rated as significantly more effective than the other systems, probably because it appeared not to be as readily confused with a turn signal due to the use of the amber turn lamp.

With the turn flasher in the "on" position, reaction times in System 3.2 and 11.2 were not significantly increased. System 9.2 led to significantly longer reaction times in all turn modes. In the S→T mode Systems 3.2 and 11.2 were significantly better than Systems 9.2 and 10.2, while System 11.2 was significantly better than System 3.2.

System 9.3 was significantly better than Systems 3.3 and 10.3 in all turn modes involving an outboard stop/turn filament malfunction. In the turn and T→S modes, System 9.3 was significantly better than System 11.3. In Systems 3.3, 10.3 and 11.3 a burned out turn signal lamp masked a turn signal half the time. In this case the second or redundant turn lamp in System 9.3 aided the subjects in signal detection, and is the principal advantage of the system.

The analysis of errors showed that overall, System 9 incurred the highest incidence of errors, with 10 incurring the least. The incidence of missed signal was great in Systems 3.3, 10.3, and 11.3 since the turn signal was not activated on the side with the lamp burned out. Systems 9 and 10, overall, had the highest incidence of missed signals.

These findings emphasize two points. First, redundancy can aid in the detection of a signal when lamp malfunctions occur. Second, the separation of stop lamps from combined turn/presence lamps provided an overall improvement in performance. The main disadvantage of Systems 3 and 11 was the number of errors in response to a single stop lamp. System 10, overall, was an effective system with respect to reaction times and produced fewer overall errors. However, in the S→T mode, System 10 had the same disadvantage of the conventional system where the stop masks the turn signal.

GENERAL CONCLUSIONS

When considering the results of the survey studies of rear lighting system malfunctions, which showed that multiple compartment vehicles retain marking and signaling with at least one compartment per side more frequently than those with single compartments, in the light of the system performance tests, a number of conclusions can be reached.

System 1 represents the combined function system found on U. S. vehicles with one rear lamp compartment per side. System 9 represents a concept using two signal lamp compartments per side. Both systems produced quite similar results when operating in normal condition. With an inboard stop lamp malfunction in System 9, and a stop/turn lamp malfunctioning in System 1, there was a significant reduction in the ability of both systems to allow drivers to identify the stop signal correctly. They mostly confused the stop signal with a turn signal and failed to rectify the error as shown by the high percent of stop signals missed. Thus, although the second compartment carrying the presence signal was increased in intensity in System 9, the intensity change was not detected on 35.7% of occassions. In this case lamp redundancy was not helpful.

Such redundancy was helpful in identifying the turn signal. Obviously, all turns on the side of a single burnt out turn lamp will go undetected because no signal will appear, whereas with System 9 the second, operating compartment on the turn side was flashing in these tests, and detected.

With the flasher remaining in the on position both Systems 1 and 9 provided signals that appeared similar and led to more than 40% of errors in identifying the steady-burning turn signal as a stop signal, with only about 10% of the signals being corrected and the rest missed. Thus, redundancy of lamp compartments did not alleviate this problem.

These findings suggest that the only benefit of signal lamp redundancy at night as commonly used on U. S. cars in which all compartments also provide presence marking, is to retain an effective turn signal when one compartment is not operating and the signal is flashing. In practice the latter may not always be the case, because the loss of one bulb may cause the constant load flashers that are normally employed to cease flashing when one filament is burnt out. Should that occur, then there would be essentially no operational advantage of multiple compartment signal/presence lamps as now used.[1]

With the signal filament malfunction on the outboard compartment or lamp of System 9, which lamp also provided the presence marking, the ability to detect the stop signal was retained (Table 29). This shows that signals of the currently used multiple compartment systems could be improved by placing presence lamps only in the outboard positions. In such a concept good stop signal effectiveness is retained in normal conditions and in case the outboard stop/turn filaments are not operating. Good turn signal visibility would also be obtained if the flasher continued to operate with the loss of one filament. It should be noted that this functional improvement in signaling would be at the expense of an expected increase of about 3% of multi compartment vehicles having no presence light marking on one side (Table 3).

System 10 also used lamp redundancy, by having all four lamps function as stop lamps, but only the outboard ones as turn signal lamps. This led to a better stop signal than System 9 when an inboard stop filament was not functioning, by reducing confusion between this signal and the turn signal. This finding was not expected and is difficult to explain. It should be confirmed by a further study.

While these findings suggest some benefits of hardware redundancy, it is evident that the advantages are not self-evident and less than might be supposed. Combined with the generally small differences in malfunction rates between single

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[1]Suggesting that variable load flashers should be used for vehicles with multiple bulb turn signal lamps.

and multiple compartment vehicles it would be concluded that greater overall improvements in system performance can be obtained by means of functional separation of lamps and color coding.

Systems that have only one turn signal lamp on each side will not be able to show a turn on the side of such a malfunctioning lamp. This is their major disadvantage. Stop signal performance of such systems, however, was generally good, particularly in systems where the turn lamp is amber.

Overall, if missed signals are taken as the measure of system performance of greatest importance, then it will be noted that:

a. System 1 performance is severely degraded in all three malfunction modes (the effect of "stop/turn filament out" being inferred).
b. System 3 performance is severely degraded by "stop filament out," and "turn filament out" and partly by "turn flasher on."
c. System 8 is inferred to be severely degraded by "turn filament out."
d. System 9 is severely degraded by "inboard stop/ turn filament out" and "flasher remains on."
e. System 10 is severely degraded by "flasher remains on" and "turn filament out."
f. System 11 is severely degraded by "turn filament out" and partly by "stop filament out."

Further, by placing emphasis on stop signal detectability, the overall effectiveness of the systems in normal and malfunctioning conditions appears ordered, from most effective to least effective, as follows:

(1) System 8; (2) System 11; (3) System 10;
(4) System 3; (5) System 9; (6) System 1.

It would be inferred from these conclusions that system integrity is best achieved by color coding and functional separation of presence, stop and turn lamps and that these concepts outweigh the minor benefits found in driver performance of lamp redundancy of multiple compartment, combined function (all red) rear lighting systems. The major drawback of not using redundant rear presence lamps is the expected greater incidence of loss of rear presence marking at night on one side of the vehicle. While the effect of such a malfunction upon rear-end crashes is not known, it can probably be largely mitigated by the use of rear retroreflectors providing greater than minimum required photometric effectiveness.

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