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Performance Requirements for Turn and Hazard Warning Signals

David V. Post

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Final Report

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16. Abstract

Turn and hazard warning signals were evaluated to determine appropriate flasher design parameters. Flash rate, duty cycle, start mode, color, and rear lighting system configuration were evaluated objectively in both day and night conditions. A subjective evaluation of flash rate and duty cycle was also conducted. The relationships between flash rate, duty cycle, nominal voltage maximum light output, and light contrast ratio during voltage on and off phases, were explored. Recommendations were made as to areas of turn signal and/or flasher specification that should be included in the FMVSS 108 Standard. Recommendations were also made regarding potential changes in parameters included in the current standard. Further research was recommended to evaluate the effectiveness of school bus "loading" lamps and of strobe lamps, the flasher and signal problems caused by adding campers and trailers to automotive vehicles, and the effectiveness and potential problems associated with deceleration signals.

Generalized results are contained in the summary of this report.

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SUMMARY

Turn and hazard warning signals were evaluated to determine appropriate flasher design parameters. Flash rate, duty cycle, start mode, color, and rear lighting system configuration were evaluated objectively in both day and night conditions. A subjective evaluation of flash rate and duty cycle was also conducted. These subjective data indicated that flash rates between 40-180 cpm produced subjectively "satisfactory" signals. The relationships between flash rate, duty cycle, nominal voltage maximum light output, and light contrast ratio during voltage on and off phases, were explored. Response time data generally indicated that flash rates of 20-60 cpm were inferior to flash rates of 120-180 cpm. Duty cycle was found to have little influence on response time for flash rates of 20-180 cpm. However, "on" time values under 25% or over 80% elicited long response times when paired with non-compatible flash rates.

Low "on" times i.e., 25% and 30%, were found to produce signals of reduced intensity for the first two flashes of a type 1157 bulb. High flash rates were found to decrease voltage on/voltage off light output ratios such that at short "on" times there was insufficient intensity produced in the on cycle and at long "on" times there was insufficient decay produced in the off cycle.

Recommendations were made as to areas of turn signal and/or flasher specification that should be included in the FMVSS 108 Standard. Among these areas were specification of flash rate and duty cycle for the first 5 flashes, specification of a minimum effective intensity required to apply to all flashes, and specification of a voltage on/voltage off light contrast level of 5:1.

Recommendations were also made regarding potential changes in parameters included in the current standard. Among parameter

changes recommended were allowance of flash rates of 80-180 cpm and duty cycles of 25 to 85% "on" times when these parameters are combined in such a way that they can produce a flashing signal capable of producing acceptable intensities and response times.

Further research was recommended to test school bus "loading" lamp systems for compliance with the SAE J887 provision regarding "full brightness." Alternatively, the language in SAE J887 could be modified in FMVSS 108 to require some other specification for the "on" period.

Research should also be conducted on the effectiveness of strobe lamps as flashing signals for school buses, turn signals, hazard warning signals, and emergency vehicles.

Also, the magnitudes of the problems caused by adding additional electrical load to fixed load flashers should be determined. The popular use of rental trailers, add-on campers, and recreational trailers for transporting boats, snowmobiles, motorcycles, and ATV's has made this a serious problem.

Flashing deceleration signals may be designed to operate in various manners. Experimental work is required to evaluate various operational dimensions. Among important considerations are the following: incandescence vs strobe, intensity (or levels thereof), flash rate (continuously variable or number and specification of levels thereof), deceleration levels for activation (or continuously variable), location (combined or separated from other functions), color, and confounding effects with turn or pumped brake signals.

INTRODUCTION

It is obviously very difficult to attempt to establish the extent to which turn signal lamps and hazard warning lamps, in proper operating condition, influence highway safety. It will be even more difficult to attempt to assess the role of malfunctions in these types of signals or changes in their operating characteristics, such as the flash rate or the "on-off" ratio. However, a recent analysis of rear-end collision data (Mortimer and Post, 1972) did show that such collisions involved a turning vehicle quite frequently. The authors concluded that the frequency of rear-end crashes involving turning vehicles appeared to be greater than would be expected based on the estimated proportion of vehicles turning compared to those going straight. However, it should be understood that the exposure of turning vehicles compared to those going straight is not known. Thus, the analysis showed that turning vehicles may be overinvolved in being struck in the rear. At the same time, it must also be noted that it was not known to the authors if the driver of the struck vehicle had used the turn signal indicator or whether it was functioning. Other data (Mortimer, Domas and Moore, 1974) showed that, in Ann Arbor, about 12% of drivers making a left turn and 23% of drivers making a right turn did not give a signal. Using these estimates, which are somewhat higher than have been reported elsewhere (Zoltan, 1963), it could be suggested that the same proportion of drivers did not signal of those which were struck in the rear.

The Mortimer and Post analysis (1972) also showed the relatively high involvement in injury producing rear-end collisions of vehicles that were parked and struck from the rear. In some of these instances, vehicles which were standing on high speed roads were struck in the rear. Unfortunately, the reports of these kinds of accidents did not provide any information as to whether or not hazard warning flashers were in use.

Turn signals are also used for indicating lane changing. While lane changing maneuvers appear to account for only a small proportion of collisions (Mortimer and Vandermey, 1971) it is possible that an appropriate signal could aid in reducing such crashes. Again, however, as with turn or hazard warning signals, these must be activated by the driver and although there have been no data reported recently concerning the frequency with which drivers signal lane changing, common observation indicates that this behavior does not occur as often as it should.

In addition to insufficient use of turn and hazard warning signals by drivers, the effectiveness of such signals is also reduced by malfunctions in various components associated with these signals. There are numerous types of failures which occur in the signal circuitry, and these have not been adequately described by reports concerned with motor vehicle inspection. In order to overcome, at least partly, this deficiency in information concerning the specific malfunctions associated with vehicle signal systems, HSRI conducted a detailed inspection on about 500 vehicles with the cooperation of their drivers (Mortimer, Domas and Moore, 1974). These data were augmented by unobtrusive observations made on about 8000 passenger cars and light trucks. The report describes the findings of specific malfunctions associated with the vehicle lighting and signaling components, including those which affect turn signal and hazard warning signal operation. The findings indicated that turn signal and hazard warning signal system component failures were somewhat related to the type of rear signal system used on the vehicle, such as whether lamp redundancy existed or lamps were separated by function.

As a means of providing some insight into the relevance for safety of failures in the turn and stop signal circuitry, some driving simulator studies were carried out in which these effects were evaluated for different rear lighting and signaling displays.

The findings of those studies have some implication for the objectives of the present study, and indicated, for example, that there may be some benefits to be derived from the use of variable-load flasher units, on those vehicles, at least, which use redundant lamps. The findings also suggested that there may be some benefits from the use of flashers which start in the "off" cycle (Mortimer, Domas and Moore, 1974).

The present FMVSS-108 Standards affecting turn and hazard warning signal flasher operation refer to SAE standard J590b and J945, which in turn were based largely on evaluations carried out by the Vehicle Lighting Committee of the Motor Vehicle Manufacturers Association, of the U.S. Those studies were entirely subjective in nature, but did consider a large number of variables. In this study, further consideration was given to the determination of bounds on the operating characteristics of flashing signals by means of subjective and objective measures. Additional variables, such as thermal inertia of the filaments of the lamps and various rear signaling displays, were evaluated.

1. FAILURE RATE OF FLASHING SIGNAL SYSTEM ELEMENTS

A study by Mortimer, Domas, and Moore (1974) surveyed automobile rear lighting system malfunctions. As part of that study, 521 vehicles were closely examined to determine the functioning of all rear presence and signaling lamps. The survey was conducted at Ann Arbor area gas stations, a drive-in window of a local bank, and in the HSRI employee parking lot. Table 1.1 shows the percent of vehicles with various rear signal lamp malfunctions. The data specifically relevant to turn signals are outlined. Hazard warning system data are not available, but the only additional malfunctions would come from defective hazard warning switches and flashers.

In vehicles where one lamp had several signal functions, 2.2% had the lamp on one side out entirely, and 1.7% had the lamps on both sides out entirely. When multiple lamps were used with combined signal functions 1.4% of the vehicles had one side entirely out and the other side partially out. In vehicles having a specific turn signal lamp which served no other function no bulb failures were found.

Turn signals on at least one side were on steady 0.9% for single lamps with combined signal functions, 2.7% for multiple lamps with combined signal functions, and 1.5% where the turn signal lamp served no other function. Turn signals on at least one side were flashing improperly (usually too short an on time or too high a flash rate) 2.6% for single lamps with combined functions, 4.1% for multiple lamps with combined functions, and 2.9% where the turn signal lamp served no other function. No turn signal switch or other circuitry failure was found where the turn signal lamp served no other function. However, failures of 1.7 and 1.8% were found for lamps with combined signal functions. Malfunctions increased with vehicle mileage.

In summary, malfunctions of 1 to 4 percent were found with improper flashing the greatest malfunction. Malfunctions were correlated with vehicle mileage.

TABLE 1.1. Percent of Vehicles with Various Rear Signal Lamp Malfunctions: Results of Cooperative Survey.

	Lamp Functions															
	Vehicles with Combined Signal Functions								Vehicles with Separated Signal Functions (All Single Compartment)							
Malfunction	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			

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[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.

2. EFFECT OF FLASHER MALFUNCTIONS ON VEHICLE SAFETY

The question of whether a defective light flasher is an accident causation factor can be answered to a certain extent by empirical evidence. Flasher failures can normally be expected to have an influence only in multiple vehicle accidents where one or both vehicles would have occasion to use their flashers, and flasher failure could be a causation factor. For the purposes of this report these accidents are taken to be those where one vehicle is turning (left or right) and the other vehicle is going straight (in the same direction or opposite direction to the turning vehicle). The vehicle whose flasher failure could be a factor in this type of accident would be the turning vehicle. On the other hand, those accidents in which both vehicles are traveling straight (in the same or opposite direction) are considered to be uninfluenced by the turn signal flasher failure of either vehicle.

The desired analysis would have to first assume that there are no confounding factors that affect the relationship between flasher operating status and whether a vehicle is struck in a flasher-affecting accident or a non flasher-affecting accident. Then, using an accident file in which flasher operating status is coded for the vehicles, determine the percentages of vehicles with failed flashers in flasher-affecting accident types, and in non-flasher affecting accident types. The test of the hypothesis that flasher operating status is independent of accident type is made by determining if vehicles with failed flashers are overrepresented in flasher-affecting accidents when compared with non flasher-affecting accidents. If not, then it must be concluded that flasher status is independent of the type of accident in which the vehicle is struck. Thus, flasher failure would not be an accident causing factor, given the assumption. However, if there is an overrepresentation, then it must be concluded that flasher failures do affect accidents, given the assumptions.

Unfortunately, such an analysis is impossible. There is no accident file in which flasher operating status is coded. Our alternative approach albeit, not as satisfactory, is to obtain a surrogate variable for flasher failure that is coded in an accident file. This surrogate variable is taken to be vehicle age.

The state of Michigan uses a checklane system of vehicle inspection. This system involves the establishment of temporary checklanes along the roads of Michigan. Vehicles are pulled over at random and given an inspection which includes a determination of the operation of the front and rear turn signal lamps. The results of these inspections are recorded in a file maintained by HSRI. Evidence from this file, as presented in Table 2.1 and Figure 2.1, indicates a positive correlation between vehicle age and the probability of lighting system failure. While the flasher is a different system, its failure would be recorded in this file as a failure of the lighting system, and therefore the assumption of a positive correlation between vehicle age and flasher failure is probably correct. Other evidence derived from surveys (Mortimer et.al., 1974) has also shown a relationship between number of rear lighting system malfunctions and vehicle age.

The use of the age of the vehicle in place of flasher status is not completely satisfactory because if there is indeed a relationship between flasher failures and accident type, the empirical evidence of this relationship would be weakened by this substitution of variables. Some older vehicles may not have flasher failures, while some new ones may, even though the probability of failure is greater for older cars. Furthermore, the assumption must be made that there are no factors confounding the vehicle age/accident relationship, an assumption that may not be as acceptable as the previous one.

Given that the vehicle age/accident assumption is made, the rest of the analysis is straightforward. Three accident files were consulted: Bexar County, Texas (San Antonio); Washtenaw County, Michigan (Ann Arbor); and Oakland County, Michigan (Pontiac).[1] Because of the weakening of the evidence for flasher involvement, it is not possible to state that in any one file there is a significant difference in the age distribution of struck vehicles in flasher-affecting versus non flasher-affecting accidents. However

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[1] See note on page 14 for a description of these accident files.

TABLE 2.1 Probability of Lighting System Failure With Vehicle Age.

	Age (years)										
	0	1	2	3	4	5	6	7	8	9	10
Prob.	.018	0.024	0.052	0.066	0.088	0.128	0.151	0.249	0.268	0.247	0.280
N	1082	952	786	799	740	569	457	414	295	178	168

TABLE 2,2 Percent Distributions of the Age of Vehicles Struck While Turning Versus Going Straight.

	Age (years)										
	0	1	2	3	4	5	6	7	8	9	
Turn	12.2	13.1	11.4	11.1	10.2	8.9	8.2	7.2	5.5	12.2	100.0 N=15708
Straight	14.3	14.5	12.8	11.3	10.9	8.6	7.9	5.8	5.0	9.0	100.0 N=17930

$X^2_{(9)}=354.5$ Prob.[age is independent of turn vs. straight accident] $\leq$ 0.001

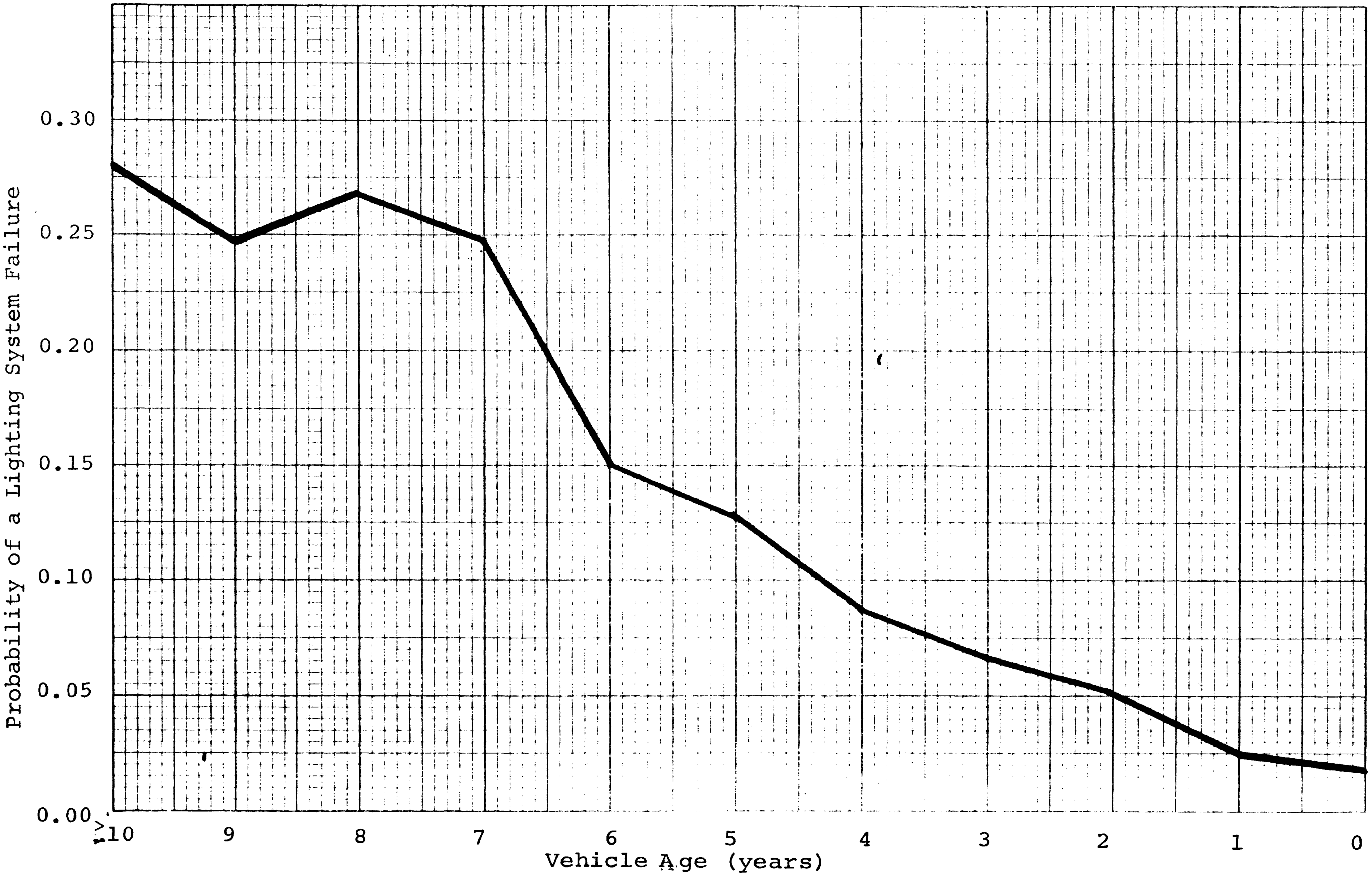

Figure 2.1 Probability of a Lighting System Failure with Age of Vehicle.

when all files are considered together, the difference is very significant. The evidence is presented in Table 2.2 and Figure 2.2.

The Chi-Square in Table 2.2 indicates that vehicle age was not independent of whether the vehicle was struck while turning or proceeding straight. Vehicles struck while turning were generally older than vehicles struck while going straight. Therefore, since older vehicles are more likely to have failed flashers, the finding that older vehicles are more likely to be struck while making turning maneuvers provides support for the hypothesis that failed flashers are a significant cause of turning accidents. This conclusion rests on the assumption that there is no confounding factor affecting the vehicle age/accident relationship; and that there is a positive correlation between vehicle age and flasher operating status.

Certain arguments can be made against these assumptions. For example, one could argue that older cars have a higher proportion of worn out or bald tires, and these tires can cause skidding when turning, thus causing accidents in this situation. In the final analysis it must be stated that the strength of the evidence supporting the conclusion that flashers are an accident causing factor is only as strong as one's belief in the underlying assumptions, but in any case the evidence presented is at least not inconsistent with that conclusion.

Another way to assess the effect of flasher failure upon accidents is to investigate accidents to determine their causal factors. Among the studies which have been done are a very comprehensive study conducted by the Institute for Research in Public Safety (IRPS, 1973) and a similar study conducted by Association of Third Party, Accident and Motor Vehicle Insurers (1973). The IRPS (1973) data show that a multi-disciplinary accident investigation of Monroe County, Indiana accidents revealed that "inoperable turn signals" were causally related

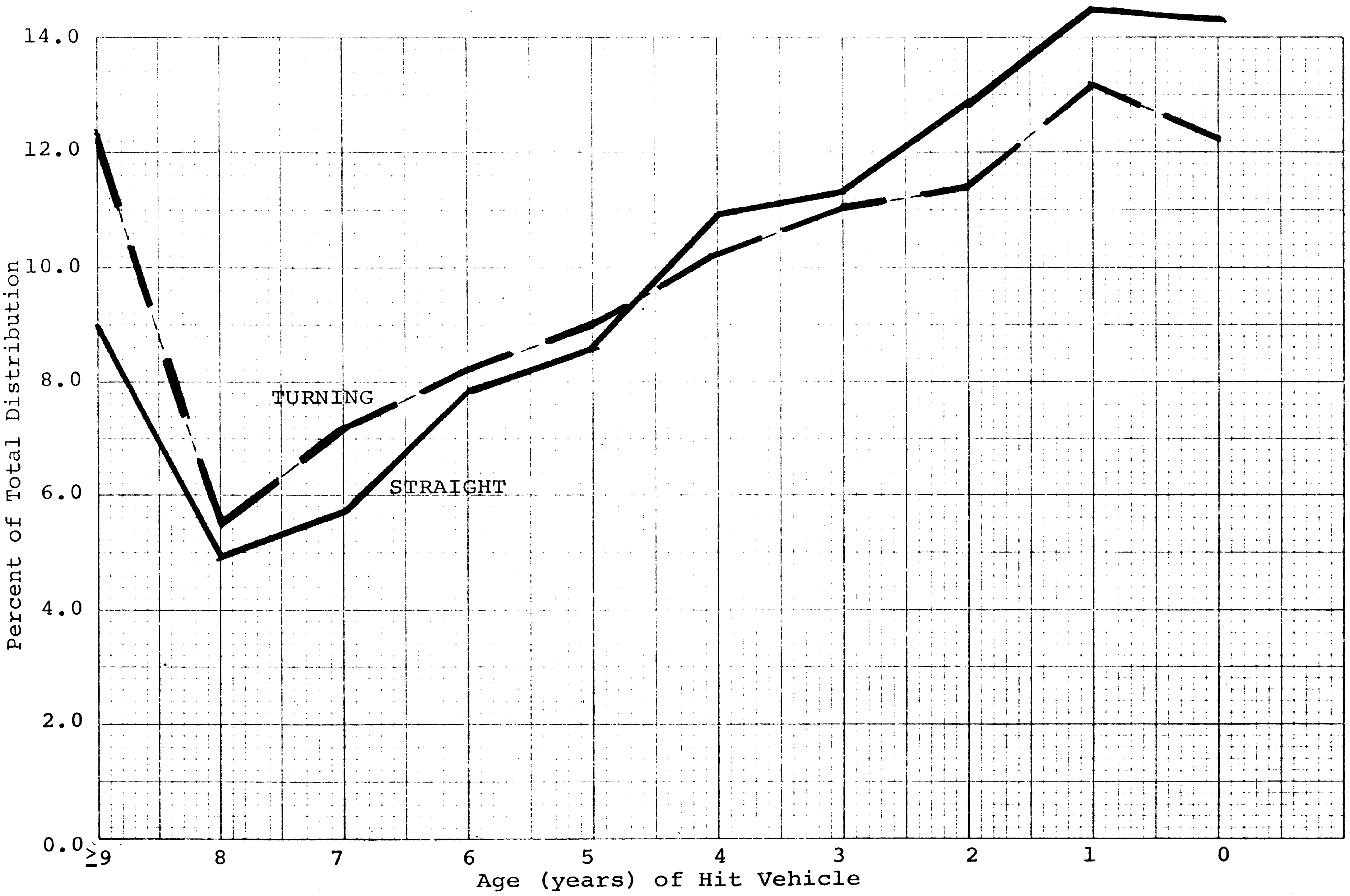

Figure 2.2 Age Distributions of Vehicles Hit while Turning and going Straight.

to an accident on a certain or probable basis .5% of the time (as determined by both the on-site and multi-disciplinary investigation teams during Phases II and III). It should be noted that this figure apparently does not include improperly operating flashers (i.e., flashers whose performance is outside the specified boundaries).

Since flasher failure is only a partial contributor to the "inoperable turn signal" category it is unknown what proportion of accidents is directly attributable to flasher failure versus bulb failure and grounding failure. Data of this specific nature are, however, included in the German study (1973).

Experts hired by insurers investigated accidents involving serious physical injury (including death) in great detail for a time period of up to nine months following an accident. These experts were asked to note technical defects of the motor vehicle "only if it could be taken for granted that the respective factor at least had contributed to the causes of the accident." Of 63,084 accidents involving serious injury investigated, 5.7% (3,608) were found to involve, "turns, U-turns, etc." Interestingly, this type of accident was more prevalent than rear-end collisions which accounted for 3.6% (2,298) of all accidents. Of the turning accidents, 1.8% (64) were found to involve vehicle defects. Thus, .1% of all accidents were turning accidents involving defects. The blinker was responsible for 48.4% (31) of the turning accident defect total found. Lamp failures were found in only 12.5% (8) of the turning accidents involving defects.

In lieu of such specific U.S. accident investigation data on flashers, a cost benefits approximation can be made, but only on the assumption that the German accident-failure data is similar to that which would be obtained in the United States, the most critical assumption being that flashers have failed in 48% of all turning accidents which involve defects. However, on the basis of these assumptions one could determine the cost of all accidents and multiply this societal cost times .049 which is the proportion of all accidents which involved struck turning vehicles with defective flashers which were considered to have at least contributed to the cause of the accident.

Upgrading of MVSS-108 in terms of psychophysical performance should have a societal payoff, but it needs to be recognized that a cost-beneficial change may be accomplished in terms of increased traffic flow, thus decreasing the cost of expansion of the traffic system. Of course, the number of accidents may be reduced in addition to or instead of the potential increased traffic flow. To reduce the number of flasher-related accidents may depend more upon reducing malfunctions than improving psychophysical performance. The relationship between flasher malfunctions and driver performance measures is reported by Mortimer, Domas and Moore (1974).

Note: The accident files used in the analysis in this section were the 1972 Bexar County, Texas (San Antonio) file which contained 32,329 cases, the 1970-1973 Washtenaw County, Michigan (Ann Arbor) file which contained 32,272 cases, and the 1972 Oakland County, Michigan (Pontiac) file which contained 34,262 cases.

3. FLASHER LIFE, DESIGN AND COST

Malfunctions of the flasher itself are considered to be primarily a function of life cycle as opposed to "infant mortality." Currently, the average life cycle is influenced by the "design life" that manufacturers use in order to produce a design that will comply with FMVSS 108 and SAE J590b and J945. Major flasher manufacturers were contacted and asked to supply information about their cost and design life; three manufacturers provided extensive data. Thermal flashers of fixed load design with automatic outage sensing were cited as costing $0.30-0.60 per flasher (presumably, manufacturered in high volume associated with passenger car usage). Flashers of electro-mechanical design were cited as costing $1.50-2.00 presently, but in high volume production costs were estimated to average $1.00 each for a flasher that would serve as both a turn signal and hazard warning flasher. Additional cost to sense bulb outage would probably be encountered in the order of $.30 each. Thus, the estimated cost for volume production and outage sensing is $1.30. Although this is more than double the current cost of thermal units it can serve as both turn signal and hazard warning flasher. Therefore, the current cost of approximately $1.00 for two fixed load flashers is somewhat less than would be required if one variable load with outage sensing were used. One manufacturer with experience in solid state design flashers estimated present costs of $5.00-20.00 even though they were presently not involved in the manufacture of these devices. It was indicated that high temperature, high load switching and transient voltage spikes relatively easily affect the operation of solid-state flasher units.

All the manufacturers who replied agreed that a broadening of flasher specifications to 40-100 cpm and 20-80% "on" time would have no dramatic increase (if any) in the life of their flashers.

One major flasher supplier and an automobile manufacturer have cited figures in the 10-15 flasher cycles/mile range as representative (5-10 years ago) of suburban/highway usage at the low end of the range and metropolitan usage at the higher values. The lane change feature and increased traffic in recent years should have brought about an increase in usage, such that, the current usage rate could be in the region of 15-20 flasher cycles/mile. Using 100,000 miles as representing the "life" of an automobile it is evident that 1,500,000 to 2,000,000 flasher cycles would be required. Assuming 12,000 miles per year is typical automobile usage, then 180,000 to 240,000 flashes per year should represent average turn signal flasher usage. Assuming an average cycle rate of 90 flashes/minute, therefore, a flasher only capable of 200 hours of intermittent usage would have a vehicle life of approximately 4.5-6.0 years. It can be estimated that 33.3-44.4 hours of intermittent usage occurs yearly. However, a fair number of vehicles are driven up to twice the estimated typical mileage. Thus, flasher failures would probably occur within 2.25 to 3 years, if flashers were only designed to meet the MVSS 108 standard. However, as flashers must exceed the standard specifications, they are normally designed to last considerably longer than the standard specification. The average life of flashers meeting MVSS 108 needs to be determined, as manufacturers cite average life figures of 2-20 times (or more) the standard life.

Another manufacturer estimated the hours of usage required by measuring flasher cycles on six vehicles over a 15-month period and calculating the number of hours of usage that would be required for 100,000 miles. The different vehicles and drivers produced values from under 200 to 400 hours of intermittent use. Except for one vehicle-driver which would require an estimated 400 hours of intermittent use to cover 100,000 miles, the other vehicle-driver combinations all would have required under an estimated 300 hours. The basic data for the estimates were collected some time ago, so that, it is quite possible that increased traffic density and the turn signal lane change feature have resulted in increased turn signal usage. Therefore, 300 hours of automobile flasher usage may be more common now and perhaps 500 hours is representative of the upper limit (this is 20% above the old data upper limit). Assuming that a typical vehicle travels 12,000 miles per year then 36-60 hours of intermittent use should occur yearly.

It is of considerable importance that it be determined whether continuous use or intermittent use is the more rigorous test. For example, one manufacturer is of the opinion that his electro-mechanical flasher far exceeds the life requirement of a typical car because the flashers have a life greater than 500 hours of continuous operation. While this is five times the life required under SAE J590b, it may not extend the life of a flasher in use to that great a degree if intermittent use is more rigorous than continuous use. Assuming that 500 hours of continuous usage is equivalent to 1000 hours of intermittent usage leads one to conclude that this flasher could extend flasher life to beyond the life of the vehicle.

4. RISE- AND DECAY-TIME MEASUREMENT OF BULBS

In order to evaluate the light output characteristics of flashing bulbs, it was necessary to select an appropriate range of bulbs on which to conduct measurements. To do this, lamp catalogs[1] were searched for lamps which are used for signaling on motor vehicles with 12 volt electrical systems.

Table 4.1 is a summary of such non-sealed-beam bulbs. Those half-dozen bulbs of this type which find most common use have an underlined bulb number. The S-8 bulb type is the standard lens size. The RP-11 is the larger size, which is too large to fit into most housings and is not available in a dual-filament configuration.

The 1034 group constitutes the first generation of these bulbs. The 1157 group was originally developed for heavy-duty use, but has now become almost standard equipment on many, if not most, new vehicles. The 198 group is the new heavy-duty, "fleet-quality" line.

Table 4.2 is a summary of sealed beam bulbs which are either designed specifically for signaling purposes (as indicated in the lamp catalogs), capable of signal use by virtue of lens filter color, or actually used as signal bulbs. Note that 4415's (of the PAR 36 group) have been included, even though their apparent use is as "fog lamps." They have been included because they are actually in use for signaling purposes. Similarly, the 4636 (of the PAR 46 group) has been included, even though no catalog indication is given that it might be useful as a signal bulb, because indeed this is the bulb used as standard equipment in certain lines of school bus loading lamps.

In actual practice, almost any sealed-beam bulb could be used as a signal lamp, with the appropriate color filter and

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[1] General Electric, Miniature Lamp Catalog, 3-6253R, revised 1-74, and General Electric, Sealed Beam Lamp Catalog, 3-6251R, revised 1-74.

TABLE 4.1. Non-Sealed-Beam Bulbs Which are Used for Signaling.

	page #	bulb #	volts	amps	MSCP	base	life	other, similar bulbs
S-8 BULBS	20-41	1034	12.8	1.80	32	DC Ind	200	1034 A (20-42):envelope has outside translucent amber coating
			14.0	.59	3	""	5000	
								1073 (20-45): SC Bay contact, has only signal fil.
								1076 (20-46): as 1073, but with DC Bay
								1165 (20-47): as 1073, but with brass contact
	20-48	1157	12.8	2.10	32	DC Ind	1200	1157 A (20-49):envelope has outside translucent amber coating
			14.0	.59	3	""	5000	1157 NA(22-1):envelope has "natural amber" coating
								2242 (20-50): as 1157, but wire terminals
								2144 (22-3): as 2242, has only signal fil.
								1156 (22-4): as 1157, has only signal fil.
	22-4a	198	12.8	2.25	32	DC Ind	1200	199 (22-4b): as 198, has only signal fil.
			14.0	.59	3	""	5000	
	20-34	1016	12.8	1.34	21	DC Ind	300	1176 (20-35): as 1016, except DC Bay
			14.0	.59	6	""	1500	1141 (20-37): as 1016, except 1.44 Amp, sig fil. o.
								1142 (20-39): as 1141, except DC Bay
	20-28	1295	12.5	3.00	50	SC Bay	300	
	20-29	93	12.8	1.04	15	SC Bay	700	94 (20-30): as 93, except DC Bay
RP-11 BULBS	16-30	1143	12.5	1.98	32	SC Bay	400	1144 (16-31): as 1143, except DC Bay
	16-32	1195	12.5	3.00	50	SC Bay	300	1196 (16-33): as 1195, except DC Bay
								1293 (16-34): as 1195, different fil. support

Page #: Refers to page and item number in GE Miniature Lamp Catalog 3-6253R (revised 1/74).
Bulb #: Industry cross referrence. A few companies will use their own number, but all will cross-reference to these standards.
MSCP: Mean Spherical Candlepower.
Base: DC Ind = Double Contact Bayonet Base, indexed.
DC Bay = Double Contact Bayonet Base, non-indexed.
SC Bay = Single Contact Bayonet Base (non-indexed).
Life: Rated average life, in hours (not subject to vibration).

S-8 Bulbs use conventional lenses. RP-11 Bulbs use a wider lens envelope.

TABLE 4.2. Sealed-Beam Bulbs Which are or Can be Used for Signaling.

page #	bulb #	size	volts	watts	beam CP	color	% transm	spread		shield	life	other
								H	V			
7-27	4414	36	12.8	18	1500	-	100	50	25	none	300	
-28	4414-A	"	"	"	450	amber	30	"	"	"	"	
-29	4414-R	"	"	"	275	red	18	"	"	"	"	
-30	4415	"	"	35	9000	-	100	40	5	cap	300	{(fog lamp)
-31	4415-A	"	"	"	7000	amber	78	"	"	"	"	
-32	* 4416	"	"	30	35000	-	100	11	4.5	none	300	
-33	* 4416-A	"	"	"	26000	amber	74	"	"	"	"	
-34	* 4416-B	"	"	"	?	blue	-	"	"	"	"	
-35	* 4416-R	"	"	"	6000	red	17	"	"	"	"	
-38	4425-R	"	{"	50	500	red	-	50	25	none	200	"C.I.M. Tail-Stop, Red"
			"	18	100	"	-	"	"	"	NG	
-43	4464	"	"	60	50000	-	100	11	5	none	300*	"Signal"
-45	4464-R	"	"	"	7500	red	15	"	"	"	" *	"Signal, Red"
8-47	4001	46	"	37.5	29000	-	100	26	5	none	300*	convention Hi Beam
-48	4001-A	"	"	"	21000	amber	72	"	"	"	"	
-49	4001-R	"	"	"	5000	red	17	"	"	"	"	
9- 1	4000	"	"	60	24300	-	100	34	7	MF	320	convention Lo Beam
				37.5	11600	-	100	"	"	none	200	convention Hi Beam
- 3	4000-R	"	"	60	3000	red	12	"	"	MF	320	
				37.5	1600	"	12	"	"	none	200	
-10	4412	"	"	35	11000	-	100	40	5		300	(fog lamp)
-11	4412-A	"	"	"	8800	amber	80	"	"		"	"
-12	4413	"	"	"	1100	-	100	80	20	none	300	(flood lamp)
-13	4413-R	"	"	"	200	red	18	"	"	"	"	
-19	4434-A	"	"	40	1000	amber	?	55	25	"	100	
-21	* 4436	"	"	35	60000	-	100	10	4	none	300	
-21a	* 4436-R	"	"	"	9000	red	15	"	"	"	"	
-27	4633-R	"	14.0	80	700	red	-	?	?	"	"	(school bus lamps)
-27a	4636	"	14.0	"	?	-	-	?	?	"	"	"
10-21	4433-A	56	12.8	{40	?	amber	-	-	-	none	200	(school bus lamps)
				"	?	"	-	-	-	"	"	
-22	4433-R	"	"	{"	?	red	-	-	-	"	"	"
				"	?	"	-	-	-	"	"	

Page #: Refers to page and item number in GE Sealed Beam Lamp Catalog 3-6251 R **(revised 1/74).**
Bulb #: Industry cross reference.
Size: PAR 36 = 4.5" diameter. PAR 46 = 5.75" diameter (size of standard "quad" headlamps).
PAR 56 = 7" diameter (size of standard large headlamps)
Beam CP: "Approximate Initial Maximum Candlepower"
Color: GE's designation.
% Transmisivity: Derived, where values for unfiltered bulb are known. Amber ranges from 30-80%, red from 12-18%.
Spread: "Approximate Total Spread to 10% (of) Maximum Candlepower."
Life: In hours, at the design voltage (stated).

*These lamps are used primarily in revolving beacon installations. Thus, they are not normally operated in an "on"/"off" fashion.

perhaps with addition of a diffusion screen. Note that even conventional headlamp bulbs, such as 4000 and 4001, are color-coated and used for signaling purposes.

For non-sealed beam bulbs, three basic bulbs (the 1034, 1157, and 198 groups) as identified above and in Table 4.1 incorporate the basic performance characteristics for all such bulbs in general use.

For sealed-beam bulbs, on the other hand, no such simple grouping is immediately possible. However, a more general grouping can be accomplished. Within the PAR 36 and 46 groups, many of the bulbs can be characterized as having a 30 or 35 watt coiled filament. Within each size group, these bulbs are probably all basically the same, varying only in fluting design (diffusion) and color filter. The unfluted, uncolored, and unshielded representatives of these two size groups would be bulbs 4416 (for PAR 36) and 4436 (for PAR 46). The others with the similar filaments could all be thought of as variants of these two basic styles.

From Tables 4.1 and 4.2 eight pairs of lamps were selected to represent the lamps in common usage and provide a range of filament wattage and bulb size. From Table 4.1 the 1034, 1157, and 198 lamps were selected for evaluation of rise-and decay-times because of their common use in turn signal lamp housings. They represent a range of power consumption of 23, 27, and 29 watts. From Table 4.2 the 4414, 4416, 4436, 4002[1], and 4636 lamps were selected for testing to provide an adequate range of power consumption and bulb size. The power consumption figures for these bulbs are 18, 30, 35, 37.5, and 80 watts (using two 40 watt filaments), respectively.

The eight pairs of lamps of various wattages and lamp sizes were obtained and burned in for several hours. Each lamp was then mounted in a lamp housing. A Prichard Spectra Photometer was used

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[1] A 4002 high beam was used in place of the 4000 bulb listed in Table 4.2.

along with a Brush Chart Recorder to produce traces of light output versus voltage. Each trace was set up so that maximum steady-state light output would produce a full-scale deflection while the voltage off condition would trace along the bottom axis. Thus a full-scale reading represents 100% of the maximum light output of a lamp and a reading on the lower axis represents 0% or no lamp output. Two bulbs having the same lamp number were measured for each of the eight lamp types and the mean of the results were calculated. All lamps were measured with the flasher operating in a normally closed (start-on) fashion. In addition, all lamps were operated at 12.8 volts. The maxima and minima light output obtained in the 1st, 3rd, and 6th flash for various duty cycles and flash rates is shown in tables comprising Appendix A.

The data in those tables indicate that not all lamps respond to flash rate and duty cycle combinations in the same way. While the 1157, 1034, and 198 bulbs responded in similar fashion, the 4002 and 4636 lamps have the greatest thermal inertia. This can be readily ascertained by looking at the 180 cpm data (Appendix A.5) as these lamps consistently have the lowest light output while the votage is on and have the highest light output when the voltage is off. Both of these lamps are PAR 46 5.75 inch bulbs. The poorer performance came from the 37.5 4002 lamp even though the 4636 lamp was run below its nominal voltage (14.0V.). The extremely slow rise time of the 4002 lamp appears to be due to two factors. First, the high wattage of the energized filament leads to increased rise times as evidenced by data derived from Tables 3.1, 3.2, and A.5:

First Flash Maximum Relative Light Output	Major Energized Filament Wattage
96-100	18-27
90-93	29-35
58-85	37.5-40

Although closer inspection will reveal a very non-linear relationship, there is evidence of a trend which associates low maximum relative light output with increased wattage. Secondly, there is the confounding factor of heat absorption by any unenergized filament which is present. It was discovered that when the 8 watt tail filament of an 1157 bulb was constantly energized, the 23 watt signal filament of the 1157 bulb had a quicker rise-time than when the 8 watt filament was unenergized. Whether a filament is radiating or absorpting heat has an effect on the rise-time of the other filament in a dual filament bulb. Thus, the rise-time of the 4002 hi beam filament is extremely slow due to the presence of the unenergized 50 watt low beam filament and the high wattage (37.5 watts) of the high beam filament. The faster rise-time of the 4636 bulb with 40 watt filaments is due to the fact that it does not have an unenergized filament.

Using the mean data from a pair of 1157 bulbs, Figure 4.1 exhibits the achievement of maximum light output for a particular flash rate and duty cycle combination by the 3rd flash. The data recorded for the 6th flash for all the lamps, flash rates, and duty cycles tested was nearly identical to that obtained on the 3rd flash. The 1st flash, however, generally produced significantly less maximum light output and occasionally this also lead to less voltage off light output compared to data obtained for the 3rd or subsequent flash. This introduces the problem of selecting a flash rate x duty cycle x lamp combination which will achieve a great enough maximum light output on the 1st flash and a low enough minimum light output (voltage off) on subsequent flashes.

In some instances this problem is so severe that certain lamps do not even maintain a five to one ratio between their voltage "on" light output and their voltage "off" light output. While this effect shows up at lower cycle rates with the high thermal inertia lamps (i.e., at 120 cpm for a 4002 lamp), eventually even lamps with as fast a response as the 1157 show the effect (i.e., at 180 cpm). As SAE Stds, J585c, J586b, and J588d all specify that at some

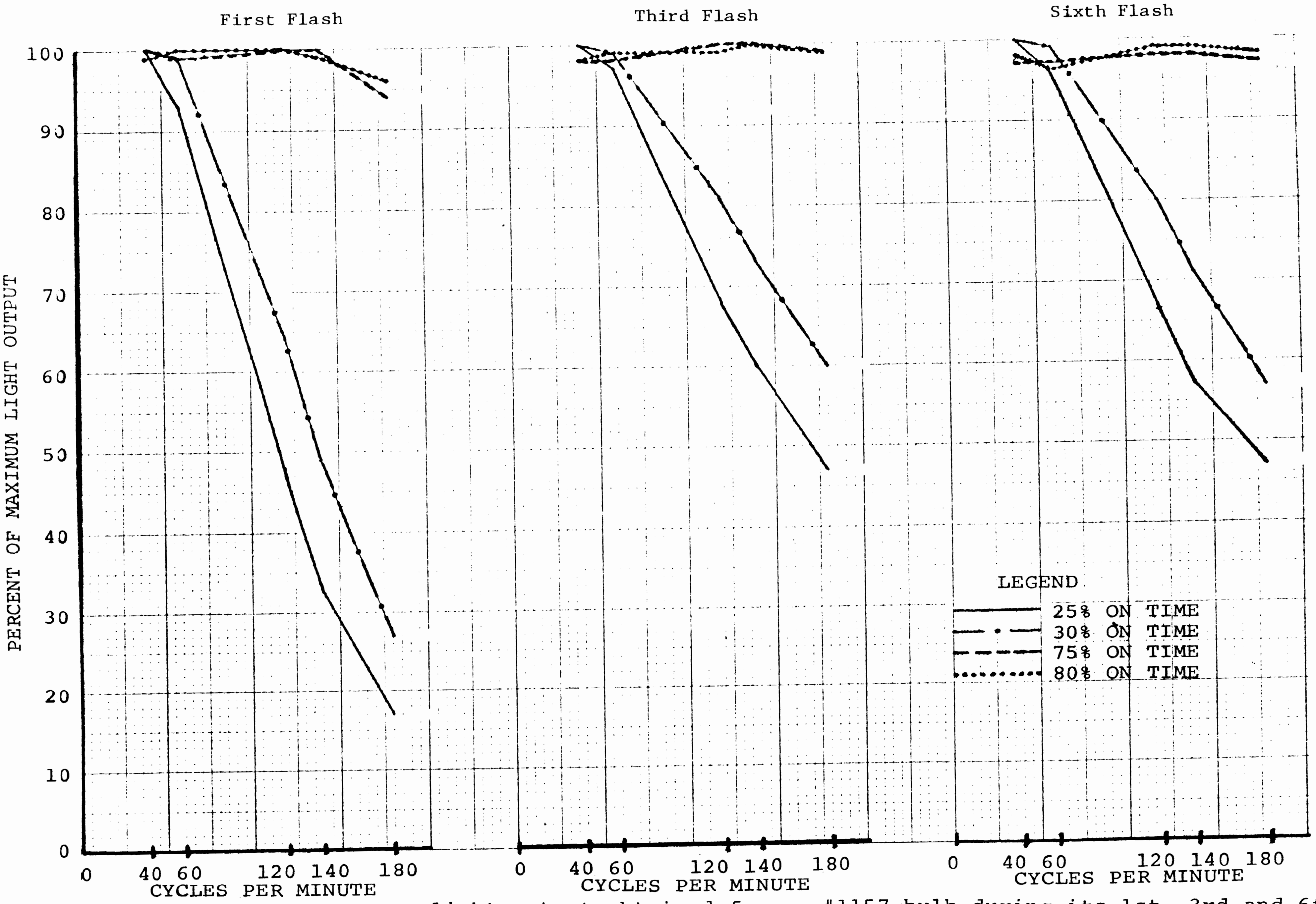

Figure 4.1. Percent of maximum light output obtained from a #1157 bulb during its 1st, 3rd and 6th flash with duty cycle on-times of 25, 30, 75 and 80 percent and at flash rates of 40-180 cycles per minute.

points near the H-V a minimum five to one candlepower ratio between the signal and taillamp is required to provide adequate contrast, it is logical to insist that the signal lamp have at least a five to one contrast ratio between its voltage "on" and voltage "off" phases. Otherwise, the signal would not provide an adequate contrast ratio between its "on" and "off" voltage phases. Flash Rate x Duty Cycle x Lamp combinations which do not meet the 5:1 ratio requirement are indicated in Tables A.1-A.5 by a minus sign following the "low" light output value. The ratio may be a determinant in selecting an upper bound for flash rate as both the 1157 and 198 bulb types were starting to fail this criterion at 180 cycles per minute.

Figure 4.2 exhibits the effect of flash duration in both the "on" and "off" cycles upon light output of a No. 1157 lamp. These data were derived from Tables A.1-A.5 by converting duty cycles and flash rates to lamp "on" and "off" durations. Fast flash rates and short duty cycles combine to produce short durations which lead to the problems of low intensity lamp output (i.e. lamp output falls off rapidly below .200 sec "on" duration) and low contrast ratio (i.e. lamp "off" output remains increasingly high below .150 sec "off" duration).

Similar light output problems would arise in specifying effective parameters for school bus red signal lamps. If cycle rates as fast as 180 cpm were permitted and the "on" period of the flasher was long enough to permit the bulb filament to come up to full brightness, as per SAE Standard J887, the "off" period light output might not allow an adequate contrast ratio. For this reason, analytical research of the data which has been collected on lamps which are used as school bus lamps, should be undertaken to determine from light output and contrast curves, the limits of "on" and "off" durations which are feasible to produce a good flash signal. This data could then be analyzed to provide information on feasible flash rates and duty cycles for school bus lamps.

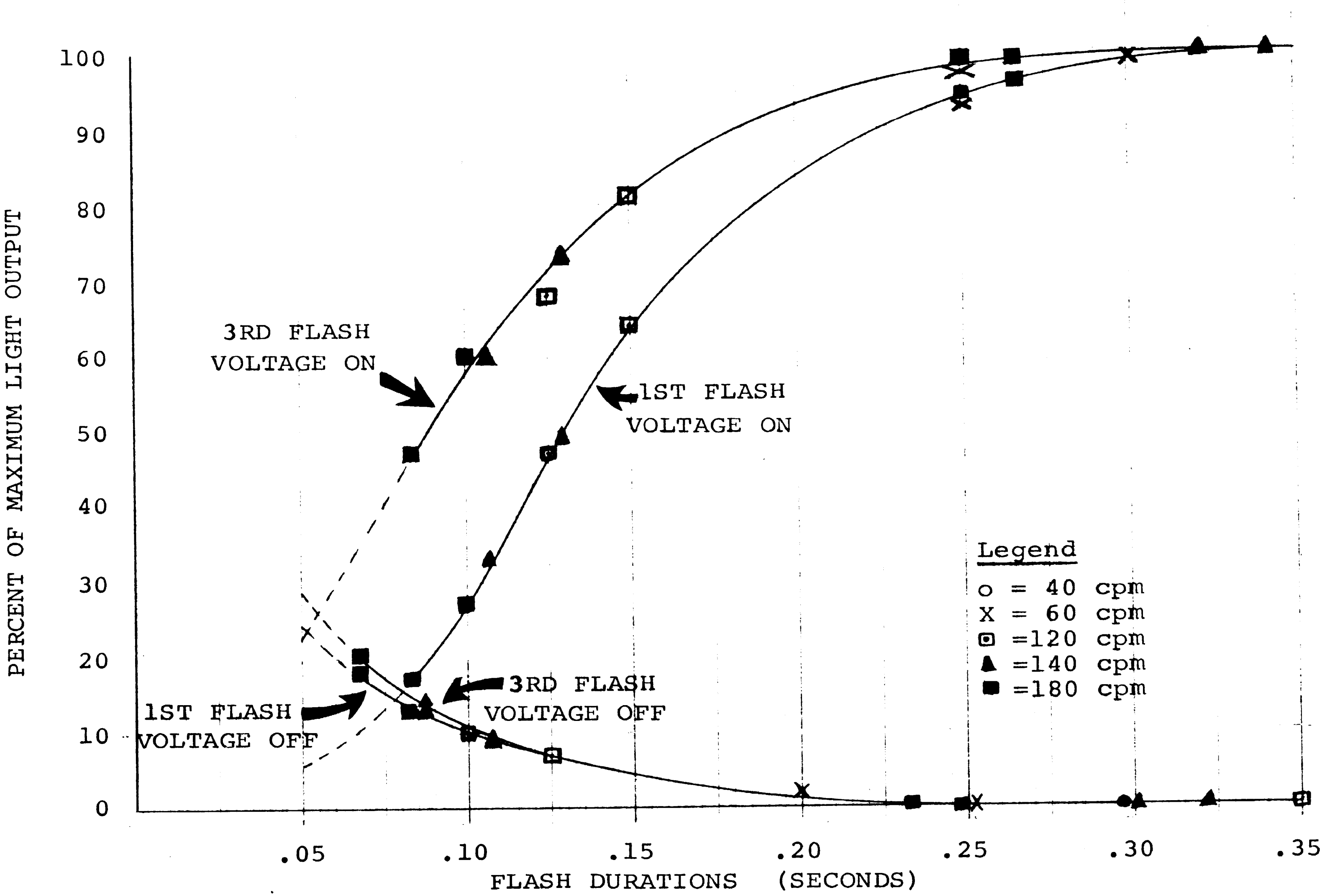

Figure 4.2. Rise and decay curves for the first and third flashes of a type 1157 bulb.

The results also suggest that performance specifications on flashers alone, ignoring the characteristics of the bulbs which the flashers control, may not be adequate to insure effective flashing characteristics of turn or hazard warning lamps.

5. THE EFFECTIVENESS OF FLASHING LIGHTS - A LITERATURE REVIEW

The effectiveness of a flashing lamp shall be considered directly related to its attention-getting value in this review, i.e. the more conspicuous the lamp the greater its effectiveness. The intent will be to summarize research which deals primarily with the contributions of factors such as shape, color, line-of-sight, flash frequency and duration, intensity, background, and adaptation to the effectiveness of flashing lights on vehicles. For the interested reader, more detailed summaries of most of the research referenced herein can be found in an exhaustive bibliography of work on flashing lights by Hargroves and Hargroves (1970).

SHAPE AND COLOR. Flash shape, the temporal distribution of light in the flash cycle, for directional indicators is usually square, but for rotating beacons it is more nearly sinusoidal. More complex distributions of intensity within the flash cycle are generally considered not practical as a coding dimension (Hargroves, 1971). However, the relative attention-getting value of different flash shapes has not been examined thoroughly.

Color coding has been examined and rejected by Projector et al. (1969) because of variation in observer color vision, desaturation of color in haze or fog, and variation in filter efficiencies. However, researchers at California University (1968) and Mortimer (1969) conclude that although the basic lighting system should employ full functional separation and be color independent, color should be used as a redundant coding parameter as this has been shown to increase effectiveness.

LINE-OF-SIGHT. In a study of flashing versus steady lights in automobile turning signals Brown and Gibbs (1958) found that when little visual search is required a steady light is more effective. However, when the signal is not seen foveally a flashing light has more attention-getting power.

Signal positional effects on reaction time to flashing lamps were further examined by Rains (1963). The shortest times were when the stimulus was presented foveally. In general the nasal side of the retina was found to be superior to the temporal side with respect to the speed of reaction. In addition, Rains believes that the difference in reaction time between the fovea and periphery would be smaller if larger areas and/or longer flash durations were employed as the periphery is capable of greater area and temporal summation.

INTENSITY, BACKGROUND AND ADAPTATION. A series of experiments by Joseph Lucas Ltd. (1956, 1958) were conducted to determine minimum and maximum preferred and acceptable rear signal lamp intensities for both steady and flashing lamps for day and night use. During the daytime higher intensities were preferred. Higher intensities were also preferred at night at greater distances while at shorter distances glare effects lead to lower preferred intensities.

The results also suggested that signal background, glare, and thus observer adaptation could have an important influence on the effectiveness of flashing lamps.

In a study by Gerathewohl (1953) the conspicuity of steady and flashing light signals as a function of contrast was examined. Test signals were 15.5 degrees from the observers visual axis. Distracting lights and two audio distractions were employed. Subjects were perceptually loaded by the presentation of signal and distraction lights at the rate of 33 presentations per minute. Background was held constant while stimulus brightness was varied. Flash frequency and flash duration were constant at 60 cpm and 20% "on" time, respectively. In general, the conspicuity of any signal was found to increase with contrast, as expected. However, little gain was achieved with signal contrasts of 6.6 or greater and flashing and steady lights showed little difference in response time above this contrast ratio. At low contrasts, flashing signals were more conspicuous than steady lights even though distraction lights were dotted around the fixation area.

Crawford (1962, 1963) found that a background of flashing lights (180 cpm, 50% "on" time) increased response time more than a background of steady lights, whether the signal was flashing or not. The subjects were perceptually loaded by signals and distraction lights occurring 20 times per minute. The advantage of using a flashing light as a signal was lost even if one other light in the background was flashing and steady lights were always more effective when 10% or more of the background lights were flashing. This illustrates the confusion that could be expected if there were too many distracting flashing lights in the area of a pertinent signal. The contrast level of the signals involved in this experiment is not reported.

Glare effects, to some extent, were reported by Mortimer and Olson (1966) when the positional effects of front-turn indicators relative to the headlamps were examined. As expected, reaction times increased when the signal was positioned near the headlamp. However, little systematic research has been done to examine the effectiveness of rear signaling systems when the observer is subjected to glare as is typically encountered in a vehicle meeting situation.

That adaptation can have an important effect on flashing light effectiveness is shown in a study by Forbes (1960). The just perceptible flash brightness after entering the dark from various field brightnesses was measured. A flash brightness of 143 ml was needed for perception upon entering darkness from a field luminance of 3266 ml (hazy day). Likewise, 3.6 ml was required after exposure to 103 ml (overcast day), and .57 ml was required after exposure to 3.3 ml (twilight). After .4 sec or more in the dark luminances required were reduced to .9 ml, .45 ml, .18 ml after prior exposure to hazy day, overcast day, and twilight illuminations, respectively.

FLASH FREQUENCY AND FLASH DURATION. In a study similar to that reported above, Gerathewohl (1957) examined the interactions of flash frequency, duration, and signal contrast. Observers were required to detect the presence of a white flashing light with 90% of the lights being distraction lights. Three brightness contrasts: .16, .95, and 11.16; three flash frequencies: 1 flash every 3 sec, 1 flash per sec, and 3 flashes per sec; and two flash durations: .1 sec and .2 sec were used. Test signals were presented 5 degrees to the left or right of the observer's central line-of-sight. Figure 5.1 illustrates the complex interactions found between flash frequency, duration and contrast. In general, reaction time was found to decrease with increasing flash frequency and flash duration. Increased contrast resulted in decreased reaction time primarily only for the low flash rate of 20 cpm. The effect of contrast was strongest under low frequency conditions. The effect of frequency was strongest under low contrast conditions. Under low contrast conditions high frequency flashes were more conspicuous than low frequency flashes. Duration appears to have no significant effect on the higher flash rates of 60 and 180 cpm. Within the range of the conditions examined, the most conspicuous signal was one flashing at 180 cycles per minute which was at least twice as bright as its background. When averaged over all contrast levels, minimum reaction time was achieved under conditions of maximum flash frequency and minimum flash duration. Gerathewohl postulated that response time may depend not only on stimulus intensity, but also on the time after onset of the signal when the retina is maximally stimulated.

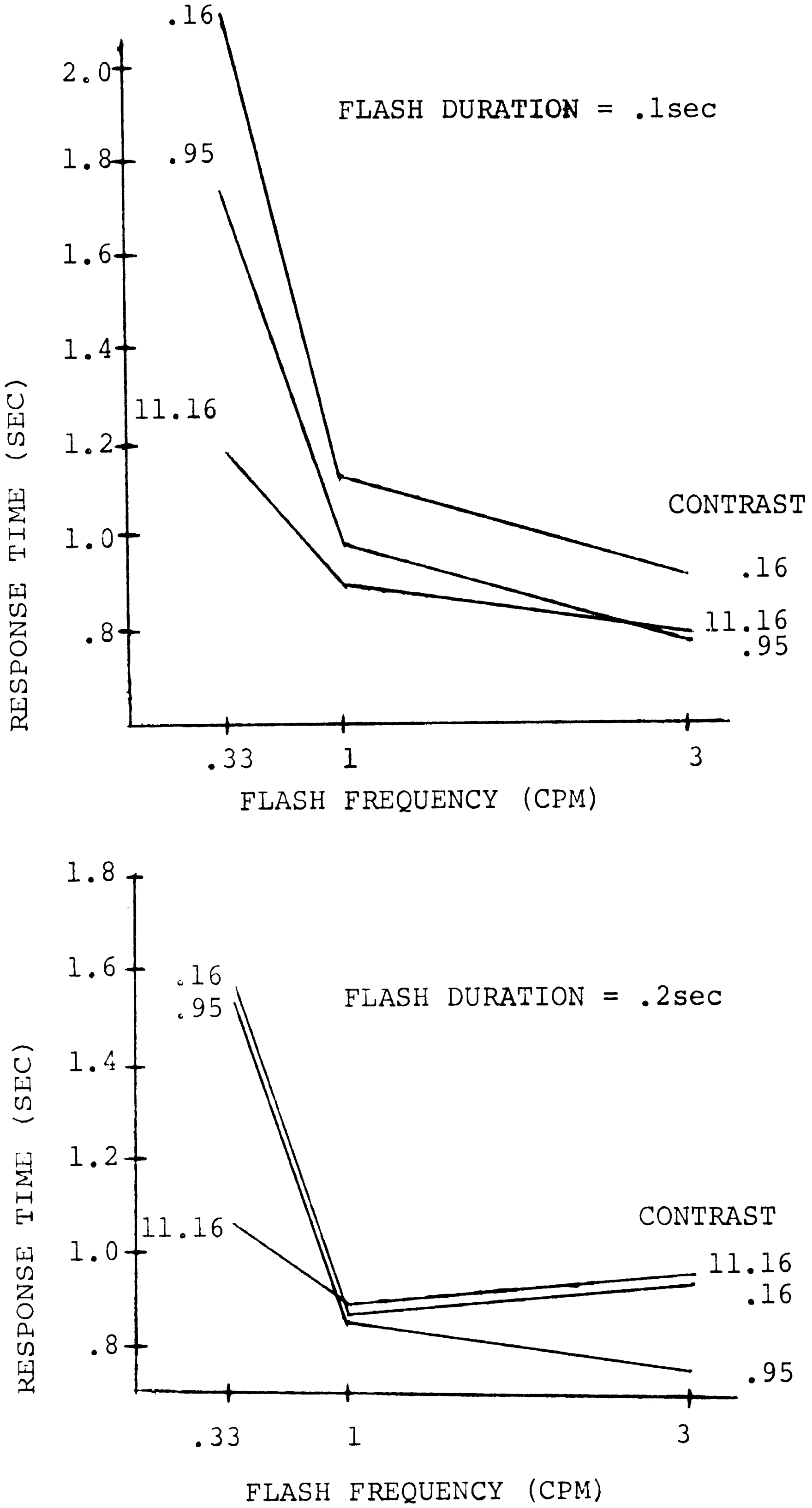

Figure 5.1. Interaction between frequency, duration and contrast.

Brown and Gibbs (1958) also examined the effects of flash frequency and duration of flash on response time. In this experiment, however, observers were required to identify that a signal was flashing. Since the majority of responses occurred before or during the second flash, one can conclude that the observers were looking at or near the general area where the signal was to be presented and that they responded to termination of the first flash. For this reason, response time is taken as the sum of flash duration and "true" reaction time. Flash frequencies from 90/min to 180/min and on-off ratios of 1:3 to 2:1 were examined. Obviously, response times were found to increase with flash duration.

One can conclude that if the observer is directing his attention toward potential signals of interest, then one flash of short duration is all that is needed for rapid response. However, an automobile driver is not always attending to visual areas of importance; therefore, as suggested by the literature, high flash frequencies and minimum flash durations should provide the best conspicuity and smallest response times. In addition, under low contrast conditions often encountered in real driving signals flashing at high flash frequencies are more conspicuous than slow flashing lights and steady lights when distractions are prevalent.

6. THE EFFECTIVENESS OF FLASHING LIGHTS - A SUBJECTIVE EVALUATION OF TURN SIGNALS.

For this study the HSRI marking and signaling research car was used to electrically control the rear turn signals of a light tan 1973 Ford Torino (Figure 6.1). Directly behind the Torino and at a distance of 200 feet sat the group of subjects who subjectively evaluated the effectiveness of the rear turn and hazard warning signals. The evaluations were made by means of a 5-point rating scale. The instructions they received are presented in Appendix B.

SUBJECTS. Six males and ten females volunteered to participate in this two-hour experiment. Their ages ranged from 18-65 with the mean being 35 years old.

CONDITIONS. Left and right turn signals were randomly presented with occasional hazard warnings inserted to vary the presentation. The electronic flasher was operated in a normally closed (start-on) fashion as is customary for the common fixed load flasher. The following percentage "on" times were presented: 20, 25, 30, 40, 50, 60, 70, 75, 80, 85. These were combined with flash rates of 20, 30, 40, 60, 90, 120, 140, 150, 180 and 210 cycles per minute. Each combination was presented twice except for the 90 cpm presentations which were presented three times and the 210 cpm presentations which were presented only once. All sixteen subjects participated in an afternoon session with the sunlight behind them at approximately a 45° vertical angle and in a nighttime session with the taillights turned on.

RESULTS. The mean daytime and nighttime signal effectiveness ratings are shown in Tables 6.1 and 6.2 along with the present SAE flash rate and duty cycle boundaries. It can be deduced from the table that the nighttime ratings are nearly always higher than the daytime ratings. In addition, it is clear that many conditions outside the SAE approved boundaries have ratings equal to or exceeding the rating that some conditions within the boundaries received.

Figure 6.1 The light tan Torino presenting a right turn signal which was controlled by the HSRI marking and signaling research car positioned to its left.

TABLE 6.1. Daytime Mean Ratings of the Subjective Effectiveness of Flashing Automobile Signals.

Percent On-Time	Cycles Per Minute									
	20	30	40	60	90	120	140	150	180	210
85	1.56	2.09	2.88	3.19	2.92	2.16	1.66	1.47	1.50	1.31
80	1.44	2.16	2.94	3.00	2.85	2.53	1.97	1.91	1.41	1.43
75	1.34	1.75	2.84	2.91	3.33	3.06	2.72	2.50	2.13	1.56
70	1.41	2.03	2.75	3.94	3.71	3.59	3.38	3.00	2.41	1.69
60	1.88	2.41	2.94	3.66	3.77	3.81	3.63	3.78	2.97	2.69
50	1.19	2.28	2.75	3.44	3.69	3.44	3.72	3.50	2.88	2.38
40	1.25	2.00	2.56	3.47	3.81	3.75	3.06	2.78	3.03	1.93
30	1.22	1.94	2.63	3.22	3.04	2.75	2.56	2.47	2.22	2.19
25	1.53	2.00	2.53	2.94	2.88	2.47	2.31	2.19	1.78	1.88
20	1.41	1.93	2.38	3.03	2.83	2.53	2.43	2.50	2.28	1.62

TABLE 6.2 Nighttime Mean Ratings of the Subjective Effectiveness of Flashing Automobile Signals.

Percent On-Time	Cycles Per Minute									
	20	30	40	60	90	120	140	150	180	210
85	1.53	2.34	2.84	3.63	3.77	2.84	2.75	2.56	2.03	1.94
80	1.75	2.38	3.03	3.41	3.77	3.19	2.84	2.63	2.22	1.94
75	1.66	2.41	3.31	3.72	3.88	3.25	2.97	2.75	2.59	2.19
70	1.53	2.47	2.97	3.50	4.06	3.41	3.16	2.94	2.38	2.25
60	1.75	2.78	3.31	4.13	4.31	3.72	3.47	3.34	3.34	2.63
50	1.63	2.19	3.13	3.91	4.06	4.03	3.43	3.13	3.19	2.44
40	1.66	2.50	2.91	3.78	4.02	3.63	3.34	3.00	2.78	2.25
30	1.78	2.28	2.84	3.28	3.63	3.31	3.06	2.78	2.66	2.31
25	1.59	1.97	2.56	3.16	3.38	2.84	2.66	2.50	2.09	2.13
20	1.66	2.44	2.53	3.16	3.19	2.66	2.22	2.28	1.88	1.69

NOTE: ☐ The black box includes the SAE limits for normally open (start "off") variable load flashers; for normally closed (start "on") fixed load flashers the shaded area would be excluded.

— — — The dashed line encompasses all conditions tested whose means equalled or exceeded the lowest rating received by a flash rate/"on" time combination which is approved by the SAE and DOT as per SAE J590b(i.e.≥2.75).

These tables show how far the boundaries would extend if they were to include all conditions with as high or higher a rating as the lowest rating received by a condition within the SAE boundaries. As can be seen from the more restrictive daytime condition exhibited in Table 6.1, all the ratings of the 20, 30, and 210 cycle per minute presentations fall below the lowest rating within the SAE approved region. Therefore it is likely that these flash rates can be excluded from further consideration. It can be noted from Table 6.2 that no flash rates that have general nighttime effectiveness across "on" time levels would be eliminated.

To take into account variability of the responses of the subjects Tables 6.3 and 6.4 were prepared to show the percent of responses which were "satisfactory" or better (i.e., $\geq$a rating of 3 or greater) for each flash rate x duty cycle combination for both daytime and nighttime, respectively.

Table 6.3 has the most restrictive flash rate and duty cycle boundary condition. All points within its criteria boundaries have a daytime and nighttime mean rating greater than or equal to the minimum rating received which is currently within the SAE and DOT approved flash region as per SAE J590b(i.e.$\geq$2.75 from Table 6.1). In addition all points within the Table 6.3 boundaries were rated as "satisfactory" or better on 66% or more of the subject presentations in both daytime and nighttime conditions. The "criteria of two-thirds or more "satisfactory" ratings is very similar to that used by members of the Automobile Manufacturers Association* Vehicle Lighting Committee in presenting the results of their turn signal demonstration conducted Dec. 1-2, 1959. It seems feasible to limit further testing to conditions within the boundaries exhibited in Table 6.3. This will limit the flash rate range to 40-150 cpm. The duty cycles used should minimally cover the range 20-85% "on" time.

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*Now The Motor Vehicle Manufacturers Association of the U.S., Inc.

TABLE 6.3. Percent of Flashing Automobile Signals Presented in the Daytime which were Rated "Satisfactory" or Better.

Percent On-Time	Cycles Per Minute									
	20	30	40	60	90	120	140	150	180	210
85	3.1	25.0	68.7	78.2	68.8	28.1	6.3	9.4	9.4	6.3
80	6.3	31.2	78.2	62.6	60.4	43.8	18.8	21.9	3.1	12.5
75	6.3	18.8	68.8	68.7	77.1	78.2	53.1	50.1	28.2	6.3
70	9.4	28.2	59.4	87.6	85.5	78.2	78.1	62.6	40.6	6.3
60	21.9	34.4	65.7	93.8	91.7	90.6	84.4	84.3	53.2	56.3
50	0.0	40.6	50.0	87.5	87.5	75.1	87.5	78.2	50.0	37.6
40	0.0	25.1	50.0	87.5	93.8	100.0	65.7	50.0	62.5	12.6
30	3.1	25.0	56.2	78.2	75.0	62.5	46.9	40.6	25.0	18.8
25	0.0	21.9	53.1	75.0	70.9	43.8	31.3	21.9	15.7	18.8
20	0.0	15.7	40.7	78.2	73.0	50.0	34.5	47.0	34.4	12.5

TABLE 6.4. Percent of Flashing Automobile Signals Presented in the Nighttime which were Rated "Satisfactory" or Better.

Percent On-Time	Cycles Per Minute									
	20	30	40	60	90	120	140	150	180	210
85	12.5	46.9	71.9	87.6	85.5	68.8	62.6	50.1	21.9	12.6
80	12.5	40.7	81.3	84.4	91.7	71.9	59.5	53.2	28.2	12.6
75	12.5	46.9	87.6	97.0	93.7	81.3	71.8	59.4	50.1	25.1
70	6.3	50.1	75.1	84.4	95.9	84.4	71.9	71.9	37.5	37.5
60	18.8	65.7	81.3	93.9	97.9	93.8	84.4	84.4	71.9	43.8
50	15.6	28.3	78.2	93.8	93.8	96.9	87.6	75.0	68.7	37.5
40	18.7	50.0	72.0	93.8	100.0	93.7	84.4	62.5	53.2	18.9
30	25.0	40.7	71.9	87.5	93.8	87.5	90.6	75.0	50.1	25.1
25	9.4	21.9	59.4	84.4	79.1	75.1	65.7	50.0	28.1	25.1
20	12.5	46.9	59.4	78.2	70.8	53.2	40.7	40.6	15.7	6.3

NOTE: ☐ The black box includes the SAE limits for normally open (start "off") variable load flashers; for normally closed (start "on") fixed load flashers the shaded area would be excluded.

— — — The dashed line encompasses all conditions tested which received a "satisfactory" or better rating on 66% or more of presentations.

7. STUDY 1: EFFECT OF FLASH RATE AND DUTY CYCLE ON TURN SIGNAL DETECTABILITY.

The objective of this task was to conduct an experimental evaluation of the effectiveness of front- and rear-mounted turn and hazard warning signal lamps in daytime as a function of the flasher, duty cycle and flash rate.

The pilot study (Section 6) indicated that duty cycle and flash rate specifications can be extended beyond their present limits without reducing rated effectiveness. However, flash rates of 20, 30 and 210 cpm were rated below the lowest mean rating received by any flash rate and duty cycle combination tested that was within the SAE J590b approved region. In addition, the 20, 30, 180 and 210 cpm flash rates failed to receive a "satisfactory" or better rating on two-thirds or more of the presentations. Therefore, it was felt that these conditions could reasonably be deleted from subsequent studies. However, flash rates of 20-180 cpm were used so that a performance comparison could be made between unsatisfactory signals and those falling within the 40-150 cpm "satisfactory" region found in the subjective pilot study. Apparently the "on" time range was not wide enough to include duty cycles that produce flashing signals rated ineffective at all flash rates. Therefore, the "on" time range was extended to 15-90% to see whether or not subjective effectiveness persists at these extreme values.

The HSRI rear lighting vehicle was used to electronically control the rear lighting system of the test car which was the same car as was used in the subjective evaluation. This was done so that the reaction times to different presentations of flash rate and duty cycle could be evaluated in the context of a typical vehicle. Thus, these data show the magnitudes of the daytime differences which can be expected to occur when signals are mounted near a chrome bumper and within the body of a vehicle which provides a typical color contrast.

Based upon the preliminary evaluation made in the pilot study, as well as a consideration of the present standard and the revisions proposed in Docket No. 69-19, concerned with flash rate and duty cycle, a determination was made of the number of levels of each of these factors that should be evaluated. One objective of the program was to define the nature of the space which is bounded by the limits of flash rate and duty cycle that produce objectively adequate and subjectively good flashing signals.

SUBJECTS. A total of 16 subjects were used in this test. The subjects had corrected or uncorrected minimum visual acuity of 20/40 and their ages ranged from 17 to 40 with a mean of 23. There were 10 male and 6 female participants. Four subjects were used in each test session.

PROCEDURE. A static test (Figure 7.1) was conducted in which the subjects were seated in two automobiles, parked adjacent to each other 200 feet from the vehicle carrying the test lamps. Fifty feet in front of the cars in which the subjects were seated was a small stand carrying two red side-task lamps 4 feet apart and 24 inches above the ground which were lighted in a random order with a frequency of about 10 cpm. The intensity was adjusted so that the lamps were adequately conspicuous.

The observers were seated in two test vehicles, and responding to the side-task lights. The two red rear signal lamps on the test car were operated at 12.8 volts at the bulb which is typical of normal operation. This was determined via photometry of a 1973 Torino to determine its typical presence and signal lamp output. It was found to produce a signal of approximately 108 candelas (cd) and a presence indication of approximately 8 cd. These intensities were found to be replicated by supplying the bulb 12.8 volts via the rear lighting vehicle. These same intensities were also used for the subjective "pilot" study.

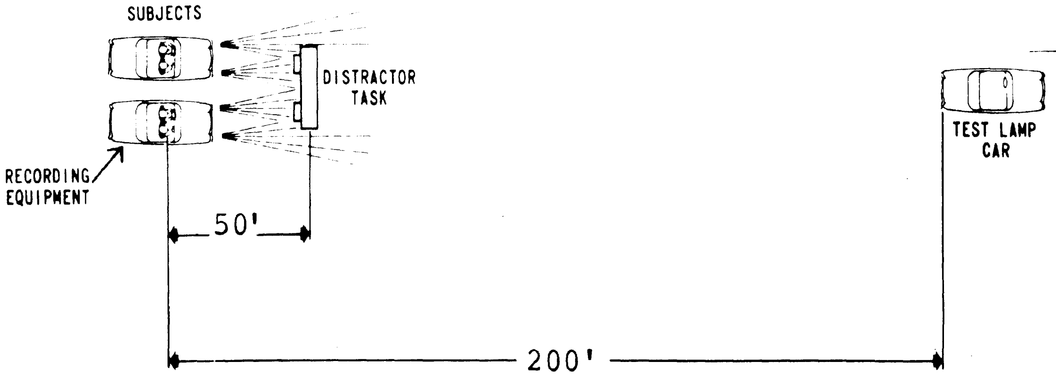

Figure 7.1. The test set-up.

The test was conducted on bright days with solar illumination falling on the test lamps at an average vertical angle of about 45°. Two replications of each flash rate and duty cycle were presented (one left turn and one right turn), except for the 20 cpm and 180 cpm which were presented once each. These extremes were added to the useful range in order to determine the magnitude of the performance change at such extremely slow and fast flash rates.

The independent variables were as follows:

1. Flash rate: 20, 40, 60, 80, 100, 120, 140, 160 and 180 cycles per minute.
2. Duty cycle: 15, 25, 30, 60, 75, 80 and 90 percent "on" time.

The dependent variables were as follows:

1. Response time to detect a right or left turn signal.
2. Frequency of missed signals (i.e., response times longer than 8 seconds).

Each subject held a box containing four pushbutton switches, two for operation with the left thumb and two for operation with the right thumb. The two upper switches were used to respond to the left or right side-task lights, while the bottom switches were used to respond to left or right turn signals. A dummy switch was located between the left and right turn switches so that the subject could respond to stop signals. The occurrence of stop signals prevented the subjects from assuming that the illumination of a lamp represented a turn signal. The instructions that were read to the subjects are included in Appendix C. The subjects were told to respond primarily to the near signal lights and secondarily to the far signal lights on the car. They were to respond as quickly as possible and correct any errors they made. Performance on the side-task was monitored for each subject by a set of lights on the experimenter's console which was arranged such that as soon as a subject responded to a side-task lamp one of the monitoring lights was extinguished. Thus, when all subjects responded all lamps were extinguished on the experimenter's console. This procedure has been used before by HSRI and provides a quick method of monitoring the individual performance of subjects on the side-task lamps. We have found that after a short practice period subjects maintain a high level of performance on the side-task throughout a test.

Reaction time measurements to the onset of turn signals were made by recording the time required for each subject to depress the correct switch. Response times of longer than 8 seconds were treated as missed signals. Turn signals were given with an average interval of 30 seconds ± 15 seconds. Each test session lasted about three hours during which ambient lighting conditions remained reasonably constant.

RESULTS. The response time data were analyzed using natural log transformation. Two analyses of variance were performed since missing data in some extreme cells prevented using one analysis for the entire flash rate and duty cycle ranges. The first analysis (Table 7.1) encompases the whole 20-180 cpm flash rate range in combination with duty cycles from 25% to 80% "on" time. Neither the flash rate nor duty cycle main effect is significant. However, the flash rate x duty cycle interaction is significant at the α=.01 level. The subject x duty cycle interaction which is also significant at the α=.01 level is due to subject variability.

The interaction of flash rate and duty cycle is represented in Table 7.2. Response time means which are significantly different are indicated by the Tukey (b) test results in Table 7.3. There were no significant differences associated with flash rates except at the lowest (25%) "on" time where response to flash rates of 140, 160 and 180 cpm were significantly longer ($\alpha \leq .05$) than those to 20 cpm. This effect is explainable by the fact that

TABLE 7.1. Analysis of Variance of Natural Log Transformed Response Times of Sixteen Subjects to Daytime Presentations of Turn Signals With Flash Rates of 20-180 cpm and Duty Cycles of 25-80%.

```
RT ANALYSIS - 15% & 90% OMITTED

     FACTOR CODES

      A       EQUALS    RATE
      B       EQUALS    SUBJ
      C       EQUALS    DUTY

             DIVISION OF VARIANCE

SOURCE OF                SUMS OF    DEGREES OF   MEAN               RATIO
VARIATION                SQUARES     FREEDOM     SQUARES

B..............         62.72140          15    4.180093

A..............         1.488446           8   0.1860558            1.2212
AB.............         18.28246         120   0.1523538            1.1459

C..............         2.080382           4   0.5200956            1.8865
BC.............         16.54192          60   0.2756985            2.0737**

AC.............         7.936954          32   0.2480298            1.8656**
ABC............         63.81638         480   0.1329508           0.98302

WITHIN CELLS            73.30409         542   0.1352473

TOTAL                   246.1520        1261
```

**$\alpha \leq .01$

TABLE 7.2. Turn Signal Response Time Cell Means for the Study 1 Experiment and Associated Voltage "On" and "Off" Durations.

Duty Cycle	Flash Rate (Cycles Per Minute)									Duration (Sec.)
	20	40	60	80	100	120	140	160	180	
15% "On"	.450	.225	.150	.113	.090	.075	.064	.056	.050	ON*
	2.550	1.275	.850	.637	.510	.425	.365	.319	.283	OFF*
	1.792	1.535	1.509	1.962	2.282	1.750	2.002	1.956	-	Response
25% "On"	.750	.375	.250	.188	.150	.125	.107	.094	.083	ON
	2.250	1.125	.750	.562	.450	.375	.322	.281	.250	OFF
	1.000	1.199	1.392	1.175	1.177	1.225	1.394	1.554	1.605	Response
30% "On"	.900	.450	.300	.225	.180	.150	.129	.113	.100	ON
	2.100	1.050	.700	.525	.420	.350	.300	.262	.233	OFF
	1.201	1.129	1.325	1.172	1.062	1.129	1.137	1.241	1.345	Response
60% "On"	1.80	.900	.600	.450	.360	.300	.257	.225	.200	ON
	1.20	.600	.400	.300	.240	.200	.172	.150	.133	OFF
	1.296	1.238	1.115	1.129	1.339	1.279	1.176	1.215	1.210	Response
75% "On"	2.250	1.125	.750	.563	.450	.375	.322	.281	.250	ON
	.750	.375	.250	.187	.150	.125	.107	.094	.083	OFF
	1.251	1.223	1.368	1.305	1.143	1.154	1.124	1.321	1.196	Response
80% "On"	2.400	1.200	.800	.600	.480	.400	.343	.300	.266	ON
	.600	.300	.200	.150	.120	.100	.086	.075	.067	OFF
	1.321	1.133	1.065	1.112	1.196	1.203	.986	1.026	1.185	Response
90% "On"	2.700	1.350	.900	.675	.540	.450	.386	.338	.300	ON
	.300	.150	.100	.075	.060	.050	.043	.037	.033	OFF
	1.321	1.165	1.229	1.256	1.263	1.197	1.078	-	1.663	Response

*These figures are the computed voltage durations.

TABLE 7.3. Tukey (b) Tests of Log Transformed Response Time Means Derived from the ANOVA in Table 5.1.

Duty Cycle (% "On")	Flash Rate(s) (Cycles Per Min)	Resulted in Mean Response Times That Were --	Flash Rate(s) (Cycles Per Min)
25	60*, 140*, 160*, 180*	Significantly longer than	20
30- 80	-	Not significant	-

Flash Rate(s) (Cycles Per Min)	Duty Cycle(s) (% "On")	Resulted in Mean Response Times That Were --	Duty Cycle(s) (% "On")
20-120	-	Not significant	-
140	25	Significantly longer than	80*
160	25	"	80**
180	25	"	60*, 75*, 80*

$*\alpha \leq .05$

$**\alpha \leq .01$

the "on" durations for these rates are only .107 to .083 sec which results in only 17-33% of maximum light output[1] on the first flash and approximately 47-62% by the third flash. Thus, these signals would be expected to be much harder to see than those producing 100% of maximum light output on all flashes (i.e., 20 cpm). All of these signals reach 0% of maximum light output in the "off" phase. The 60 cpm signal was also significantly different from the 20 cpm at an $\alpha = .05$ level. This is an isolated case and is probably spurious since both signals produce well over 90% light output on all flashes.

There were no signficant differences in response time to various duty cycles, except at the high flash rates of 140, 160 and 180 cpm. As indicated by the flash rate and duty cycle interaction means shown in Table 7.2, these high flash rates when combined with the 25% duty cycle produced significantly longer response times than some of the longer "on" time combinations (i.e., 60-80% duty cycle). Again, this is due to the short voltage "on" durations, occasioned by high flash rates and short duty cycles, producing low intensity flashes. However, in this instance it may be notable that the signals did not all approach 0% light output in the "off" phase. For example, the 180 cpm and 80% duty cycle signal which had "on"/"off" maximum light output ratio of just over 5:1, still produced a signal capable of eliciting a response nearly as fast as the 180 cpm and 60% duty cycle signal which had a contrast ratio of just over 10:1. Apparently, the fact that the contrast ratio between on/off light output for signals with long "on" times was relatively low, due to the short period of time available for decay, is of lesser importance in determining response time than the lamp intensity reached.

Another ANOVA was conducted to determine whether the significant differences found at the 25% duty cycle are also prevalent at the 15% duty cycle. This ANOVA evaluated the 15-80% duty cycle

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[1] Percentages of maximum light output are derived from the mean rise and decay curves for a pair of type 1157 bulbs, Figure 4.2.

range in combination with the 20-160 cpm range. The analysis shown in Table 7.4 shows a significant ($\alpha \leq .01$) duty cycle main effect in combination with a significant ($\alpha \leq .01$) Flash Rate x Duty Cycle interaction. Significant Subject x Duty Cycle ($\alpha \leq .01$) and Subject x Flash Rate x Duty Cycle ($\alpha \leq .01$) interactions were also found, but are due to subject variability.

The significant interaction of flash rate and duty cycle is represented in the table of interaction means, Table 7.2. Significant response time mean differences indicated by the Tukey (b) test are exhibited in Table 7.5. At the high flash rate of 140 and 160 cpm the significant difference between 25% and 80% duty cycles replicated the finding of the first ANOVA, that those lamp "on" duration differences which represent large differences in maximum lamp intensity, lead to response time differences. In addition, the extremely short duration (low intensity) of the 15% duty cycle is responsible for this "on" time producing significantly longer response times than <u>all</u> the other duty cycles (25-80% "on") over the range of 80 to 160 cpm (except that no significant difference was found between 15% and 25% at 160 cpm). This exception is explained by the fact that at 160 cpm, the 15% (.056 sec) and 25% (.094 sec) "on" times produce light outputs which are not visually different in bright daylight since the light output ratio is only 7% to 23% of maximum light output on the first flash (rising to 27% to 54% by the third flash). Thus, the lack of a significant difference in response times to 15% and 25% duty cycles at 160 cpm would be expected to apply to all higher flash rates as well, since higher flash rates would produce even lower intensity flashes. At somewhat lower flash rates, i.e., 140 cpm and below, the 15% and 25% "on" times produce significantly different response times; in these cases the light output ratio is minimally 9% to 33% of maximum light output on the first flash (rising to 31% to 62% by the third flash).

TABLE 7.4. Analysis of Variance of Natural Log Transformed Response Times of Sixteen Subjects to Daytime Presentations of Turn Signals With Flash Rates of 20-160 cpm and Duty Cycles of 15-80%.

```
RT ANALYSIS - 90%ON & 300CPM OMITTED

     FACTOR CODES

      A        EQUALS    RATE
      B        EQUALS    SUBJ
      C        EQUALS    DUTY

           DIVISION OF VARIANCE

 SOURCE OF                  SUMS OF    DEGREES OF   MEAN              RATIO
 VARIATION                  SQUARES     FREEDOM     SQUARES

 B..............           78.83989          15    5.255992

 A..............          0.8639558           7    0.1234222         0.69656
 AB.............           18.60489         105    0.1771894          1.0608

 C..............           34.57455           5     6.914910         27.690**
 BC.............           18.72954          75    0.2497271         1.4950**

 AC.............           10.98183          35    0.3137665         1.8784**
 ABC............           87.69644         525    0.1670408         1.1547*

 WITHIN CELLS              93.16414         644    0.1446648

 TOTAL                     343.4551        1411
```

$*\alpha \leq .05$

$**\alpha \leq .01$

TABLE 7.5. Tukey (b) Tests of Log Transformed Response Time Means Derived from the ANOVA in Table 5.4.

Duty Cycle (% "On")	Flash Rate(s) (Cycles Per Min)	Resulted in Mean Response Times That Were --	Flash Rate(s) (Cycles Per Min)
15	100	Significantly longer than	60**, 40**
25	60*, 140*, 160**	"	20
30-80	-	Not significant	-

Flash Rate(s) (Cycles Per Min)	Duty Cycle(s) (% "On")	Resulted in Mean Response Times That Were --	Duty Cycle(s) (% "On")
20	15	Significantly longer than	25**, 30**, 60*, 75*, 80*
40	-	Not significant	-
60	15	Significantly longer than	80*
80	15	"	25**, 30**, 60**, 75**, 80**
100	15	"	25**, 30**, 60**, 75**, 80**
120	15	"	25**, 30**, 60**, 75**, 80**
140	15	"	25**, 30**, 60**, 75**, 80**
	25	"	80*
160	15	"	30**, 60**, 75**, 80**
	25	"	80**

---

*$\alpha \leq .05$

**$\alpha \leq .01$

Therefore, there may be a daytime flashing signal intensity threshold, for lamps similar to the 1157, such that, signals whose intensity is low require a signal of minimally 20%-30% greater intensity to produce a significantly different response time between the two signals.

At 40 and 60 cpm and 15% "on" time the duration is large enough to produce between 60-100% of maximum light output on the first flash and 80-100% of maximum light output by the third flash and therefore few significant differences are found between response times to duty cycles at these flash rates. However, the attention-getting quality of the flash may be low as evidenced by the long response times to these 15% "on" time signal combinations.

At 20 cpm the attention-getting characteristic of a 15% duty cycle flash is low, as evidenced by the very long response time, which is significantly longer than that of each of the other duty cycles. This effect is not attributable to intensity since 100% of maximum light output is reached at the "on" duration provided by this Flash Rate x Duty Cycle combination.

To more clearly demonstrate the Flash Rate x Duty Cycle interaction which was found to be significant at the $\alpha \leq .01$ level in both analyses of variance, the response time means were plotted in Figures 7.2 and 7.3. Figure 7.2 shows the interaction effect most markedly by the association of low "on" times and high flash rates (140-180 cpm) with increasing response times. The fact that the short duration flashes produced long response times is due to the lower lamp intensities produced at these durations as previously shown.

Figures 7.4 and 7.5 show subject response variability as a function of flash rate and duty cycle. These figures show that subject response variability is high at both very low and very high flash rates (see Figure 7.5).

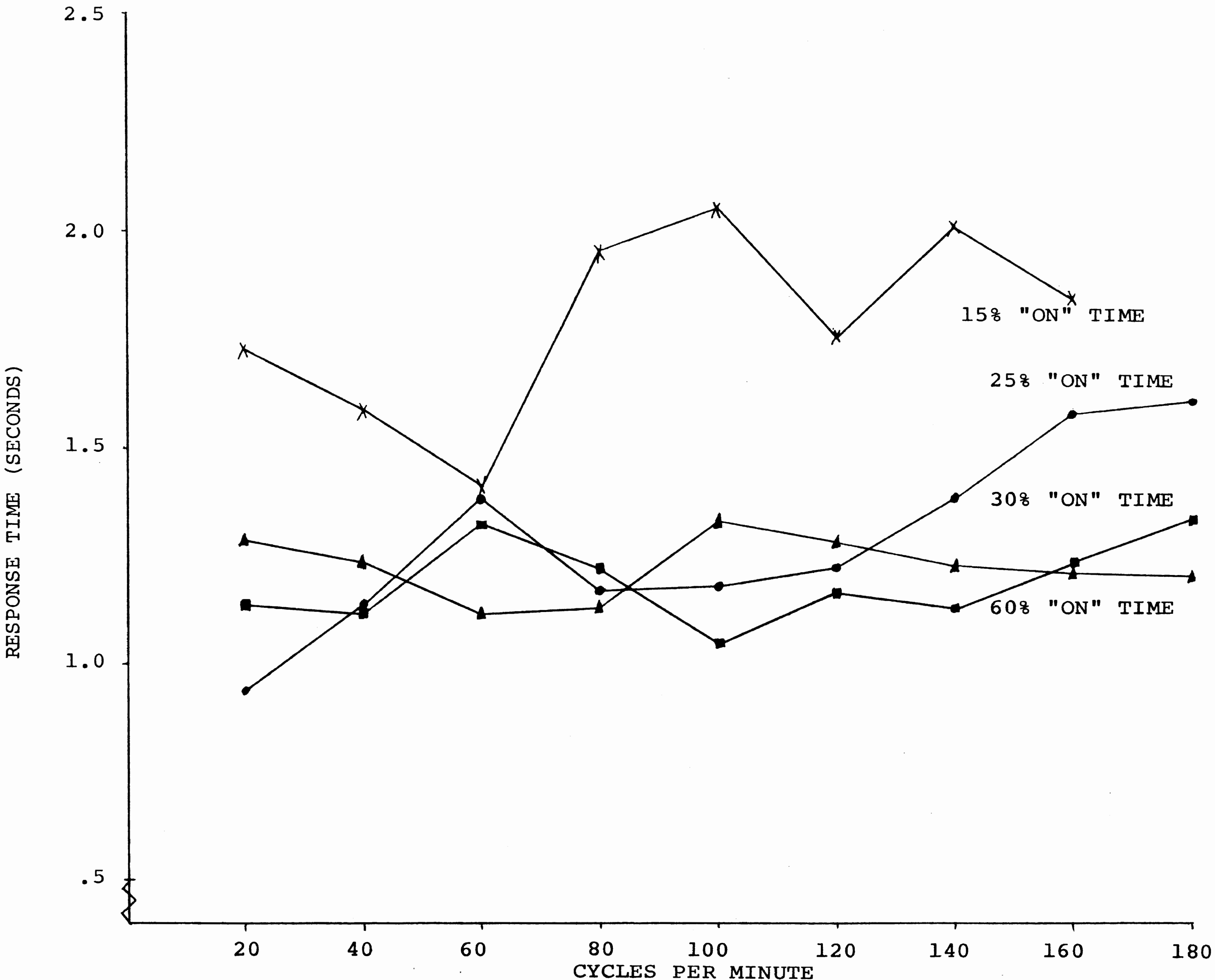

Figure 7.2. Response time as a function of flash rate and duty cycle.

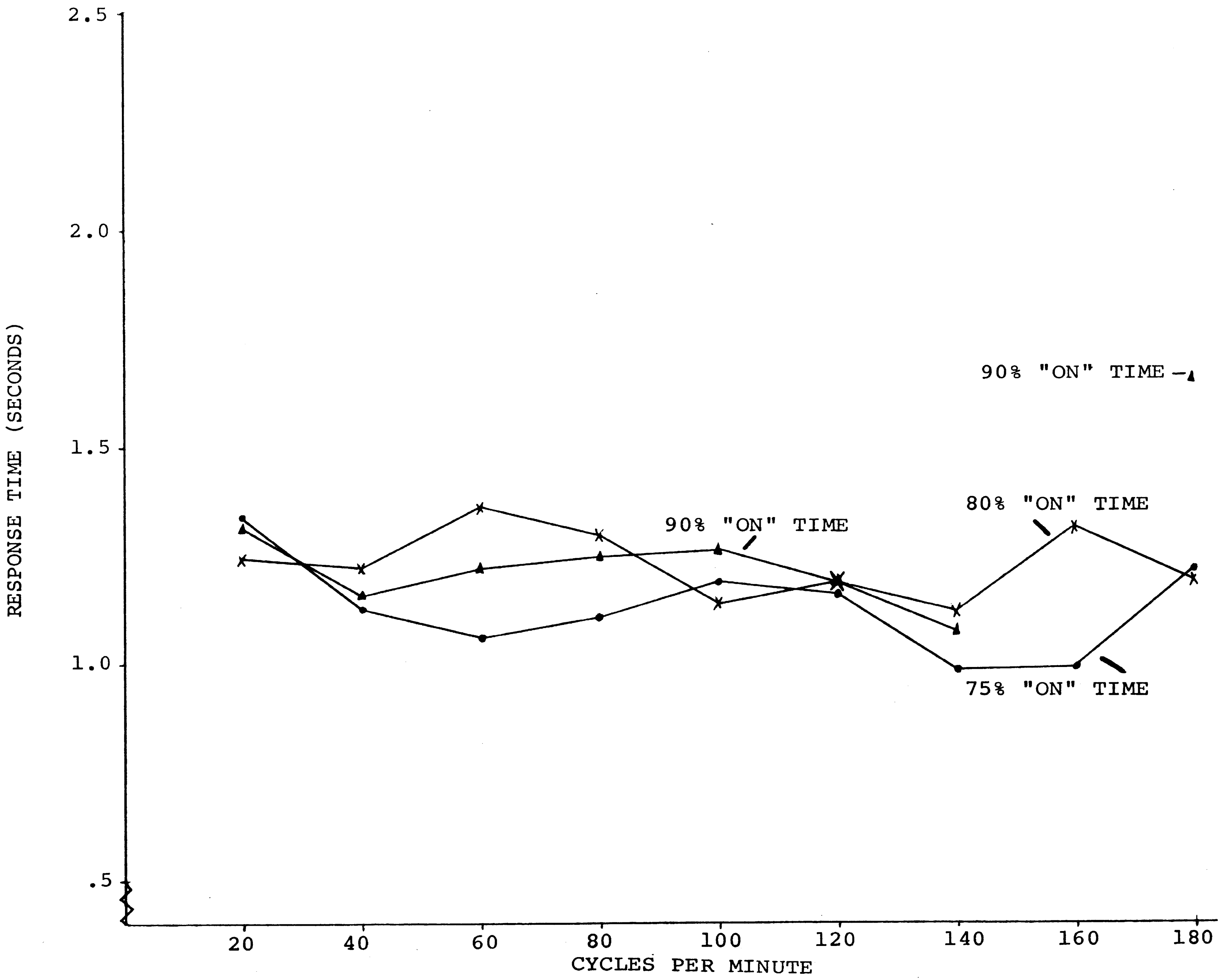

Figure 7.3. Response time as a function of flash rate and duty cycle.

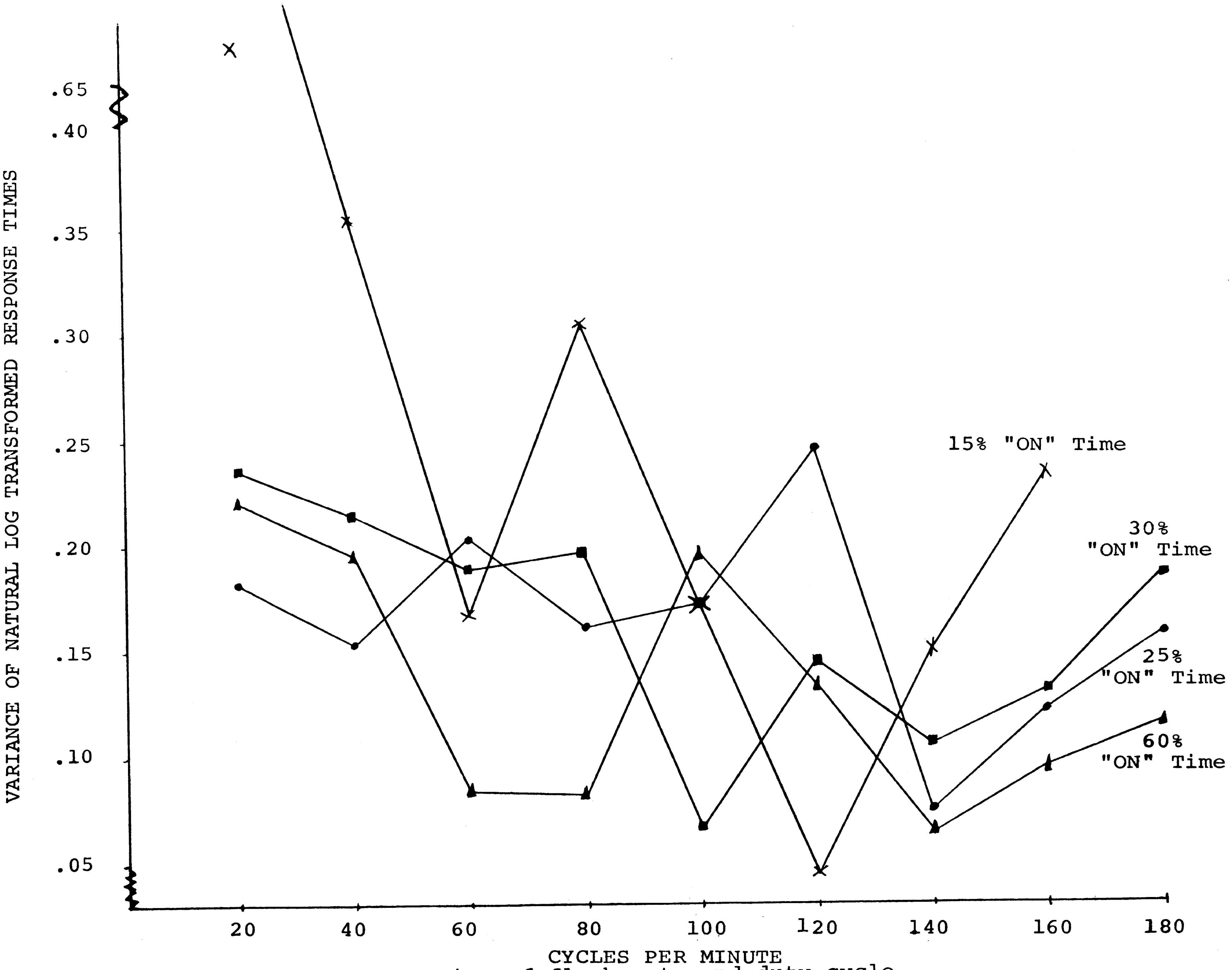

Figure 7.4. Variance as a function of flash rate and duty cycle.

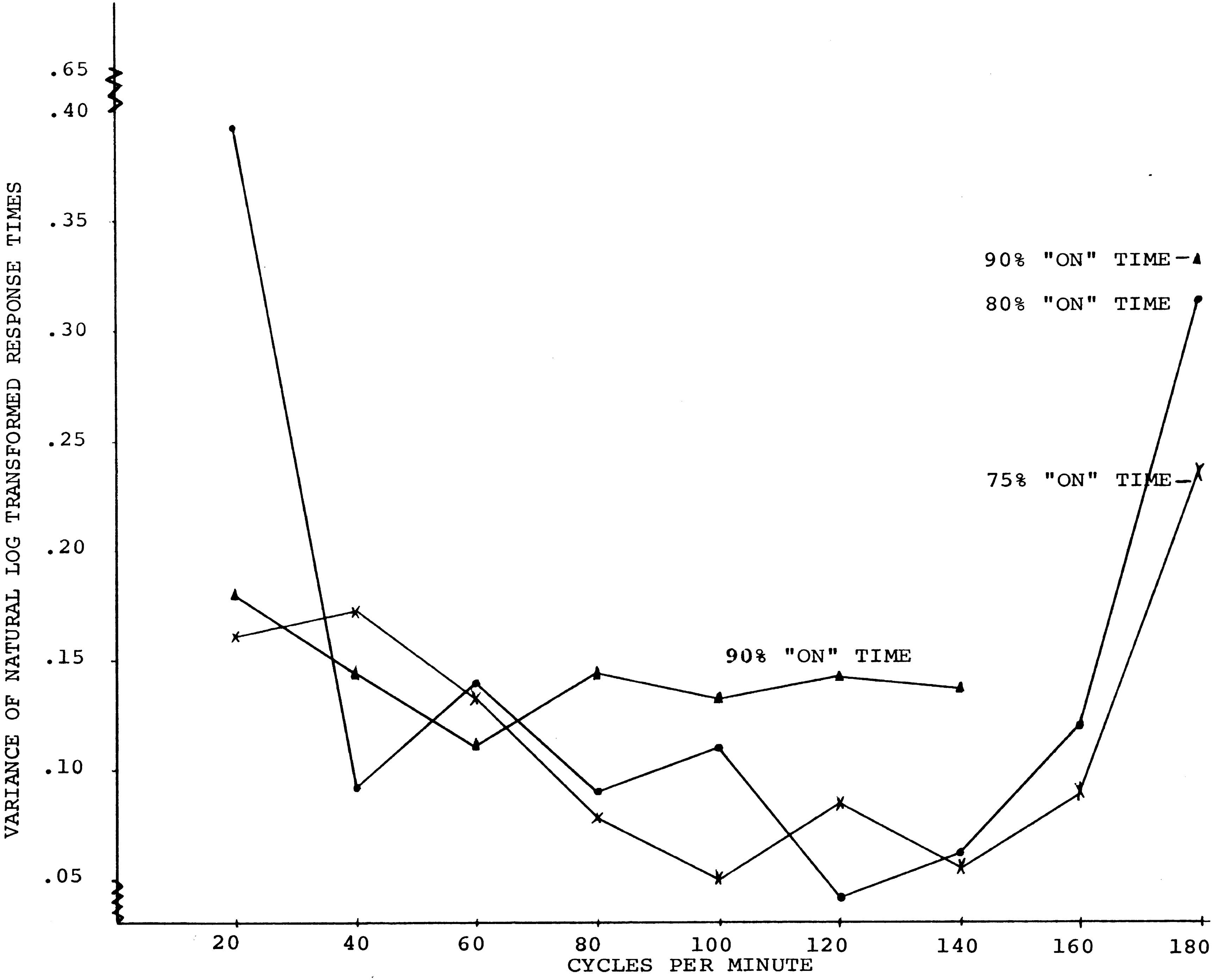

Figure 7.5. Variance as a function of flash rate and duty cycle.

An analysis of the missed signals (RT $\geq$ 8 sec) produced the following totals:

	Flash Rate (Cycles per Minute)									
	20	40	60	80	100	120	140	160	180	Total
Frequency of Missed Signals	5	2	3	0	4	2	1	5	0	22

	Percent "on" Time (Duty Cycle)							
	15	25	30	60	75	80	90	Tot.
Frequency of Missed Signals	9	3	2	1	1	3	3	22

Without resorting to statistics it is evident from the data that while no trend in frequency of misses occurs across flash rates, there is an abnormality in the duty cycle data for the 15% "on" time cell. It is evident from the foregoing discussion of these signals that their low intensity would make them difficult to see in daylight and thus lead to missed signals. The missed signal rate overall was approximately 1.2% of all signals presented.

8. STUDY 2. EFFECT OF FLASH RATE, DUTY CYCLE, FLASHER START MODE, REAR LIGHTING SYSTEM CONFIGURATION, AND AMBIENT ILLUMINATION ON TURN AND HAZARD WARNING SIGNAL EFFECTIVENESS

The objective of this study was to evaluate a number of variables which can affect turn and hazard warning signal effectiveness, in day and night conditions. A delimited set of combinations of flash rate and duty cycle were used based on the results of study 1. In addition, the effect of the flasher starting in the "on" and "off" mode was evaluated. However, it should be noted that evaluation of this variable was only meaningful when different signal modes were considered, such as the effect of a stop signal preceding a turn signal, and when different system configurations were also evaluated. For example, the effect of turn signals which were given by lamps different from those which gave stop signals was evaluated. The effect of lamp color was also evaluated, and this inherently meant that the turn signal lamp was in a separate compartment from that providing the stop signal or the presence (i.e., tail) indication. For these reasons, three rear lighting system configurations were considered the minimum that should be evaluated in this test under day and night conditions.

SUBJECTS. A total of 28 daytime and 27 nighttime subject runs were made. Several subjects had to be excluded because they were not alert enough to maintain a constant response level as determined by side task response and the number of missed signals throughout the experimental session. Thus, the 26 subjects who were run successfully at night were paired with 26 subjects who were run successfully during the day. Eighteen of the subjects successfully participated in both the day and night sessions. These 18 subjects were used for the analyses so that a more powerful statistical test could be applied. Preliminary ANOVA's indicated that the reduced subject number did not affect the significance of the results. Males and females were used as subjects in equal numbers. The age span was 17 to 45 years with a mean of 25 years.

PROCEDURE. The same basic procedures as have been described eariler (Section 7) were used in this test. However, the HSRI rear lighting vehicle (Figure 8.1) powered its own lamps which were amenable to changes of color and system operation characteristics. These type 4416 lamps have rise and decay functions (Figure 8.2) very similar to those found for type 1157 bulbs (Figure 4.2). Because these lamps had to be operated at less than nominal voltage, due to their greater light output relative to the type 1157 lamp, a electronic circuit was used to boost the light output rise curve obtained at the lower voltages. This circuit was calibrated to closely approximate the rise curve of a type 1157 bulb at 12.8 volts regardless of the voltage applied to the type 4416 lamps. This enhancement was evaluated visually to determine whether there was any detectable difference between signals presented by the enhanced type 4416 lamps at the voltages required and unenhanced type 1157 lamps operated at 12.8 volts. No difference in signal appearance was detected. The test conditions to be used are described below.

Night Test of Rear Signals. In this test the presence lamps were lighted continuously. The red lamps operated at 8 candelas. The intensity of the signal lamps (turn or hazard warning) were 110 candelas for red lamps and 275 candelas for amber (yellow) lamps. The red lamp intensities are the same as those used in the subjective test (Section 6) and objective study (Section 7). The amber intensity was chosen to represent the same increment over the minimum amber intensity allowed by SAE J588d as was found to exist for the red lamps on the production vehicle used in the earlier tests. The independent variables evaluated were as follows:

1. Signal modes: turn (left or right), hazard warning, stop followed by turn*(after a variable interval of 1.5-4.5 secs).

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*This signal will generally be represented by "stop→turn" in tables and text and is accompanied by the flasher start mode in parentheses when this information is appropriate.

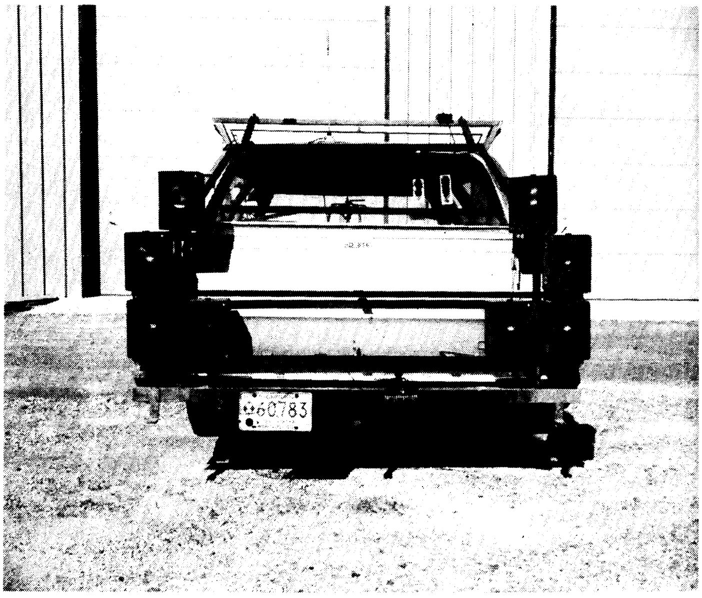


Figure 8.1 (a). The HSRI marking and signaling research car.

Figure 8.1 (b). The lamp control and monitoring panel.

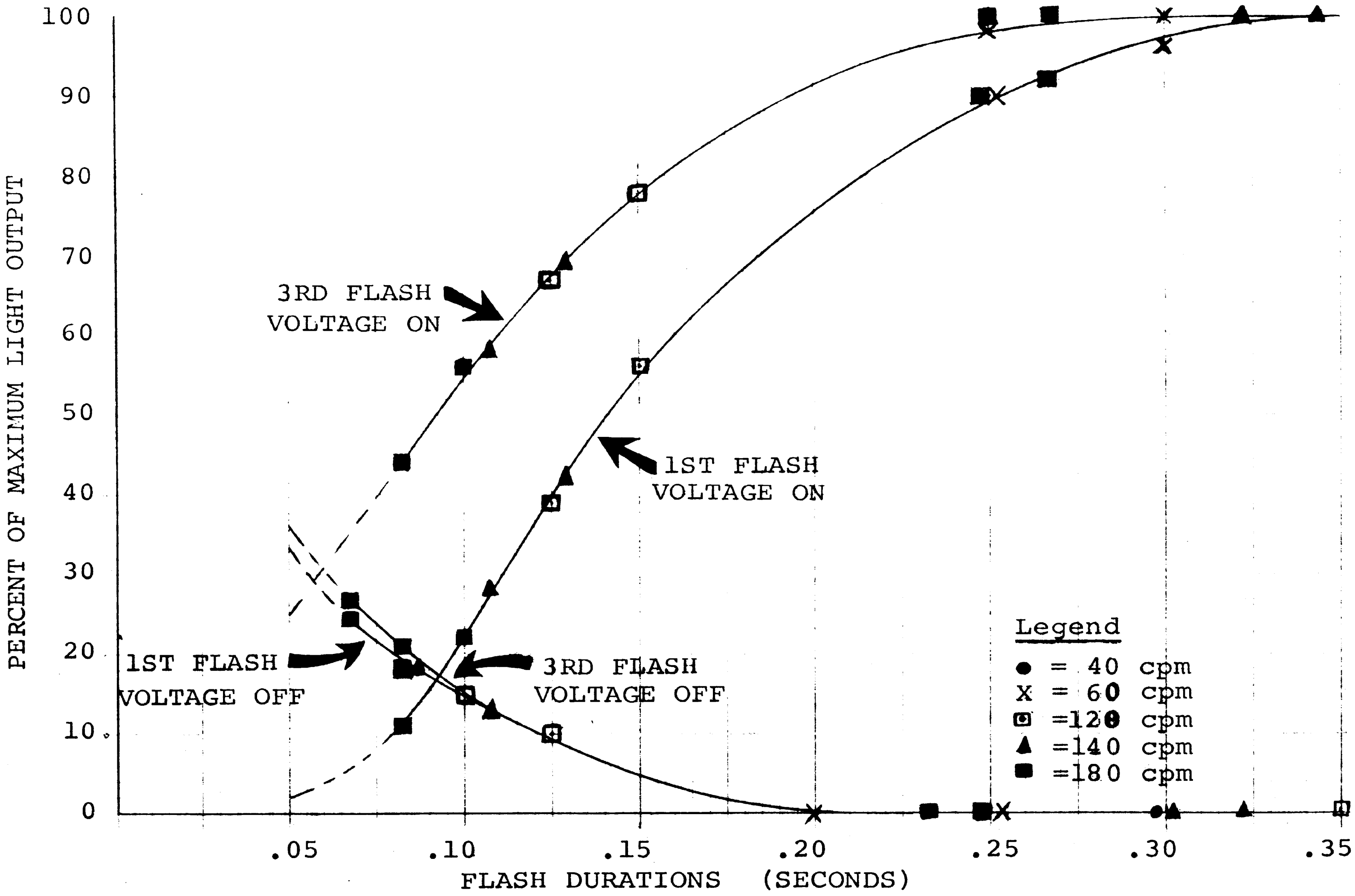
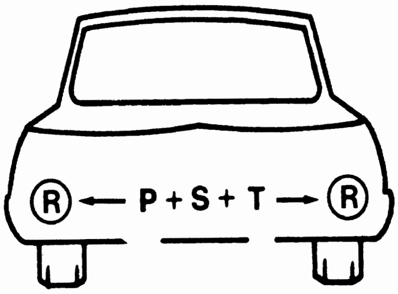
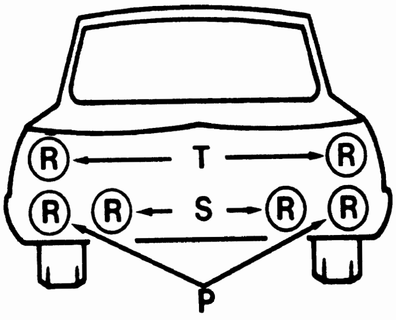


Figure 8.2. Rise and decay curves for the first and third flashes of a type 4416 bulb.

SYSTEM 1



SYSTEM 4



SYSTEM 11

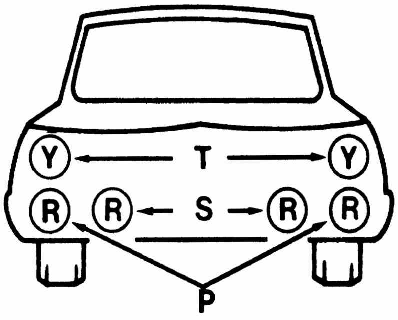


Figure 8.3. The rear lighting systems. (P=presence, S=stop, T=turn, R=red, Y=yellow.

2. Rear lighting system: system 1, system 4, system 11. (These systems are described in Figure 8.3.)
3. Flash start mode: on, off (for systems 1 and 4 only).
4. Duty cycle: 20, 30, 75 and 85 percent "on" time.
5. Flash rate: 20, 40, 60, 120, 150 and 180 cycles per second.

Daytime Test of Rear Signals. The independent variables evaluated in this test were the same as those listed above for the night test. By using the same parameters during both day and night conditions, ambient illumination (hereafter referred to as "ambient") became a testable factor across all parameters.

DATA ANALYSIS. Each of the response times obtained in this experiment were transformed to its natural log value, in order to reduce the effects of response time skewness. Where a signal was not responded to in eight seconds (i.e., a "missed" signal"), the mean response time for that condition was used. An analysis of variance (ANOVA1) was then conducted using signal, mode, flash rate, duty cycle, rear lighting system, subjects, and ambient (day and night) as factors. A second analysis of variance (ANOVA2) was conducted to include the flasher start phase as a signal mode factor for systems 1 and 4 [stop → turn (start- off) was evaluated as a fourth signal mode]. Both analyses of variance were followed by Tukey (b) tests to evaluate the significance of the differences between the various cell means.

RESULTS. The results of the first ANOVA are presented in Appendix D. Eighteen sources of variance were found to be significant at the $\alpha = .01$ level. Of these 18 sources of variation only four contributed over 5% of the variance. Of the four primary sources of variance, two are main effects which are included among an interaction which was significant at the $\alpha = .01$ level. Variables found to be significantly contributing to the variance at a level of 5% or greater were signal mode, flash rate, system, and Mode × System. Only one other factor contributed over

5% of the variance; ambient was found to contribute substantially to the variance even though it was only significant at the $\alpha = .05$ level. The individual factors each accounting for over 5% of the variance, accounted for over 85% of the total response time variance (when the random factor, subjects, is included).

The results of the second ANOVA are presented in Appendix E. Fifteen sources of variance were found to be significant at the $\alpha = .01$ level. Of these fifteen sources of variance only four contributed over 5% of the variance. Again, ambient was found to contribute substantially (over 5%) to the variance, even though it was not found to be significant ($p \leq .05$) in this analysis. The main factors again were signal mode, flash rate, system, and Mode x System. These factors and the random factor (subjects) accounted for over 82% of the total response time variance. Thus, an explanation of how these factors influence response time can account for the primary results of both ANOVAs that were conducted.

Post hoc tests using the Tukey (b) test were conducted on all factors of interest with the $\alpha = .01$ level used to determine significance. The results of these tests (Table 8.1) show that of the signal modes presented the turn signal produces significantly shorter response times than the stop-turn and hazard modes. The hazard produces significantly longer response times than the other modes presumably because both sides of the vehicle must be monitored for flashing to avoid mistaking this signal for a stop signal.

The flash rate data show that the higher the flash rate the shorter the response time, except within the 120-180 cpm region where increasing benefits were not found due to the uniformly short response times at these flash rate levels.

The separated function systems (11 and 4) were found to lead to shorter response times than the single lamp (one side) combined function system (1). The system with the amber turn lamps (11) also produced shorter response times than the system with the red turn lamps (4).

TABLE 8.1.

GEOMETRIC MEANS AND TUKEY (b) TESTS OF LOG TRANSFORMED RESPONSE TIMES FROM ANOVAS 1 AND 2.

	Signal Modes			
Anova	Turn	Stop-Turn(On)	Stop-Turn(Off)	Hazard
Anova 1	1.32	1.44	-	1.63
Anova 2	1.35	1.57	1.54	1.78

Mode	Resulted in Mean Response Times That Were - -	Mode
Turn	Significantly shorter than	Stop-Turn(Off), Stop-Turn(On)
Stop-Turn(Off) Stop-Turn(On)	" " "	Hazard

	Flash Rate (cpm)					
Anova	20	40	60	120	150	180
Anova 1	1.81	1.59	1.48	1.30	1.31	1.33
Anova 2	2.16	1.75	1.54	1.34	1.34	1.35

Flash Rate(s) (cpm)	Resulted in Mean Response Times That Were - -	Flash Rate(s) (cpm)
40,60,120,150,180	Significantly shorter than	20
60,120,150,180	" " "	40
120,150,180	" " "	60

	System		
Anova	1	4	11
Anova 1	1.71	1.42	1.28
Anova 2	1.61	1.50	-

System(s)	Resulted in Mean Response Times That Were - -	System(s)
11, 4	Significantly shorter than	1
11	" " "	4

The interaction of Mode x System is shown in Table 8.2. Within system 1 the hazard and stop-turn modes have significantly longer response times than the turn mode. Systems 4 and 11, on the other hand, have hazard mode response times significantly longer than turn and stop-turn response times which are relatively low.

In the hazard mode response times are significantly quicker to system 11 than to the other two systems. In this mode system 4 also has response times significantly shorter than those of system 1. In the turn mode there were no significant differences at the .01 α level. In the stop-turn (on) mode system 11 and system 4 response times are significantly shorter than those to system 1, but systems 4 and 11 do not differ significantly. In the stop-turn (off) mode system 1 produced a significantly shorter response time than system 4.

Systems 1 and 4 elicited response times that were significantly different for all signal modes except the turn signal. This indicates that functional separation is effective in producing substantially quicker responses to the hazard signal (by over 1/3 second) and to the turn (start-on) following a stop (by over 6/10 second). System 11 which differed from 4 only in the use of amber, lead to significantly shorter response times only in the hazard mode. This Color x Mode interaction was primarily responsible for the overall system effect which indicated that system 11 with yellow (amber) produced shorter response times than system 4. In the "off" flasher start mode, the combined signal system (1) produced a response time to a stop-turn signal equal to what was elicited by the turn (start-on) mode. In both cases the turn can be perceived immediately. In the "on" flasher start mode, the separated signal systems (4 and 11) produced response times to the stop-turn signal nearly equal to those elicited by the turn (start-on) mode. Again, the turn signal can be perceived immediately in both

TABLE 8.2

GEOMETRIC MEAN RESPONSE TIME AS A FUNCTION OF SIGNAL MODE, FLASHER START MODE, AND REAR LIGHTING SYSTEM

Rear Lighting System	SIGNAL MODE			
	Hazard	Turn	Stop-Turn(On)	Stop-Turn(Off)
1	1.90	1.37	1.91 *	1.37
4	1.67	1.33	1.30	1.76 **
11	1.37	1.26	1.21	----

* The expected value for this cell is the response time (RT) to the unobscured system 1 stop-turn (off) signal (1.37 seconds) plus the average amount of time the turn signal was obscured by the stop signal (.569 seconds). Thus, the expected stop-turn (on) response time is 1.94 seconds. The difference between the expected RT value and that obtained is obviously not significant in this case.

** The expected value for this cell is the response time of the similar undelayed signal (system 4 stop-turn (on) RT = 1.30 seconds) + the average amount of time that the signal was delayed by the flasher unit (.533 seconds). Thus, the expected RT is 1.83 seconds which is obviously not significant from that obtained in this case.

Note -- The average "on" time in this experiment was .569 seconds while the average "off" time was .533 seconds.

-- The finding that the expected response times were not significantly different from those obtained supports the assumption, within the parameter values tested, that one can perceive illumination of a lamp (with relatively fast rise and decay functions) as easily as extinction. Therefore, in the case where a signal cannot be perceived until a visual change occurs, the signal will elicit a response time equal to the response time to a similar unobscured/undelayed signal plus the amount of time that the signal is obscured/delayed.

instances. However, with the functionally combined system (1) operating in a start-on mode, the stop-turn signal is responded to with a response time that is not significantly different from what would be expected if one added the average interval that the turn signal is visually obscured by illumination of the stop signal (.569 seconds), to the response time elicited by an unobscured turn signal following a stop signal (1.37 seconds). Similarly, in the separated system (4), the start-off stop-turn signal is responded to with a response time which is not significantly different from the response time which would be expected if one added the average flasher delay interval, .533 seconds, to the response time (1.30 seconds) elicited by a stop-turn signal which was not delayed by the flasher mechanism.

Table 8.3a shows how response time varies as a function of flash rate and signal mode. For the main factor mode, the subjects responded to the turn signal significantly faster than the other signal modes. They also responded to the stop-turn significantly faster than to the hazard warning signal. For the main factor flash rate, the subjects responded to 120, 150 and 180 cycles per minute flashes quite fast with no significant differences between them. All of these high flash rates were responded to significantly faster than the 20, 40, and 60 cpm flash rates. These differences in response time associated with flash rates are primarily a function of similar significant differences between flash rates in the hazard and stop-turn modes. Within the turn mode, however, 20 cpm was indicated as being significantly slower than 120 cpm and 180 cpm, while 60 cpm also was indicated as producing response times significantly longer than those associated with the 120 cpm flash rate.

These results are quite similar to those obtained in the other analysis (Table 8.3b) which included start mode. For the main factor mode, the significant results are the same with stop-turn in either the start-off or start-on mode (no significant

TABLE 8.3a

GEOMETRIC RESPONSE TIME AS A FUNCTION OF FLASH RATE AND SIGNAL MODE--ANOVA 1.

Mode	Flash Rate (Cycles Per Minute)					
	20	40	60	120	150	180
Hazard	2.34	1.79	1.60	1.40	1.41	1.43
Turn	1.40	1.36	1.37	1.25	1.29	1.26
Stop→Turn	1.81	1.65	1.48	1.26	1.24	1.29

TABLE 8.3b

GEOMETRIC RESPONSE TIME AS A FUNCTION OF FLASH RATE AND SIGNAL MODE--ANOVA 2.

Mode	Flash Rate (Cycles Per Minute)					
	20	40	60	120	150	180
Hazard	2.87	2.04	1.70	1.45	1.47	1.50
Turn	1.48	1.43	1.36	1.26	1.29	1.29
Stop→Turn (On)	2.20	1.84	1.59	1.33	1.32	1.34
Stop→Turn (Off)	2.37	1.74	1.52	1.34	1.30	1.27

difference overall across systems 1 and 4). The stop-turn in either start mode produced response times significantly shorter than those produced by the hazard signal mode, but significantly longer than those produced by the turn signal mode. For the main factor flash rate, the subjects responded in a fashion such that the results of the start-off mode were the same as those obtained in the start-on mode in terms of significant differences in the results. In both start modes the 120, 150, and 180 cpm flashes were responded to significantly quicker than the 20, 40, and 60 cpm flashes. Within the turn mode, however, 20 cpm was indicated as being significantly slower than 120, 150, and 180 cpm, while 40 cpm also was indicated as producing response times slower than those associated with the 120 cpm flash rate.

The actual response time values associated with the interaction of mode and the flash rate are presented in Table 8.4 as a function of system. Most noteworthy of the effects shown is that the response time differences which do exist between these systems decrease as flash rate increases. For example, at 20 and 40 cpm systems 1, 4, and 11 are significantly different, at 60 cpm the difference is smaller and only 1 and 4 are significantly different, and at 120, 150, and 180 cpm the differences are minimal and non-significant (except for an apparent abberation resulting in a significant difference between 1 and 11 at 180 cpm). In the turn mode system 1 produces a significantly longer RT than systems 4 and 11 at 20 cpm, while at 40 cpm system 11 produces a significantly shorter RT than the other systems, but at 60-180 cpm there is no significant difference between systems. In the stop-turn (on) mode system 11 elicits significantly shorter RT's than system 1 at all flash rates. However, the magnitude of the improvement in RT offered by system declines as flash rate is increased to 120 cpm. Thereafter, the effect is nearly

TABLE 8.4

GEOMETRIC MEAN RESPONSE TIME AS A FUNCTION OF SIGNAL MODE, FLASHER START MODE, FLASH RATE AND REAR LIGHTING SYSTEM.

		Signal Mode				
	CPM	Hazard	Turn	Stop → Turn(On)	Stop → Turn(Off)	
FLASH RATE	20	3.47	1.61	3.44	1.89	
	40	2.20	1.43	2.36	1.47	
	60	1.81	1.35	1.95	1.37	
	120	1.46	1.25	1.51	1.22	SYSTEM 1
	150	1.47	1.30	1.41	1.19	
	180	1.58	1.29	1.44	1.18	
	Overall	1.90	1.37	1.91	1.37	
FLASH RATE	20	2.37	1.35	1.41	2.97	
	40	1.89	1.44	1.44	2.06	
	60	1.59	1.37	1.30	1.69	
	120	1.43	1.28	1.16	1.47	SYSTEM 4
	150	1.47	1.29	1.23	1.42	
	180	1.43	1.30	1.25	1.36	
	Overall	1.67	1.33	1.30	1.76	
FLASH RATE	20	1.56	1.26	1.21	-	
	40	1.38	1.22	1.32	-	
	60	1.41	1.38	1.28	-	
	120	1.32	1.22	1.13	-	SYSTEM 11
	150	1.30	1.29	1.10	-	
	180	1.30	1.20	1.20	-	
	Overall	1.37	1.26	1.21	-	

constant. Thus, flash rates of 120-180 cpm minimized response time differences between systems and color had no effect on response time at these high flash rates. The stop-turn mode demonstrates that system 1 is capable of producing response times in this mode equal to those obtained using systems 4 and 11, if the flash rate is high and the system incorporates a start-off flasher for the stop-turn signal while retaining a start-on flasher for the turn signal.

The Flash Rate x Duty Cycle interaction shown in Table 8.5 indicates that 120-180 cpm response times at all duty cycles tested were significantly shorter than response times to 20-60 cpm flash rates. For the 30-85% "on" times the response times elicited by the 40 and 60 cpm flash rates were also significantly shorter than those obtained at the 20 cpm flash rate. However, at 20% "on" time, the mean response times to 20 and 40 cpm were not shown to differ and both means were significantly longer than that obtained at 60 cpm.

Data are presented in Tables 8.6-8.8 which show the significant interaction of flash rate and duty cycle with signal mode for all three rear lighting systems. Basically, the results show that the turn signal mode was less sensitive to the Flash Rate x Duty Cycle interaction than the hazard and stop-turn modes.

The interaction of signal mode, duty cycle, and system is presented in Table 8.9. For the hazard signal, as the duty cycle

TABLE 8.5

GEOMETRIC MEANS AND TUKEY(b) TESTS OF LOG TRANSFORMED RESPONSE TIMES FOR THE FLASH RATE AND DUTY CYCLE INTERACTION FOUND SIGNIFICANT IN ANOVA 1.

"On" Time	Flash Rate (cpm)					
	20	40	60	120	150	180
20%	1.62	1.67	1.45	1.29	1.37	1.31
30%	1.76	1.54	1.42	1.29	1.26	1.32
75%	1.96	1.56	1.53	1.31	1.30	1.33
85%	1.91	1.58	1.53	1.32	1.34	1.34

Flash Rate(s) (cpm)	Resulted in Mean Response Times That Were---	Flash Rate(s) (cpm)
120, 150, 180	Significantly shorter than	20, 40, 60

For "on" times of 20, 30, 75 and 85 percent

40, 60	Significantly shorter than	20

For "on" times of 30, 75 and 85 percent

60	Significantly shorter than	20, 40

For "on" times of 20 percent

TABLE 8.6

GEOMETRIC RESPONSE TIME FOR SYSTEM 1 AS A FUNCTION OF FLASH RATE, SIGNAL MODE AND "ON" TIME

Mode	Flash Rate (Cycles Per Minute)						"On" Time
	20	40	60	120	150	180	
Hazard	2.31	1.83	1.70	1.27	1.36	1.54	20%
Turn	1.49	1.62	1.34	1.23	1.35	1.31	
Stop→Turn (On)	2.98	2.05	1.66	1.42	1.32	1.45	
Stop→Turn (Off)	1.89	1.71	1.46	1.20	1.29	1.11	
Hazard	3.56	1.86	1.50	1.51	1.36	1.49	30%
Turn	1.51	1.33	1.20	1.14	1.27	1.43	
Stop→Turn (On)	2.99	2.21	1.76	1.31	1.19	1.26	
Stop→Turn (Off)	2.46	1.58	1.42	1.17	1.08	1.09	
Hazard	4.02	2.36	1.98	1.45	1.47	1.48	75%
Turn	1.74	1.39	1.45	1.32	1.22	1.24	
Stop→Turn (On)	4.06	2.53	2.11	1.58	1.56	1.50	
Stop→Turn (Off)	1.75	1.39	1.27	1.17	1.13	1.20	
Hazard	4.41	2.93	2.14	1.63	1.73	1.85	85%
Turn	1.73	1.38	1.42	1.31	1.36	1.20	
Stop→Turn (On)	3.86	2.70	2.35	1.79	1.60	1.55	
Stop→Turn (Off)	1.54	1.23	1.33	1.33	1.26	1.35	

TABLE 8.7

GEOMETRIC RESPONSE TIME FOR SYSTEM 4 AS A
FUNCTION OF FLASH RATE, SIGNAL MODE AND "ON" TIME

Mode	Flash Rate (Cycles Per Minute)						"On" Time
	20	40	60	120	150	180	
Hazard	1.88	1.82	1.55	1.41	1.50	1.34	20%
Turn	1.40	1.57	1.30	1.34	1.39	1.26	
Stop→Turn (On)	1.27	1.61	1.22	1.08	1.34	1.22	
Stop→Turn (Off)	4.19	2.67	2.13	1.73	1.58	1.42	
Hazard	2.35	1.76	1.50	1.51	1.54	1.40	30%
Turn	1.28	1.43	1.46	1.30	1.21	1.37	
Stop→Turn (On)	1.43	1.54	1.39	1.29	1.18	1.27	
Stop→Turn (Off)	3.75	2.29	1.89	1.45	1.45	1.41	
Hazard	2.96	2.16	1.60	1.33	1.35	1.46	75%
Turn	1.36	1.41	1.42	1.27	1.24	1.28	
Stop→Turn (On)	1.42	1.22	1.35	1.21	1.30	1.37	
Stop→Turn (Off)	2.48	1.64	1.46	1.45	1.28	1.34	
Hazard	2.43	1.87	1.74	1.49	1.49	1.53	85%
Turn	1.38	1.36	1.32	1.20	1.33	1.28	
Stop→Turn (On)	1.54	1.42	1.24	1.09	1.21	1.16	
Stop→Turn (Off)	2.01	1.79	1.41	1.27	1.39	1.30	

TABLE 8.8

GEOMETRIC RESPONSE TIME FOR SYSTEM 11 AS A FUNCTION OF FLASH RATE, SIGNAL MODE AND "ON" TIME

Mode	Flash Rate (Cycles Per Minute)						"On" Time
	20	40	60	120	150	180	
Hazard	1.40	1.56	1.55	1.36	1.43	1.31	20%
Turn	1.34	1.29	1.45	1.29	1.33	1.22	
Stop→Turn (On)	1.22	1.84	1.34	1.22	1.29	1.21	
Stop→Turn (Off)*	3.62	3.04	2.14	1.62	1.61	1.48	
Hazard	1.43	1.44	1.28	1.30	1.22	1.35	30%
Turn	1.32	1.31	1.39	1.12	1.30	2.72	
Stop→Turn (On)	1.25	1.21	1.33	1.19	2.08	1.22	
Stop→Turn (Off)*	3.35	2.26	2.03	1.54	2.36	1.45	
Hazard	1.86	1.29	1.42	1.34	1.31	1.29	75%
Turn	1.27	1.17	1.38	1.28	1.25	1.19	
Stop→Turn (On)	1.13	1.20	1.23	2.23	1.35	1.23	
Stop→Turn (Off)*	1.88	1.58	1.48	2.36	1.45	1.31	
Hazard	1.58	1.26	1.41	1.28	1.26	1.24	85%
Turn	1.12	2.66	1.31	1.20	1.26	1.29	
Stop→Turn (On)	1.25	1.12	1.24	1.50	1.25	1.16	
Stop→Turn (Off)*	1.70	1.35	1.39	1.58	1.31	1.21	

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*Estimated Response Times which were computed by adding the flasher delay interval to the stop-turn (on) response time.

TABLE 8.9

THE SIGNIFICANT MODE x DUTY x SYSTEM INTERACTION OF GEOMETRIC MEANS FROM ANOVA 1

Signal Mode	System			"On" Time
	1	4	11	
Hazard	1.63	1.57	1.43	20%
Turn	1.38	1.37	1.32	
Stop→Turn (On)	1.74	1.28	1.34	
Hazard	1.77	1.65	1.33	30%
Turn	1.31	1.34	1.25	
Stop→Turn (On)	1.69	1.35	1.21	
Hazard	1.97	1.73	1.41	75%
Turn	1.38	1.33	1.26	
Stop→Turn (On)	2.07	1.31	1.15	
Hazard	2.29	1.73	1.33	85%
Turn	1.39	1.31	1.21	
Stop→Turn (On)	2.19	1.25	1.14	

increased so did the magnitude and the number of significant differences between systems. For the stop-turn (on) the same holds true. However, for the turn signal there were no significant differences, except at the 85% "on" time, where system 11 did produce significantly shorter response times than system 1. Across modes, systems 11 and 4 had response times that were significantly shorter than system 1 at all duty cycles tested. In addition, system 11 had response times that were significantly shorter than system 4 at all duty cycles, except 20% "on" time. Amber lamps afforded System 11 a response time advantage over system 4 in the hazard and stop-turn modes at both 30 and 75% "on" times and in the hazard mode at 85% "on" time.

The other interactions all involve the ambient lighting condition. Table 8.10 exhibits the geometric means for day and night which were significantly different at the $\alpha = .05$ level with the night condition associated with the shorter response times. The Ambient x Flash Rate interaction is also shown in Table 8.10. Both day and night conditions show lower response times at 120, 150 and 180 cpm. At night there is a significant decrease in response time for each increase in flash rate up to 120 cpm, beyond which response time is stable. In the daytime the results are similar except that there is no significant response time differential between 20 and 40 cpm.

The interaction of ambient with mode is shown in Table 8.11a and with system is shown in Table 8.11b. In daytime and nighttime the response times associated with the hazard signal were longer than those associated with the other modes. At night the response times to the stop-turn (on) were also longer than those to the turn signal. In both day and night conditions the separated function systems were associated with shorter response times than the combined function system. At night the system using amber (yellow) also elicited shorter response times than the all red separated system. This may be due to the fact that

TABLE 8.10

RESPONSE TIME(SEC) AND TUKEY(b) TESTS FOR DAYTIME, NIGHTTIME, AND THE AMBIENT x FLASH RATE INTERACTION

	Flash Rate (cpm)						Geometric Mean
	20	40	60	120	150	180	
Daytime	1.81	1.72	1.59	1.38	1.39	1.40	1.54
Nighttime	1.80	1.46	1.37	1.23	1.24	1.25	1.38

Flash Rates(cpm)	Resulted in Mean Response Times That Were--	Flash Rate(s)
120, 150, 180	Significantly Shorter Than	20, 40, 60
60, 120, 150, 180	" "	20, 40
40*, 60, 120, 150, 180	" "	20

---

*Significant at night only

TABLE 8.11a

GEOMETRIC MEAN RESPONSE TIME(SEC) AND TUKEY(b) TESTS FOR THE MODE x AMBIENT INTERACTION

	Signal Mode		
	Hazard	Turn	Stop→Turn (On)
Day	1.70	1.45	1.48
Night	1.57	1.20	1.40

Mode		Mode
Turn, Stop→Turn (on)	Significantly shorter than	Hazard
Turn*	" "	Stop-Turn(on)

---

*Significant at night only

TABLE 8.11b

GEOMETRIC MEAN RESPONSE TIME(SEC) AND TUKEY(b) TESTS FOR THE SYSTEM x AMBIENT INTERACTION

	System		
	1	4	11
Day	1.82	1.45	1.38
Night	1.60	1.40	1.18

System	Resulted in Mean Response Times That Were--	System
11, 4	Significantly Shorter Than	1
11*	" "	4

---

*Significant at night only

at night the higher intensity of the amber was more readily perceptable.

The Mode x Duty x Ambient interaction demonstrated that the interactions previously discussed from Table 8.11 are not entirely consistent across duty cycle with abnormalities primarily confined to the 20% "on" duty cycle. The Rate x Duty x Ambient interaction demonstrated that in the daytime as duty cycle increased, the number of significant differences between flash rates decreased (i.e., at 85% "on" time only 20 cpm was significantly different from other flash rates [60, 120, 150, 180]). At night the number of significant differences between the flash rates increased as duty cycle increased (i.e., at 85% "on" time 20, 40, and 60 cpm were significantly different from nearly all other flash rates).

The Flash Rate x System x Ambient interaction demonstrated that System 1 had the same number of significant flash rate differences in both day and night indicating that under both conditions, 20, 40, and 60 cpm elicited response times significantly longer than all flash rates higher than themselves. Thus, and acceptable flash rate span for System 1 should probably exclude 20-60 cpm.

For System 4, this reasoning would, in the daytime, exclude flash rates of 20 and 40 cpm and at night exclude only 20 cpm. For System 11 it would not be necessary to exclude any flash rates from consideration at night as no significant difference between flash rates was determined. However, the daytime data for System 11 were inconsistent and it could not be determined whether a wider span of flash rates could also be used with System 11 in the daytime.

An analysis of the missed signals (RT $\geq$ 8 sec.) produced the following totals:

	Flash Rate (Cycles per Minute)						
	20	40	60	120	150	180	Total
Frequency of Missed Signals	60	33	28	22	15	12	170

	Duty Cycle (% "on" Time)				
	20	30	75	85	Total
Frequency of Missed Signals	43	40	29	58	170

Signals were missed at an overall rate of 1.8% of all signals presented. Since there appeared to be a significant trend associating flash rate and response time, statistical tests of significance were performed. These tests included "on" time as a factor since there were apparently significant differences also associated with "on" time.

Using a conservative statistical model with the highest order interaction as the error term, several significant effects were found. An ANOVA (1m) of frequency of missed signals involving all three rear lighting systems with the flasher starting in the on mode indicated that flash rate and Flash Rate x System were significant at the α = .01 level. Similarly, an ANOVA (2m) involving systems 1 and 4 in both on and off start modes indicated the same factors were significant.

In ANOVA (1m) 20 cpm was shown to produce significantly more missed signals than any other flash rate for system 1. This finding was also found in ANOVA (2m). For system 4, 40 cpm was found to produce significantly more missed signals than 180 cpm, while for system 11 the analysis indicated that no flash rate produced more missed signals than any other. ANOVA (2m) concurred in the system 4 effect but showed a significance level of $p \leq .05$. ANOVA (1m) indicated that the stop-turn mode elicited significantly more misses than the hazard mode. In ANOVA (2m) this was not shown to be significant. Duty was not shown to have an effect upon the miss rate of flashes starting in the "on" mode. However, when the "off" mode was included for stop-turn signals, 85% on time was shown to be associated with significantly more misses than 75% "on" time. This is primarily due to the poorer performance of 85%"on" time at night, where it elicited significantly more misses than 75% and 25% "on" times. System 11 produced significantly ($p \leq .05$) fewer misses at night than during the day (high intensity may be a factor) and had a significantly lower nighttime miss rate than both systems 1 and 4. This effect is shown in Table 8.12a. Table 8.12b is similar to the previous table, but the number of missed signals occurring in systems 1 and 4 in the flasher start off mode is also included. System 11 was not presented in the flasher start off mode, since the results would be similar to those obtained with system 4. Therefore, the 11+ column was constructed to give an estimate of the number of misses that would have been expected if system 11 had been presented in both start modes. This table demonstrates that system 11 would probably have produced fewer misses than systems 1 and 4 at night even if both flasher start modes had been used for the stop-turn signal.

TABLE 8.12a

FREQUENCY OF MISSED SIGNALS (RT $\geq$ 8 sec) FOR THE HAZARD, TURN, AND STOP-TURN (ON)* SIGNAL MODES

	System		
	1	4	11
Day	28	17	28
Night	26	26	9
Total	54	43	37

---

*Flasher start phase

TABLE 8.12b

FREQUENCY OF MISSED SIGNALS (RT $\geq$ 8 sec.) FOR THE HAZARD, TURN, STOP-TURN (ON)* AND STOP-TURN (OFF)* SIGNAL MODES

	System			
	1	4	11**	11+[1]
Day	37	23	28	34
Night	36	37	9	20
Total	73	60	37	54

---

*Flasher start phase

**Start "on" mode only

[1] These values include the frequency expected in the stop-turn (off) mode assuming that amber has no effect. Thus, these figures represent the maximum expected frequency across all 4 signal modes presented.

9. DISCUSSION OF RESULTS

The superiority of the 120-180 cpm flash rates in eliciting short response times in the modes that were difficult to perceive (hazard and stop-turn) is shown (Table 8.4) by the fact the mean response times for these high flash rates are equal to or less than 1.30 seconds for unimpeded stop-turn signals in all three systems. The turn signals presented at these flash rates also have mean response times equal to or less than 1.30 seconds. Similarly, at 120-180 cpm all three systems elicited their shortest mean response times to the hazard signal. The attention getting hazard signal produced by system 11 (as evidenced by its significantly shorter mean response time) elicited mean response times equal to or less than 1.32 seconds. Therefore, the consensus is that the high flash rates (120-180 cpm) which are significantly more attention getting, elicited mean response times of less than 1.33 seconds in this experimental paradigm. Therefore, the goal of a response time to a turn signal of less than 1.33 seconds seems desirable in this experimental paradigm.

It also seems reasonable to desire this goal to be met in cases where a stop precedes the turn signal. One counter argument is that in the stop-turn signal mode, the following driver has been warned by the stop signal that the lead car is decelerating or about to decelerate. Thus, whether the driver then signals a turn and/or executes a turn maneuver is of little consequence. However, this argument is weakened by the potential occurrance of specific incidents. In the first case, a disadvantage accrues when the brake lights are malfunctioning or inoperable and the turn signal is delayed because the flasher started in the "off" mode (especially for flash rates of 60 cpm or lower). In other cases, response time to the stop-turn is critical when the lead driver is riding the brake lightly for a long enough period, that the following driver ignores the "potential deceleration message"; in this case the turn signal becomes the deceleration signal just prior to the turn maneuver. This case occurs in situations where some drivers drive for long periods while resting their foot on the brake pedal, and where drivers use the brake to decelerate slightly when approaching an intersection, and then signal a turn just as the vehicle undergoes rapid deceleration in order to make the turn maneuver. In the latter instance, the following driver often cannot predict that the lead driver will turn after he has decelerated slightly, because in many instances he proceeds straight through an intersection after his cautious approach.

In this experimental paradigm all three rear lighting systems were capable of meeting the goal of having a 1.33 second response time to turn and stop-turn signals. This requires systems to be paired with particular flash rates for certain duty cycles and flasher start modes. Functional separation allows more latitude in the selection of these combinations. Amber was not shown to be effective in daytime to reduce response times. However, amber was shown to be very effective at night, but this may be due to its higher intensity.

Using Table 8.4 as a guide to choose flash rate, mode, and system combinations leads to the various possibilities for effective flasher design for the three rear lighting systems. It should, however, be remembered that by choosing appropriate duty cycle regions more latitude can be gained for specification of flash rate and start mode.

The response time goal for effective flasher design was met by system 1 in both the turn (on) and stop-turn (off) modes for flash rates from 120-180 cpm. The start on flasher now in prevalent use in the U.S. was not able to meet this goal in broad system 1 application because of the excessively long response times in the stop-turn (on) mode at all flash rates (except 150 cpm). The start off flasher did meet the goal in the stop-turn mode for the same flash rates that were effective for the turn mode. However, unless a vehicle employed a start off flasher for the stop-turn mode and a start on flasher for the turn mode, the start off flasher used to meet the stop-turn mode goal would also have to function for the turn mode. It may be possible for the start off flasher to function effectively in both signal modes since the expected system 1 response time is 1.25-1.30 seconds + the flasher delay interval. The flasher delay time required is thus approximately .03-.08 seconds. This required delay is provided by flash rates of 150-180 cpm paired with "on" times of approximately 80% or larger.

System 4 met the response time goal in both the turn and stop-turn modes with a start on flasher which had a flash rate of 120-180 cpm.

System 11 met the response time goal for both turn and stop-turn modes with a flasher starting in the on mode which had a flash rate of 20-180 cpm. However, during the daytime system 11 would have to be restricted to whatever flash rate range is effective for system 4 since the wider flash rate range for system 11 is apparently due to short response times occasioned by higher intensity flashes at night. It should be noted that the flash rate span that is effective for system 4 is not 120-180 cpm as one might infer from the discussion of system 4 above. This is because many flash rates not tested would have probably provided nearly as good response time performance, as indicated by the fact that at 60 cpm system 4 nearly meets the response time goal. Thus, the effective flash rate span for system 4 is probably about 80-180 cpm.

Previous extensive studies of rear lighting reported by Mortimer (1970) have found that system 1 (functionally combined) produced longer response times than all other systems with which it was compared. Based on this finding Mortimer urged that system 1 be replaced with a system employing more functional separation and redundant color coding and attempted via simulation studies to show the real world effect that such improved rear lighting systems would have on accident frequency and crash severity.

Mortimer used a 60 cpm - 75% on time flash signals which in effect would cause a delay interval (DI) of .75 seconds to be added to the response times in signal modes where the signal being measured was visually masked by a preceding signal, such as the system 1 stop-turn mode. A 1.941 second RT was reported (Mortimer, 1970, p. 35) for this case. This response time is composed of a .75 delay interval (DI) + a 1.191 response time to the visual change caused by the turn signal. Therefore, the magnitude of the overall system 1 response time differences reported by Mortimer would be reduced substantially by advantageous use of flasher start mode. System 3 (Mortimer, 1970) which has separated stop signals only, then would become the rear lighting system which produced the longest response time (rather than system 1). The long response time of system 3 (proposed in Docket No. 69-19, notice 3) in the stop-turn mode may be due to the separate stop inhibiting perception of the turn/presence intensity change since both systems had a flashing red turn overlaid on a red presence lamp.

The static research and earlier dynamic city driving research by Mortimer (1970) demonstrates that in situations where attention level is high (e.g. in an experimental setting and/or in heavy traffic), drivers generally respond to the first (1st) flash of a turn signal. This must be the case since even in the dynamic studies using a 1.00 second flash cycle, response times to the turn signal varied from 1.01 to 1.16 seconds. Since some minimal time is required for a finger-button response, subjects must have responded to the first flash. Therefore, it is important that the first flash be an effective flash. Also, in many typical lane change maneuvers the vehicle intrudes upon the next lane after only a few flashes have occurred and the driver then cancels the turn signal. Thus, the characteristics of the turn signal during the first five (5) flashes are of practical importance in real driving situations.

For a lamp with a particular light output characteristic such as exhibited in Figure 3.2, there is a minimum time required for both the "on" and "off" durations to reach light output levels consistent with the notion of a "good flashing signal." Figure 3.2 shows that if one assumes that a flashing 1157 lamp should reach its maximum brightness in the first "on" phase, that .325 seconds is required and at 150 cpm a duty cycle of 82% "on" time is required. This "on" time can be derived for any lamp brightness criterion from the following formula:

$$\frac{\text{Time Duration (Sec) Required to}}{\text{Reach Criterion Lamp Brightness}} \div \frac{\text{Time (Sec) Required}}{\text{to Complete a Cycle}} = \frac{\text{Percent Duty}}{\text{Required}}$$

On Figure 9.1 the maximum brightness criterion is indicated by the 100% line. All points above the 100% line reach maximum brightness in the "on" phase. It is of interest that nearly one-half of the SAE J590b rectangle falls below this line. To include the entire SAE J590b rectangle requires having a line go through the lower right corner so that the entire rectangle falls above the criterion line. When this is done it is found that this criterion is 64% of maximum brightness. Clearly, if the intensity standards are meaningful they should be applied to flashing lamps in a manner that will ensure that effective intensities of flashing lamps are comparable to those of steady lamps. In other words, the minimum effective intensity should be specified to apply to both steady state (stop) signals and flashing (turn) signals. This might allow flashing signals to be of slightly reduced luminance in cases where it could be demonstrated that due to the Broca-Sulzer effect the effective intensity was greater than that obtained for a steady state light of the same luminance. However, it would require each flash of a turn signal to have an effective intensity at least equal to the minimum required by SAE J588d (turn signal lamps) which requires the same intensities for red as is required for SAE J586b (stoplamps).

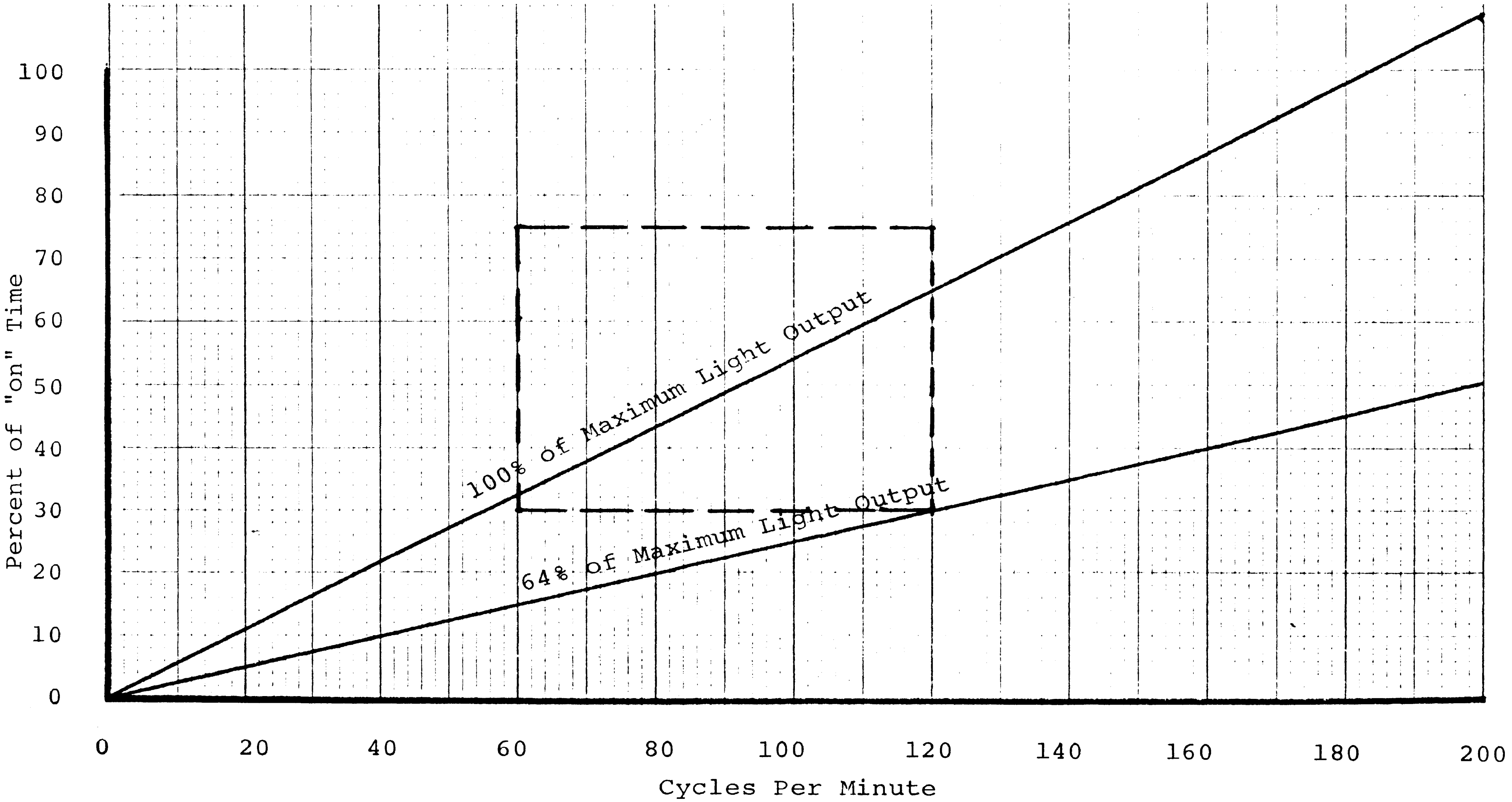

Figure 9.1. Light Output Criterion for First Flash Rise and Decay of a Type 1157 Bulb. (The rectangle represents the current parameter limits of SAE 590b and MVSS 108)

10. CONCLUSIONS

1. Subjective test data indicated that flash rates of 40-180 cpm were acceptable when combined with a reasonable duty cycle that ensured an adequate level of intensity and on/off light output contrast.

2. "On" times of 30-80% did not produce statistically different turn signal response times for flash rates of 20-180 cpm.

3. Response time data indicated that 15% "on" time was too low to be a viable duty cycle for flash rates ranging from 20-180 cpm.

4. Response time data also indicated that 25% "on" time was associated with long response times at the higher flash rates (esp. 180 cpm). The suitability of a duty cycle of 25% "on" time or less in eliciting an adequate response time depends upon the flash rate with which it is paired.

5. Flash rates of 120-180 cpm produced shorter response times than flash rates of 20-60 cpm.

6. For automotive rear lighting systems with combined function lamps the start "on" flasher is particularly disadvantageous in the stop-turn mode.

7. The difference between a start "on" and start "off" flasher is greatly decreased with increased flash rates of 120-180 cpm.

8. Duty cycles of up to 85% "on" time were capable of eliciting good response time performance. However, 85% "on" time was associated with a high missed signal rate at night when the flasher started in the "off" mode.

9. Start "off" flashers with short signal delay times, i.e., short "off"/long "on" durations paired with high flash rates, are capable of eliciting good response time performance.

10. Amber (yellow) as used in system 11 was found to be advantageous in eliciting short response times in the hazard mode and resulted in few missed signals at night.

11. RECOMMENDATIONS

1. The turn signal flasher standard should include flash rate and duty cycle for the first five consecutive cycles with attention given to ensure an adequate first and second flash.

2. The turn signal should produce at least the minimum effective intensity required for such a signal on the first flash and all subsequent flashes. [In effect this would currently require each turn signal flash to have an effective intensity of at least 80 candlepower for red lamps and 200 candlepower for yellow lamps.]

3. The turn signal should incorporate a voltage on/voltage off light contrast level equivalent to that required at the H-V for turn signal lamps combined with tail lamps (parking lamps). [In effect this would currently require a light contrast level of 5:1 for turn signals in the voltage on/off phases].

4. Flash rate, "on" time, and bulb combinations should be capable of eliciting a reasonable response time which may be approximated by response times of 1.33 seconds or less in the experimental paradigm in Study 2. This criterion should also be met where the turn signal is preceded by a stop signal. Keep in mind that response time differences in this study will be reflected in the real driving environment although response magnitudes may be increased greatly. [In effect this would determine potential flash rate, duty cycle, start mode, and system combinations. For example, flash rates of 60 cpm or less would be excluded for all duty cycles. Flash rates of 80-180 cpm would be permitted for various duty cycles between 20-85% "on" time.]

Using the currently common type 1157 bulb with a tungsten filament operated at 80 cpm on the first flash, the entire 20-85% duty cycle range could probably meet all of the above recommendations. At 120 cpm, duty cycles at the low end of the "on" time range would be prohibited. Thus, duty cycles of approximately 50-85% "on" time might be required. By 140 cpm, the duty range would be further restricted to possibly 65-85% "on" time. Flash rates of 180 cpm would meet recommendations 2 and 4 at high flash rates, but would fail to meet recommendation 3 except within a narrow band of "on" times of approximately 70-80% "on" time.

5. Research should be conducted to determine whether school bus lamp, flash rate, and "on" time combinations "permit the bulb to come up to full brightness" as is specified in SAE J887, School Bus Red Signal Lamps.

6. Research should be conducted upon the strobe light warning systems to determine their effectiveness as school bus "loading" lamps, turn or hazard warning signals, and flashing warning lamps for authorized emergency, maintenance and service vehicles. Standards should be promulgated to permit effective strobe lamps to serve these functions while prohibiting lamp light output and location combinations that are visually disabling.

7. A survey should be made of the extent of the problem caused by adding campers and various types of trailers onto vehicles equipped with fixed load flashers. Adding additional electrical load onto these flashers alters the signal to an extent that requirements of SAE J590b and J588d may both be violated. Some aspects of this problem have been noted by Ford Motor Company in docket 73-33, notice of which appeared in Federal Register, vol. 39, p. 822, 1-3-74.

8. Research should be conducted upon flashing deceleration signals to determine whether they enhance the effectiveness of rear lighting systems and whether any confounding effects occur when the turn signal is activated or the brakes are pumped while the deceleration signal is operating.

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APPENDICES

APPENDIX A

Light Output as a Function of Lamp Rise and Decay Characteristics

Tables A.1 through A.5 exhibit the percent of maximum light output obtained from various flashing signaling bulbs on the 1st, 3rd, and 6th FLASH using various duty cycles and flash rates.

Note -- a dash (-) after the percent of maximum light output obtained in the voltage off phase indicates a voltage on/off light output ratio of less than 5:1.

TABLE A.1. Percent of Maximum Light Output Obtained from Various Flashing Signaling Bulbs on the 1st, 3rd and 6th Flash Using Various Duty Cycles and a Flash Rate of 40 CPM.

	Flash Sequence Number						
	1st		3rd		6th		
	Voltage		Voltage		Voltage		Lamp
Percent "On" Time	On	Off	On	Off	On	Off	Type
25	100	0	100	0	100	0	1157
	100	0	100	0	100	0	1034
	100	0	100	0	100	0	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	0	100	0	100	0	4436
	83	0	93	0	93	0	4002
	98	0	100	0	100	0	4636
Range	83-100	0-0	93-100	0-0	93-100	0-0	
30	100	0	100	0	100	0	1157
	100	0	100	0	100	0	1034
	100	0	100	0	100	0	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	0	100	0	100	0	4436
	92	0	98	0	98	0	4002
	100	0	100	0	100	0	4636
Range	92-100	0-0	98-100	0-0	98-100	0-0	
75	100	0	98	0	97	0	1157
	100	0	100	0	100	0	1034
	100	0	100	0	100	0	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	0	100	0	100	0	4436
	100	1	100	1	100	1	4002
	100	1	100	1	100	1	4636
Range	100-100	0-1	98-100	0-1	97-100	0-1	
80	99	0	98	0	98	0	1157
	100	0	98	0	97	0	1034
	100	0	100	0	100	0	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	1	100	1	100	1	4436
	100	2	100	2	100	3	4002
	100	1	100	1	100	1	4636
Range	99-100	0-2	98-100	0-2	97-100	0-3	

TABLE A.2. Percent of Maximum Light Output Obtained from Various Flashing Signaling Bulbs on the 1st, 3rd and 6th Flash Using Various Duty Cycles and a Flash Rate of 60 CPM.

	Flash Sequence Number						
	1st		3rd		6th		
Percent "On" Time	Voltage On	Voltage Off	Voltage On	Voltage Off	Voltage On	Voltage Off	Lamp Type
25	93	0	97	0	96	0	1157
	100	0	100	0	100	0	1034
	91	0	96	0	96	0	198
	100	0	100	0	100	0	4414
	90	0	98	0	98	0	4416
	92	0	98	0	98	0	4436
	52	0	75	0	76	0	4002
	82	0	95	0	95	0	4636
Range	52-100	0-0	75-100	0-0	76-100	0-0	
30	99	0	99	0	99	0	1157
	100	0	100	0	100	0	1034
	97	0	100	0	99	0	198
	100	0	100	0	100	0	4414
	96	0	100	0	100	0	4416
	96	0	100	0	100	0	4436
	68	0	86	0	86	0	4002
	93	0	98	0	99	0	4636
Range	68-100	0-0	86-100	0-0	86-100	0-0	
75	99	0	98	0	97	0	1157
	100	0	100	0	100	0	1034
	100	0	100	0	100	0	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	1	100	1	100	1	4436
	99	5	99	6	99	6	4002
	100	2	100	2	100	2	4636
Range	99-100	0-5	98-100	0-6	97-100	0-6	
80	100	2	99	2	96	2	1157
	100	1	99	1	97	1	1034
	100	2	100	2	100	2	198
	100	0	100	0	100	0	4414
	100	0	100	0	100	0	4416
	100	2	100	3	100	3	4436
	100	9	100	9	100	9	4002
	100	3	100	4	100	4	4636
Range	100-100	0-9	98-100	0-9	96-100	0-9	

TABLE A.3. Percent of Maximum Light Output Obtained from Various Flashing Signaling Bulbs on the 1st, 3rd and 6th Flash Using Various Duty Cycles and a Flash Rate of 120 CPM.

	Flash Sequence Number						
	1st		3rd		6th		
Percent "On" Time	Voltage		Voltage		Voltage		Lamp Type
	On	Off	On	Off	On	Off	
25	47	0	68	0	67	0	1157
	69	0	88	0	85	0	1034
	37	0	65	0	62	0	198
	64	0	85	0	86	0	4414
	39	0	67	0	67	0	4416
	43	0	72	0	71	0	4436
	8	0	40	1	40	1	4002
	23	0	59	1	59	1	4636
Range	8-69	0-0	40-88	0-1	40-86	0-1	
30	64	0	81	0	80	0	1157
	84	0	94	0	91	0	1034
	54	0	77	0	75	0	198
	90	0	98	0	98	0	4414
	56	0	78	0	78	0	4416
	58	1	80	1	81	1	4436
	14	1	51	1	51	1	4002
	38	1	72	1	72	1	4636
Range	14-90	0-1	51-98	0-1	51-98	0-1	
75	100	7	100	7	98	6	1157
	100	4	99	4	99	4	1034
	100	7	100	7	100	7	198
	100	2	100	2	100	2	4414
	100	10	100	10	100	10	4416
	99	8	100	9	100	8	4436
	83	18-	97	19-	97	19-	4002
	98	11	100	11	100	11	4636
Range	83-100	2-18	97-100	2-19	97-100	2-19	
80	100	10	99	10	99	10	1157
	100	7	100	6	99	6	1034
	100	12	100	12	99	11	198
	100	4	100	4	100	4	4414
	100	15	100	15	100	15	4416
	100	13	100	13	100	13	4436
	86	25-	99	27-	99	28-	4002
	98	17	100	17	100	17	4636
Range	86-100	4-25	99-100	4-27	99-100	4-28	

TABLE A.4. Percent of Maximum Light Output Obtained from Various Flashing Signaling Bulbs on the 1st, 3rd and 6th Flash Using Various Duty Cycles and a Flash Rate of 140 CPM.

Percent "On" Time	Flash Sequence Number						Lamp Type
	1st		3rd		6th		
	Voltage		Voltage		Voltage		
	On	Off	On	Off	On	Off	
25	33	0	60	0	57	0	1157
	57	0	78	0	75	0	1034
	24	0	55	0	52	0	198
	64	0	85	0	86	0	4414
	28	0	58	0	58	0	4416
	33	0	63	0	63	0	4436
	3	0	34	1	35	1	4002
	15	0	51	1	51	1	4636
Range	3-64	0-0	34-85	0-1	35-86	0-1	
30	49	0	73	0	71	0	1157
	71	0	88	0	86	0	1034
	41	0	69	0	67	0	198
	81	0	92	0	93	0	4414
	42	0	69	0	69	0	4416
	46	1	74	1	74	1	4436
	8	1	45	1	46	1	4002
	20	1	65	1	63	1	4636
Range	8-81	0-1	45-92	0-1	46-93	0-1	
75	100	9	100	9	98	9	1157
	100	5	100	5	99	5	1034
	99	10	100	9	100	10	198
	100	4	100	4	100	4	4414
	100	13	100	13	100	13	4416
	97	11	100	12	100	11	4436
	73	20-	95	23-	96	24-	4002
	94	14	100	15	100	15	4636
Range	73-100	4-20	95-100	4-23	96-100	4-24	
80	99	13	100	14	99	13	1157
	100	1	99	1	97	1	1034
	99	14	100	15	100	14	198
	100	7	100	7	100	7	4414
	100	18	100	18	100	19	4416
	98	16	100	18	100	17	4436
	82	26-	97	32-	97	32-	4002
	96	21-	100	21-	100	21-	4636
Range	82-100	1-26	97-100	1-32	97-100	1-32	

TABLE A.5. Percent of Maximum Light Output Obtained from Various Flashing Signaling Bulbs on the 1st, 3rd and 6th Flash Using Various Duty Cycles and a Flash Rate of 180 CPM.

	Flash Sequence Number						
	1st		3rd		6th		
	Voltage		Voltage		Voltage		
Percent "On" Time	On	Off	On	Off	On	Off	Lamp Type
25	17	0	47	0	47	0	1157
	43	0	67	0	62	0	1034
	9	0	41	0	40	0	198
	44	0	66	0	69	0	4414
	11	0	44	0	45	0	4416
	17	0	48	1	50	1	4436
	1	0	24	1	28	1	4002
	4	1-	45	2	45	2	4636
Range	1-44	0-1	24-67	0-2	28-69	0-2	
30	27	0	60	0	57	0	1157
	52	0	74	0	76	0	1034
	21	0	56	0	53	0	198
	59	0	83	0	79	0	4414
	22	0	56	0	57	0	4416
	28	1	61	2	62	2	4436
	2	1-	34	3	36	3	4002
	10	1	52	2	52	2	4636
Range	2-59	0-1	34-83	0-3	36-79	0-3	
75	94	13	99	13	97	14	1157
	100	10	100	10	99	9	1034
	90	14	99	15	99	14	198
	100	7	100	7	100	7	4414
	90	18	99	21-	99	19	4416
	91	17	99	17	98	17	4436
	52	20-	92	31-	92	31-	4002
	82	19-	98	21-	98	22-	4636
Range	52-100	7-20	92-100	7-31	92-100	7-31	
80	96	18	99	20-	98	20-	1157
	100	15	100	14	99	15	1034
	90	20-	99	21-	98	21-	198
	100	12	100	12	100	12	4414
	92	25-	100	26-	100	25-	4416
	93	23-	99	25-	99	24-	4436
	58	26-	95	40-	95	40-	4002
	85	26-	100	30-	100	30-	4636
Range	58-100	12-26	95-100	12-40	95-100	12-40	

APPENDIX B

Instructions for the Subjective Evaluation of Turn and Hazard Warning Signals

Please rate the signals presented for their effectiveness in presenting a TURN or HAZARD WARNING signal. An effective TURN or HAZARD WARNING (i.e., Emergency Flasher) signal should quickly attract your attention. It should be easily perceived and be clearly distinguishable from other signals (i.e., not confusing). Both TURN signals and HAZARD WARNING signals will be presented, while rate of flash, light duration, and brightness are varied. Choose a number from the rating scale below which represents your opinion regarding the effectiveness of the TURN or HAZARD WARNING signal.

Record your answer next to the number of the trial presented. When trial numbers are announced, please check to see that you are on the right number. Print your name, sex and age. Three practice trials (A,B,C) will now be shown, after which any questions you may have will be answered.

RATING SCALE FOR EFFECTIVENESS OF TURN AND HAZARD WARNING SIGNALS

1	2	3	4	5
Not Effective at all Unsatisfactory)	Very Poor Signal Effectiveness	Satisfactory Signal Effectiveness	Very Good Signal Effectiveness	Extremely Effective

Name____________________Sex___Age___Account 012988

A__________ B__________ C__________

D __________ E __________ F __________

APPENDIX C

Instructions for the Objective Evaluation of Turn and Hazard Warning Signals

In this experiment, you are requested to respond to various kinds of signal presentations. Each of you will have a small white response box, which you should hold with both hands. Your left thumb should be so positioned that you can press either the "LEFT" or "LEFT TURN" buttons easily and rapidly. Similarly, your right thumb should be so positioned that you can press either the "RIGHT" or "RIGHT TURN" buttons easily and rapidly. The button labeled "STOP" can be pressed with either your left or right thumb. Try now holding the box and pressing these various buttons.

Your primary task will be to respond to the near signal lights, located on the bar with the white light about 50 feet in front of these vehicles. Whenever the red light on the left of this bar comes on, respond as quickly as possible by pressing the upper left button ("LEFT") with your left thumb. Similarly, whenever the red light on the right side of this bar comes on, respond as quickly as possible by pressing the upper right button ("RIGHT") with your right thumb. If you make a mistake, for instance you press the left button when the right red light is on, correct yourself as soon as possible. This is your primary task so please concentrate by focusing on this near set of lights which represent signals which might be given by a car immediately ahead of you. Your responses to these near signal lights are being monitored and recorded throughout the experiment, except for those times when I will tell you specifically to take a break.

The "Driver One" participant should respond to these near lights not by using the thumb switches, but instead by using the single foot switch located below the dimmer switch on the floor. Driver, would you press that switch with your left foot a couple times to get the feel of it? Let your left foot gently rest on that switch. Respond to the near right or left lights by pressing on the footswitch. Both left and right near focus lights can be responded to in this way.

(cont.)

APPENDIX C [cont.]

Your second task will be to respond to the far signal lights, located on the car at the end of the driveway. Occasionally, a left turn signal, right turn signal, stop signal, or a hazard signal will be presented on that vehicle. Whenever you see a flashing light on the left side of the rear of that car, respond as quickly as possible by pressing the button labeled "LEFT TURN" with your left thumb. Similarly, whenever you see a flashing light on the right side on the rear of that car, respond as quickly as possible by pressing the button labeled "RIGHT TURN" with your right thumb. Whenever you see a stop signal on that car, respond by pressing the button labeled "STOP" with either your left or right thumb. And when you see a hazard warning (both flashing) press both "TURN" buttons. Occasionally, overlapping signals be presented and you are to respond to these in the order that you see them. If you make an error in responding to these signals, please correct yourself as soon as possible.

We will now show you what these signals look like on that car. (Radio request: Are there any questions:
LEFT TURN, STOP, HAZARD, STOP→RIGHT TURN)

During this experiment, we ask that you not smoke, and that you not talk about any phase of the experiment with the other participants. If you have any questions, we would like to answer them now. If any occur to you during the experiment, please wait until one of the break periods unless it is urgent.

If there are no further questions, we shall start with a practice run. Begin responding to the near lights please. Signals on the far car will start shortly. Primarily, your task is to correctly and quickly respond to the near focus lights. Secondarily, you should also respond to the far signal lights as they occur. (They should respond to the near focus lights for about 30 sec before starting the practice signals. After 12-24 signal presentations and as soon as it appears that asymptotic performance is established for both the near focus and far signal lights for all subjects, the practice should be terminated.)

This terminates the practice run. Are there any further questions at this point? (Change test car from 4 red lamp separated stop system [HSRI-system 6] to the first experimental system.) We will now demonstrate what the rear signals will look like using a different system on the same car. (Radio request: LEFT TURN, STOP, HAZARD, STOP→RIGHT TURN) Are there any questions? Please be alert now and start responding to both the near focus lights and the far signal lights as they occur as we are starting testing now. (After all trials are completed including repeats, demonstrate the next system and continue.)

APPENDIX D

ANOVA1

```
LOG TRANSFORMED RT DATA ANALYSIS


TRANSFORMATION IS: NAT. LOG   SCORES INCREMENTED BY   0.0

   FACTOR     LEVEL      MEAN

     MODE
                  1 0.4907602
                  2 0.2777538
                  3 0.3643631

     RATE
                  1 0.5929437
                  2 0.4628385
                  3 0.3917150
                  4 0.2630268
                  5 0.2724599
                  6 0.2829685

     DUTY
                  1 0.3675733
                  2 0.3506601
                  3 0.3936436
                  4 0.3986557

     SYST
                  1 0.5337217
                  2 0.3539239
                  3 0.2452381

     SUBJ
                  1-0.1277090
                  2 0.4780343
                  3 0.6912416E-01
                  4 0.5764564
                  5 0.1852942
                  6 0.3086770
                  7 0.5447315
                  8 0.8808022
                  9 0.4550788
                 10 0.4837584
                 11 0.2061364
                 12 0.3468450
                 13 0.3678591
                 14 0.2799722
                 15 0.2482405
                 16 0.3480357
                 17 0.4469182
                 18 0.7004557

     AMB
                  1 0.4323213
                  2 0.3229358

 GRAND MEAN         0.3777149
```

(cont.)

APPENDIX D [cont.]

```
LOG TRANSFORMED RT DATA ANALYSIS

    FACTOR CODES

     A      EQUALS   MODE
     B      EQUALS   RATE
     C      EQUALS   DUTY
     D      EQUALS   SYST
     E      EQUALS   SUBJ
     F      EQUALS   AMB

          DIVISION OF VARIANCE

SOURCE OF                SUMS OF    DEGREES OF   MEAN              RATIO    Percent of
VARIATION                SQUARES     FREEDOM     SQUARES                     Variance

E..............         391.8037        17       23.04727          ------      11.9

A..............         59.48778         2       29.74388          59.405*     15.8
AE.............         17.02382        34      0.5007005         0.0

B..............         112.7493         5       22.54985          139.22*     11.7
BE.............         13.76728        85      0.1619679         0.0

AB.............         31.52881        10       3.152881          19.956*      1.6
ABE............         26.85828       170      0.1579899         0.0

C..............         2.968816         3      0.9896052          2.9139
CE.............         17.32043        51      0.3396164         0.0

AC.............         4.936690         6      0.8227817          6.6252*
ACE............         12.66737       102      0.1241899         0.0

BC.............         8.474456        15      0.5649637          3.4009*
BCE............         42.36153       255      0.1661236         0.0

ABC............         8.260313        30      0.2753437          2.1068*
ABCE...........         66.65292       510      0.1306920         0.0

D..............         110.0535         2       55.02675          71.911*     28.5
DE.............         26.01717        34      0.7652107         0.0

AD.............         44.73705         4       11.18426          48.678*      5.8
ADE............         15.62368        68      0.2297601         0.0

BD.............         58.96431        10       5.896431          27.941*      3.1
BDE............         35.87581       170      0.2110341         0.0

ABD............         16.96429        20      0.8482147          6.4362*
ABDE...........         44.80763       340      0.1317871         0.0

CD.............         18.91171         6       3.151952          16.199*      1.6
CDE............         19.84654       102      0.1945739         0.0

ACD............         5.793342        12      0.4827784          3.3825*
ACDE...........         29.11626       204      0.1427267         0.0

BCD............         4.731447        30      0.1577149          1.1010
```

APPENDIX D [concl.]

BCDE............	73.05423	510	0.1432436	0.0	
ABCD............	10.12616	60	0.1687694	1.1677	
ABCDE..........	147.4190	1020	0.1445284	1.0501	
F..............	23.26649	1	23.26649	7.9274**	12.1
EF.............	49.89392	17	2.934937	0.0	
AF.............	6.797844	2	3.398922	6.9660*	1.8
AEF............	16.58954	34	0.4879276	0.0	
BF.............	5.089755	5	1.017951	7.3119*	
BEF............	11.83357	85	0.1392184	0.0	
ABF............	2.471883	10	0.2471883	1.4790	
ABEF...........	28.41316	170	0.1671362	0.0	
CF.............	4.712893	3	1.570964	7.7927	
CEF............	10.28129	51	0.2015938	0.0	
ACF............	2.712962	6	0.4521604	3.5741*	
ACEF...........	12.90419	102	0.1265116	0.0	
BCF............	7.667194	15	0.5111462	3.2211*	
BCEF...........	40.46478	255	0.1586854	0.0	
ABCF...........	4.705924	30	0.1568641	1.0324	
ABCEF..........	77.49156	510	0.1519442	1.1040	
DF.............	5.330616	2	2.665308	8.5080*	1.4
DEF............	10.65123	34	0.3132715	0.0	
ADF............	2.045413	4	0.5113533	2.5933	
ADEF...........	13.40852	68	0.1971841	0.0	
BDF............	4.009102	10	0.4009101	2.6695*	
BDEF...........	25.53082	170	0.1501813	0.0	
ABDF...........	2.198914	20	0.1099457	0.74163	
ABDEF..........	50.40451	340	0.1482486	1.0772	
CDF............	0.4801649	6	0.8002746E-01	0.46225	
CDEF...........	17.65878	102	0.1731253	0.0	
ACDF...........	3.203741	12	0.2669784	2.0146	
ACDEF..........	27.03452	204	0.1325221	0.96290	
BCDF...........	4.943233	30	0.1649411	1.1536	
BCDEF..........	72.91750	510	0.1429754	1.0388	
ABCDF..........	10.55714	60	0.1759523	1.2785	
ABCDEF.........	140.3813	1020	0.1376287	0.0	
TOTAL	2174.961	7775	193.058		85.8

NUMBER OF REPLICATIONS 1

* $\alpha \leq .01$

** $\alpha \leq .05$

APPENDIX E

ANOVA2

```
LOG TRANSFORMED RT ANALYSIS OF START ON/OFF FOR STOP-TURN


TRANSFORMATION IS: NAT. LOG   SCORES INCREMENTED BY   0.0

   FACTOR     LEVEL      MEAN

     MODE
                       1 0.5770149
                       2 0.3013052
                       3 0.4531767
                       4 0.4373670

     RATE
                       1 0.7741777
                       2 0.5595959
                       3 0.4312087
                       4 0.2934424
                       5 0.2949725
                       6 0.3000528

     DUTY
                       1 0.4355832
                       2 0.4294183
                       3 0.4438617
                       4 0.4599964

     SYST
                       1 0.4780646
                       2 0.4063414

     SUBJ
                       1-0.1321570E-01
                       2 0.5468867
                       3 0.1489101
                       4 0.6582320
                       5 0.2387692
                       6 0.3586680
                       7 0.6923745
                       8 0.9414418
                       9 0.5313785
                      10 0.5812827
                      11 0.2692571
                      12 0.3982070
                      13 0.4269266
                      14 0.2287622
                      15 0.2757377
                      16 0.4130290
                      17 0.5025954
                      18 0.7619647

     AMB
                       1 0.4829026
                       2 0.4015139

  GRAND MEAN          0.4422979
```

(cont.)

APPENDIX E [cont.]

LOG TRANSFORMED RT ANALYSIS OF START ON/OFF FOR STOP-TURN

FACTOR CODES

A EQUALS MODE
B EQUALS RATE
C EQUALS DUTY
D EQUALS SYST
E EQUALS SUBJ
F EQUALS AMB

DIVISION OF VARIANCE

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	RATIO	Percent of Variance
E..............	365.0605	17	21.47414	-----	12.9
A..............	65.96484	3	21.98828	52.665*	13.2
AE.............	21.29309	51	0.4175116	0.0	
B..............	216.7637	5	43.35272	203.95*	26.1
BE.............	18.06845	85	0.2125700	0.0	
AB.............	39.00185	15	2.600122	18.049*	1.6
ABE............	36.73523	255	0.1440597	0.0	
C..............	0.9099137	3	0.3033046	0.66441	
CE.............	23.28163	51	0.4565026	0.0	
AC.............	28.11278	9	3.123642	25.399*	1.9
ACE............	18.81613	153	0.1229813	0.0	
BC.............	5.107799	15	0.3405199	2.0487	
BCE............	42.38504	255	0.1662158	0.0	
ABC............	23.79257	45	0.5287238	3.6482*	
ABCE...........	110.8692	765	0.1449270	0.0	
D..............	8.889784	1	8.889784	8.7111*	5.4
DE.............	17.34879	17	1.020516	0.0	
AD.............	91.12375	3	30.37457	81.427*	18.3
ADE............	19.02441	51	0.3730277	0.0	
BD.............	12.24722	5	2.449443	12.199*	1.5
BDE............	17.06696	85	0.2007877	0.0	
ABD............	30.87352	15	2.058234	13.125*	1.2
ABDE...........	39.98718	255	0.1568124	0.0	
CD.............	13.15469	3	4.384896	21.373*	2.6
CDE............	10.46335	51	0.2051638	0.0	
ACD............	3.560726	9	0.3956362	2.5230	
ACDE...........	23.99231	153	0.1568124	0.0	
BCD............	2.444785	15	0.1629856	0.94413	

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BCDE............	44.02058	255	0.1726297	0.0	
ABCD............	6.731659	45	0.1495924	0.94410	
ABCDE..........	121.2136	765	0.1584491	1.0651	
F..............	11.44961	1	11.44961	3.8849	6.9
EF.............	50.10243	17	2.947202	0.0	
AF.............	5.701736	3	1.900578	6.3263*	1.1
AEF............	15.32162	51	0.3004239	0.0	
BF.............	3.820708	5	0.7641416	4.5900*	
BEF............	14.15079	85	0.1664799	0.0	
ABF............	5.223611	15	0.3482407	2.0472	
ABEF...........	43.37727	255	0.1701069	0.0	
CF.............	2.533901	3	0.8446337	2.6264	
CEF............	16.40099	51	0.3215879	0.0	
ACF............	4.840512	9	0.5378346	3.5609*	
ACEF...........	23.10918	153	0.1510403	0.0	
BCF............	6.129074	15	0.4086049	2.2238*	
BCEF...........	46.85501	255	0.1837451	0.0	
ABCF...........	7.505556	45	0.1667901	1.0923	
ABCEF..........	116.8163	765	0.1527010	1.0265	
DF.............	5.251675	1	5.251675	25.736*	3.2
DEF............	3.469057	17	0.2040622	0.0	
ADF............	1.936294	3	0.6454312	3.8095	
ADEF...........	8.640761	51	0.1694267	0.0	
BDF............	2.157038	5	0.4314075	3.0896	
BDEF...........	11.86878	85	0.1396327	0.0	
ABDF...........	2.772246	15	0.1848164	1.1474	
ABDEF..........	41.07449	255	0.1610764	1.0828	
CDF............	0.2878613E-01	3	0.9595376E-02	0.56640E-01	
CDEF...........	8.639869	51	0.1694092	0.0	
ACDF...........	2.288748	9	0.2543053	1.6652	
ACDEF..........	23.36536	153	0.1527147	1.0266	
BCDF...........	2.193110	15	0.1462073	0.87524	
BCDEF..........	42.59712	255	0.1670475	1.1229	
ABCDF..........	9.905876	45	0.2201306	1.4797	
ABCDEF.........	113.8032	765	0.1487623	0.0	
TOTAL	2131.637	6911	166.1406		82.8%

NUMBER OF REPLICATIONS 1

* $\alpha \leq .01$