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Enhanced Rear Lighting and Signaling Systems Task 2 Report:

Testing and Optimization of High-Level and Stopped/Slowly-Moving Vehicle Rear Signaling Systems

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16. Abstract

Rear-end crashes account for approximately 25% of all crashes and result in a substantial number of injuries and fatalities each year. The goal of this research effort is to develop and test a small number of enhanced rear-lighting concepts that have the potential to reduce the number of rear-end collisions, including crashes with stopped or slowly-moving vehicles. This document reports on Task 2 of the research effort, which consisted of two experiments to design and optimize systems with regard to four dependent measures (Attention-Getting Rating, Discomfort-Glare Rating, Horizontal Peripheral Detection Angle, and Diagonal Peripheral Detection Angle) while also taking system complexity into account.

In Experiment 1, 12 subjects evaluated 17 configurations. These configurations included variants of the Task 1 recommendations as well as baseline systems, including several highly attention-getting devices. Experiment 1 was conducted using white lights and clear lenses to provide a consistent comparison across all configurations. The results showed that the Traffic Clearing Light (TCL), a lamp with a motorized reflector moving in an "M-sweep" pattern, was the top candidate for a high-level signal (e.g., for imminent crash warning), while a pair of centrally located alternating halogen lamps would be optimal for a stopped/slowly-moving vehicle signal.

Experiment 2 also used a mixed factors design with 12 subjects to evaluate four configurations (the TCL, along with three variations of the alternating halogen lamp pair) and three lens tints (clear, amber, and red). The results showed that the TCL was superior to the alternating pair configurations in attention-getting and peripheral detection and would thus be best used as the high-level signal with tinted lenses in either red or amber. The results also suggested that the high-output halogen alternating pair with dispersive lenses represents the best available configuration for the stopped/slowly-moving vehicle signal with tinted lenses in either red or amber.

The final system recommendation is for an additional three-lamp bar to be mounted somewhere below the CHMSL. The center lamp would be the high-level signal and would consist of the TCL with a nondispersive red lens. The outside signal pair would be the stopped/slowly-moving vehicle signal and would consist of the high-output halogen alternating pair with dispersive amber lenses. The recommended final system is fully described in terms of functional requirements and system specifications. The report also contains an appendix describing the algorithms to be used for the activation of each signal type. These two elements combine to completely specify a promising rear signaling system to the point of readiness for further system development and field or fleet testing.

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ABSTRACT

Rear-end crashes are the most frequently occurring type of crash, making up approximately 25% of all crashes. There were an estimated 1,848,407 rear-end crashes in 1999, out of a total of 6,271,524 crashes (29.5%; GES database), resulting in 951,822 injuries (GES database) and 2,195 fatalities (FARS database). Rear-end crashes in which the lead vehicle is stopped or moving very slowly prior to the collision are an especially serious problem, accounting for about two-thirds of all rear-end crashes. The magnitude of the rear-end crash problem has been a source of concern for a number of years, and much effort has been put forth to reduce this type of crash.

In-depth analyses of rear-end crashes have shown that approximately 60% of daytime rear-end crashes occur when the driver of the following vehicle is looking away from the lead vehicle. Approximately 25% of rear-end crashes occur when the driver of the following vehicle is looking at, but not seeing, the lead vehicle due to inattention or distraction. Thus, there is a need to detect stopped and slowing lead vehicles with peripheral vision, as well as a need to detect stopped and slowing lead vehicles with foveal vision more quickly.

Researchers at the Virginia Tech Transportation Institute (VTTI) conducted two experiments in an effort to develop systems that are potentially more attention-getting in the forward field of view and can be seen further into the peripheral field of view, yet do not have an unacceptable amount of discomfort glare. Both experiments used the same four dependent measures: Attention-Getting Rating, Discomfort-Glare Rating, Horizontal Peripheral Detection Angle, and Diagonal Peripheral Detection Angle.

Experiment 1 used a mixed factors design. There were three independent variables: gender and age group (between-subjects), each with two levels; and configuration (within-subject), with 17 levels. There were twelve participants, 6 younger (ages 21 to 28) and 6 older (ages 59 to 70), with each age group balanced for gender. The 17 configurations covered the gamut from simple to complex, including several highly attention-getting devices. The 17 configurations were variants of the recommendations from Task 1 of the project (light bar, strobes, and additional simpler attention-getting systems) as well as baseline systems (constant on, flashing, and single/dual devices). This initial experiment was conducted using white lights and clear (non-tinted) lenses to provide a consistent comparison across all configurations.

The Experiment 1 results showed that the Traffic clearing light (TCL), a lamp with a motorized reflector that moves in an “M-sweep” pattern, was the top candidate for a high-level signal (e.g., for imminent crash warning), while a pair of centrally located alternating halogen lamps would be optimal for a stopped/slowly-moving vehicle signal. These conclusions were based on an analysis of all available data, including comparisons within configuration classes (e.g., all strobe lamps compared to one another) and comparisons of system complexity.

Experiment 2 also used a mixed factors design. There were four independent variables: gender and age group (between-subjects), each with two levels; configuration (within-subject), with 4 levels; and lens tint (within-subject), with three levels. There were twelve participants, 6 younger (ages 20 to 28) and 6 older (ages 53 to 63), with each age group balanced for gender.

The configurations tested included the TCL, a medium-output halogen alternating lamp pair with dispersive lenses, a medium-output halogen alternating lamp pair with nondispersive lenses, and a high-output halogen alternating pair with dispersive lenses. Each of the four configurations was tested with lenses in three different tints: clear, amber, and red.

The Experiment 2 results showed that the TCL is superior to the alternating pair configurations in attention-getting and peripheral detection; however, it possesses somewhat higher levels of discomfort glare, a shortcoming that can be offset to some degree by the use of tinted lenses in either red or amber. The results also suggest that the high-output halogen alternating pair with dispersive lenses represents the best available configuration for the stopped/slowly-moving vehicle signal. Once again, either amber or red appears satisfactory for use in a modified rear-lighting system.

The final system recommendation is for an additional (to the rear-lighting system as it currently exists) three-lamp bar to be mounted somewhere below the CHMSL (either directly below in the trunk lid, or midway between the bumper and the CHMSL). The center lamp would be the high-level signal and would consist of the TCL. The outside signal pair would be the stopped/slowly-moving vehicle signal and would consist of the high-output halogen alternating pair. The TCL would use a nondispersive lens in red (red was chosen mainly for the sake of consistency in the need for heavy braking). The alternating pair would use dispersive lenses in amber (the overriding consideration for the selection of amber is that the signal is cautionary).

The recommended final system is fully described in terms of functional requirements and system specifications. The report also contains a lengthy appendix describing the algorithms to be used for the activation of each signal type. These two elements combine to completely specify a promising rear signaling system to the point of readiness for further system development and field or fleet testing.

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The opinions, findings, and recommendations contained herein are those of the authors and do not necessarily represent those of NHTSA or any other organization.

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INTRODUCTION TO THE TASK 2 EXPERIMENTS

Purpose

This study had two purposes: 1) to optimize the parameters of the lighting configurations to be used for Task 3, the limited field tests; and 2) to determine which configurations have the greatest daytime attention-getting levels, lowest annoyance/glare level, and greatest peripheral vision detectability, while possessing minimal system complexity.

General Operating Hypotheses

- Approximately 68% of rear-end crashes occur in broad daylight under good weather conditions. This condition is such that current rear-lighting standards are least effective (have lowest contrast).
- Hypothesized model of drivers in broad daylight rear-end crashes:
    1. Approximately 60% of drivers are looking away from the vehicle in front of them, either into the vehicle or out of the vehicle in another direction (visual distraction or visual wandering).
    2. Approximately 20% of drivers are looking in the vicinity of the vehicle in front of them, but are not perceiving it (not paying sufficient attention/daydreaming/looking but not seeing).
    3. Approximately 5% of drivers are paying attention but are unable to judge that the closing rate is too high to avoid a crash (or not perceiving the closing rate in time).
    4. Approximately 15% of rear-end crashes are the result of all other causes.
- There is a need to detect stopped and slowing lead vehicles with peripheral vision (approximately 60% of daytime rear-end crashes).
- There is a need to detect stopped and slowing lead vehicles with foveal vision more quickly (approximately 25% of rear-end crashes).
- Signal saliency must be greater for use in daytime than it is now.
- Any system that is capable of providing adequate luminance (attention-getting qualities) in broad daylight must be attenuated in subdued light or at night.

Therefore, the solution is to develop/evolve configurations with the highest saliency and acceptable annoyance levels, with good or best detectability in peripheral vision. Hardware complexity and signal coding aspects must also be taken into account. Tests were set up to accomplish this.

Review of the Task 1 Results

A major subtask for Task 1 of this project was to conduct a trade study analysis using an expert group to help evaluate several rear-lighting candidates for further study. The Kepner-Tregoe trade study technique was used. This technique is helpful when a decision must be made between two or more alternatives (in this case, enhanced rear-lighting concepts). As implemented for the purposes of this project, the technique had three main steps. First, the criteria against which each alternative would be judged were developed with the help of the expert panel. Second, these criteria were divided into MUSTs and WANTs, with MUSTs being those criteria that each alternative must have in order to qualify for further consideration, and WANTs being those attributes that are desirable for the alternatives under consideration but which are not absolutely necessary. During this second step, the WANTs were weighted according to their overall importance, again by the expert panel. In the third step, the concepts were presented to the experts, who rated them according to how well they met the MUSTs and WANTs criteria. In a final, in-house step, the weightings developed in step 2 were multiplied by the ratings provided by the experts in step 3 to determine which alternatives had the highest overall score (and thus best met the criteria developed in step 1).

Eight concepts were developed for consideration by the expert panel and three of these were selected as the best enhanced rear-lighting configurations. Therefore, the lighting optimization process proposed for Task 2 (the currently reported experiments) included these three configurations, in various forms, along with other promising, less complex configurations developed by the researchers. The first configuration was a sequential light bar with two modes of operation, as shown in Figure 1: inside to outside illumination of lights when the lead vehicle is undergoing heavy braking (lines 1-6), and a solid light bar when the lead vehicle is stopped or moving very slowly (line 5). The latter is an open-loop system, so named because all of the necessary information for activating and deactivating the signal comes from lead vehicle parameters.

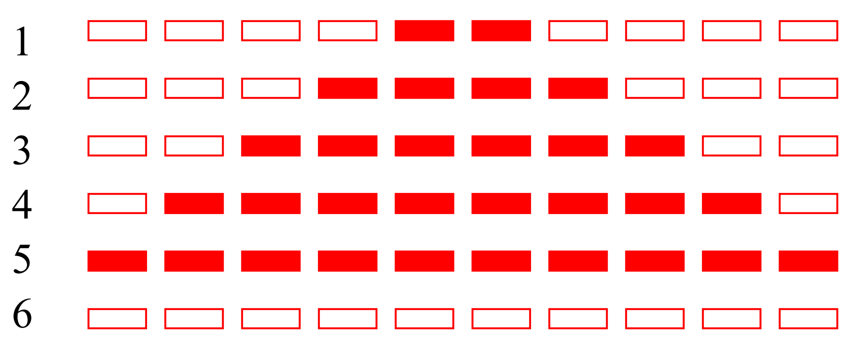


Figure 1. Open-loop, radar activated horizontal array of lights.

The second concept recommended by the expert panel consists of the same sequentially activated light bar, but in a closed-loop version. Closed loop refers to the fact that there would be feedback to the lead vehicle about the status of the following vehicle, and the light bar would be activated according to this feedback. It is anticipated that a radar or laser would be used to determine range, range rate, and angle. This configuration only uses the sequential mode (lines

1-6 in Figure 1). With the closed loop system, there would be a high probability of correct detection of an impending collision, and the system would thus be activated only rarely.

The final configuration chosen by the expert panel involves an inner/outer flash mode using strobes. Again, this system would be used only in a closed-loop system, due to its perceived high annoyance potential (it would be activated only rarely under threat of an impending collision). This system is presented in Figure 2.

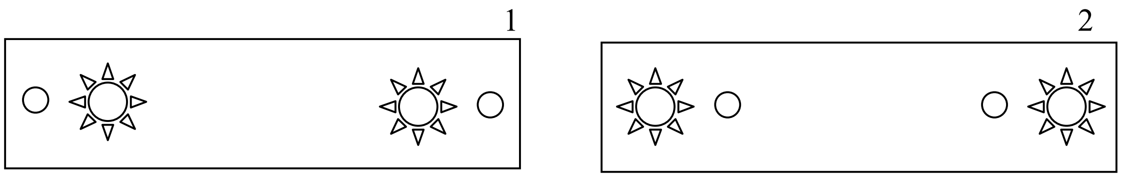


Figure 2. Closed-loop, radar-activated high-intensity strobe lights.

During completion of the Task 1 report, concern was expressed by several expert reviewers that these concepts would be too complex. A further concern was the fact that, although the activation criteria include the stopped-vehicle situation, none of these concepts includes a dedicated stopped-vehicle signal. Therefore, additional, simpler signals were also considered during the development of this Task 2 workplan, along with the concepts recommended above.

General working hypotheses developed during Task 1

- Current rear-lighting standards are such that there is no information provided on the magnitude of deceleration of the lead vehicle (only brake pedal application is indicated).

- Derivations demonstrate that rapid deceleration by a lead vehicle substantially increases the required stopping distance for the following vehicle (over that for a slowly decelerating or slower constant velocity lead vehicle). (See Appendix A of this report.)

- Derivations demonstrate that a stopped/slowly moving lead vehicle requires the largest stopping distances for the following vehicle. (See Appendix A of this report.)

- Any system that is capable of providing adequate luminance (attention-getting qualities) to redirect the driver's attention in broad daylight must be used sparingly and with reasonably low false alarm rates because of glare and annoyance.

Open-loop hypotheses

- A stopped/slowly moving lead vehicle signal would be desirable because this case requires the longest stopping distances.

- A stopped/slowly-moving vehicle signal represents a difficult trade-off because it should have adequate luminance and attention-getting qualities, while minimizing annoyance to the following driver when both vehicles are stopped or moving slowly in traffic.

- A rapidly decelerating lead vehicle signal would be desirable, because this case requires long stopping distances.

- The rapidly decelerating signal should remain activated for a short time interval after the deceleration to help insure that the following driver detects the change in condition of the lead vehicle.

Closed-loop hypotheses

- A closed-loop system with a radar (or possibly a laser) installed at the rear of the lead vehicle would be capable of providing a rear-end crash warning with few missed detections and few false alarms.

- Because of the low numbers of missed detections and false alarms, a closed-loop system is not likely to cause undue annoyance. It can therefore employ high luminance and attention-getting components.

- Because of the low numbers of missed detections and false alarms, a stopped/slowly moving lead vehicle signal may not be needed in a closed-loop system. However, such a signal might be used as an enhancement to detection.

Task 2 Test Plan Detail

Specific questions to be answered

Questions for a variety of candidate configurations within the envelope of those recommended by the Task 1 results, and for a variety of simpler candidate configurations, are as follows:

1. What is the subjective salience, given a uniform color (hue)?

2. What are the subjective annoyance and/or glare, given a uniform color?

3. How well can the configuration be detected in peripheral vision, given a uniform color?

4. For two or three of the better configurations, what is the effect of color on saliency, annoyance/glare, and peripheral detection?

5. Based on the experimental data, which configuration or configurations are recommended for testing in Task 3?

Purposes of Experiments 1 and 2 of Task 2

Two experiments were run to answer the five research questions proposed above. Experiment 1 of Task 2 was intended to answer research questions 1, 2, and 3. Experiment 1 allowed the evaluation of a wide variety of rear-lighting configurations (all within the scope of the Task 1 report results) independent of color, i.e., using the same hue. This provided a fair comparison of configurations.

In the way of further explanation, it is important to understand that luminance and hue interact in human vision. Also, tinted lenses vary in transmissivity with predominant hue. Therefore, uniform hue in Experiment 1 was deemed necessary for fair initial evaluation.

Note that Tests 1 and 2 taken together make it possible to recommend one or more configurations showing the greatest promise and including color.

PROCEDURES FOR EXPERIMENT 1 OF TASK 2

This section describes in detail the methodologies used in Experiment 1. The purpose of this experiment was to evaluate 17 rear-lighting configurations in terms of their attention-getting qualities, discomfort-glare levels, and peripheral detectability.

Experimental Design

The experiment used a mixed factors design with 12 participants. The four dependent variables consisted of subjective ratings on the discomfort-glare and attention-getting qualities of 17 configurations, as well as their horizontal and diagonal peripheral detectability. There were three independent variables involved. The between-subjects variables were gender and age group, each with two levels. The within-subject variable was the configuration being evaluated, with 17 levels.

Three subjective ratings were made for each of the 17 configurations, one for discomfort glare at a distance of 40 feet (12.2m) and two for attention getting at 150 feet (45.7m). In the first attention-getting task, the subject made preliminary rating judgments while becoming familiar with the range of possible configurations. A second exposure allowed a more precise comparison of values; this revised rating was used in the final data analysis. The greatest angle of peripheral detection was measured both horizontally and diagonally, using repeated-measures ascending and descending trials.

Attention-getting rating scale

This dependent measure was intended to assess how well the display condition attracted the subject's attention. The attention-getting property of each display condition was rated by each subject on an 8-point ordinal scale as shown in Figure 3. Subjects provided their ratings verbally and the experimenter wrote them down. Subjects were also permitted to use half values (e.g., 4.5) between the anchor points. Subjects had a laminated copy of the rating scale at all times for reference purposes when providing their attention-getting ratings.

Visual Attention-Getting Rating Scale

We would like for you to rate how attention-getting this system would be when viewed again backgrounds with different levels of clutter. An uncluttered background might be one in which you are driving in a rural area with no more than one other vehicle in sight, and there are also very few billboards, traffic signals., or traffic signs. A highly cluttered background might be one in which you are driving in a highly congested urban area with many vehicles, traffic signals, traffic signs, and billboards. Tell the experimenter the number that most closely matches the attention-getting capability of the system (note the half-values such as 2.5 are permitted.

Description	Scale	Viewer's Reaction		
Not at all ***attention getting***	1	I would not notice this system, even against an uncluttered background.	NONE	DEGREE OF ATTENTION GETTING
Inconsequential level of ***attention getting***	2	I might not notice this system, even against an uncluttered background.	LITTLE BIT	
Minor level of ***attention getting***	3	I would probably notice this system, but only against an uncluttered background.		
Small level of ***attention getting***	4	I would probably notice this system, but only against a relatively uncluttered background.		
Moderate level of ***attention getting***	5	I would notice this system, even against a relatively cluttered background.	A LOT	
Quite ***attention getting***	6	I would notice this system, even against a cluttered background.		
Extensive level of ***attention getting***	7	I would definitely notice this system, even against a highly cluttered background.		
Extremely ***attention getting***	8	This system would get my attention under any circumstances.	FULLY	

Figure 3. Attention-getting rating scale.

Discomfort-glare scale

This dependent measure was intended to assess the negative aspects of each signal configuration, which was expected to consist primarily of perceptual discomfort glare. The DeBoer scale for discomfort glare was modified substantially for use in this experiment (primarily to make it more descriptive). The discomfort-glare characteristic of each display condition was rated by each subject on the modified DeBoer 9-point scale as shown in Figure 4. Again, subjects were permitted to provide half value ratings (such as 5.5). Subjects provided their ratings verbally and had a laminated copy of the scale available at all times for reference.

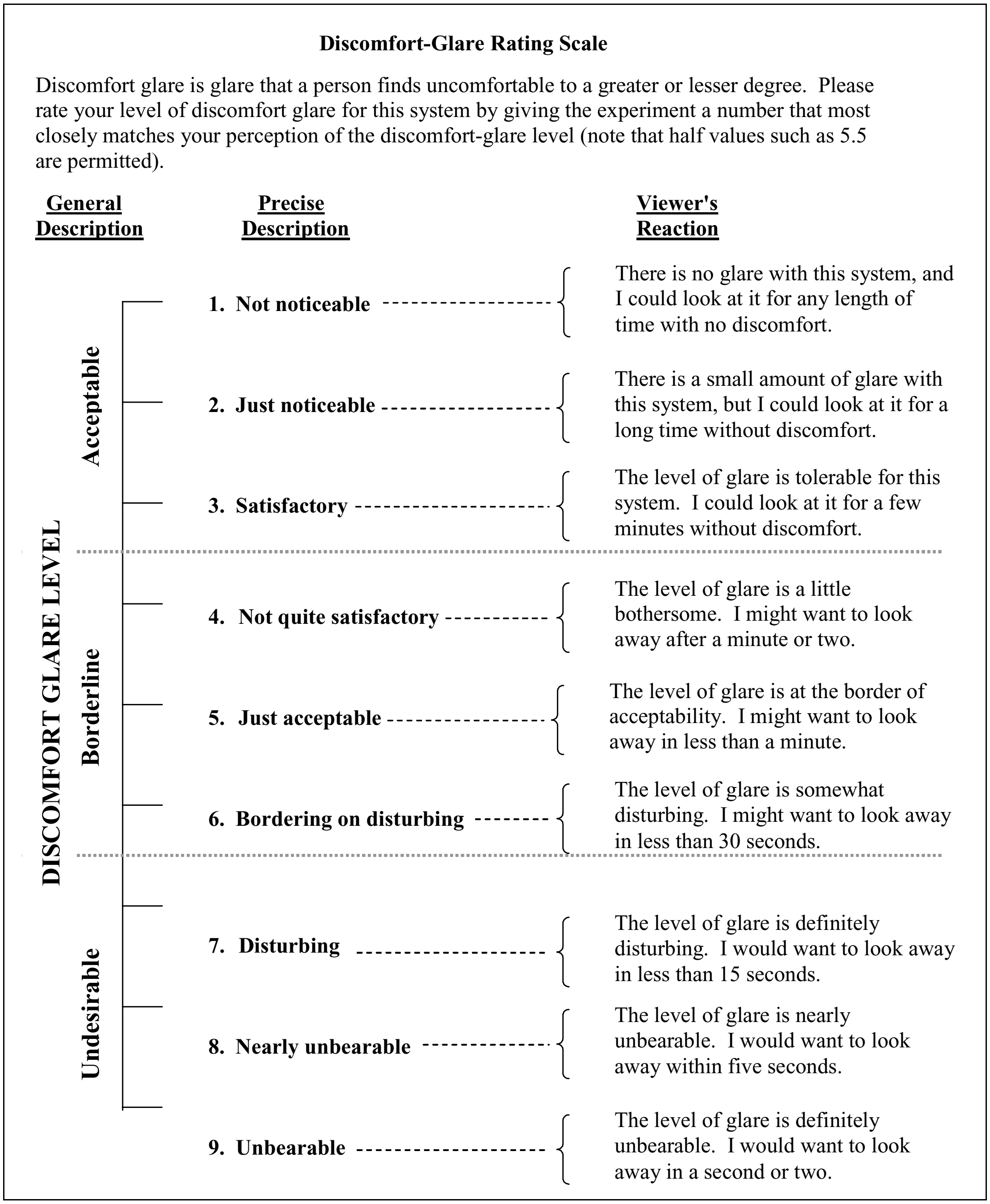


Figure 4. Discomfort-glare rating scale.

Horizontal maximum peripheral detection angle

For this measure, subjects were required to look at spots pre-positioned in the horizontal plane on the inside of the vehicle corresponding to points from 0° to 90° from the center forward view to the right. These angles correspond to common driving tasks such as scanning for adjacent vehicles through the windows and checking the right or left side rear-view mirrors. Ascending and descending trials were used; the process is described more fully in the protocol section. The experimenter noted the maximum angle at which the signal could be detected for both the ascending and descending trials, and the results were averaged. Serious discrepancies (e.g., >20°) were re-tested. The horizontal peripheral detection task is depicted in Figure 5.

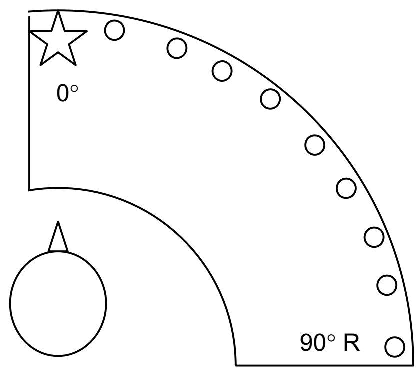


Figure 5. Horizontal peripheral detection task. This is the task as seen from above as the driver's head moves to the right.

Diagonal maximum peripheral detection angle

For this measure, subjects were required to look at spots pre-positioned on the diagonal plane on the inside of the vehicle corresponding to points from approximately 0° to 30° downward and from 0° to 60° to the right from the center forward view. These angles correspond to common in-vehicle tasks such as tuning the radio and adjusting the HVAC system. Ascending and descending trials were used, and are described more fully in the protocol section. The experimenter noted the maximum angle at which the signal could be detected for both the ascending and descending trials and the results were averaged. Serious discrepancies (e.g., >20°) were re-tested. The diagonal peripheral detection task is depicted in Figure 6, while the entire experimental layout is shown in Figure 7.

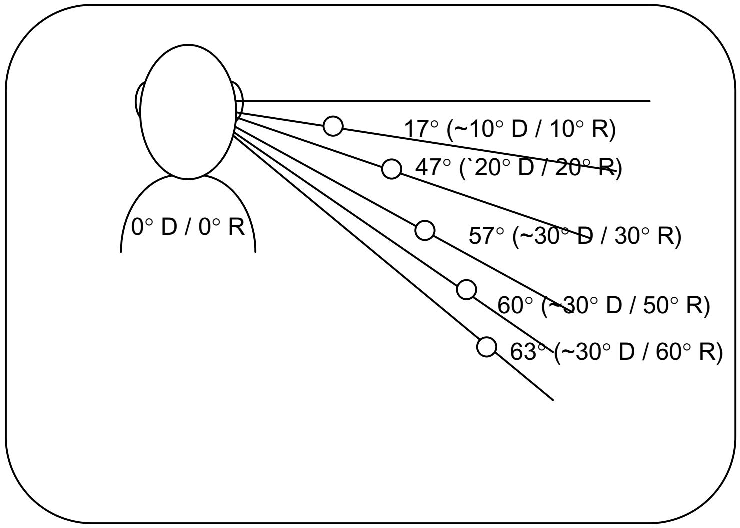


Figure 6. Diagonal peripheral detection task as seen when looking at the driver from the rear.

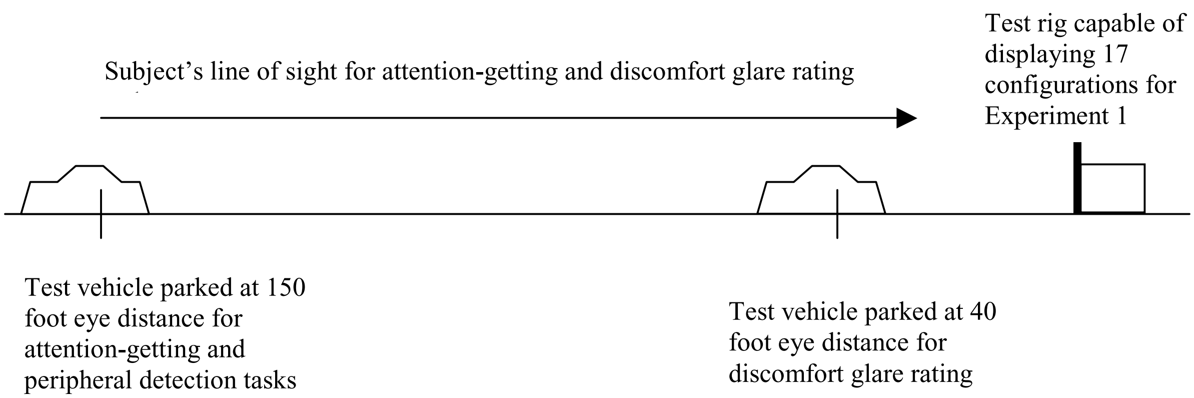


Figure 7. Experimental layout.

Participants

Twelve participants were recruited from the subject database at the Virginia Tech Transportation Institute, six younger drivers (ages 21 – 28) and six older drivers (ages 59 – 70). Of each age group, three were male and three were female to balance for gender effects. The screening criteria required that participants should be no greater than 6'1" in height and have a valid driver's license, have no history of epilepsy, and have no functionally disruptive visual problems.

If they were required to wear glasses while driving, they were also required to wear them for the experiment.

Those who chose to participate were asked to sign an Informed Consent Form. They were informed that their responses would be treated with anonymity and combined with data from 11 other subjects. Participants were also informed that they were free to refuse to answer any question or to withdraw from the study at any time without penalty; should an experiment be cut short on account of this or any other reason, the participant would be paid for the amount of time that he or she actually participated. The pay rate was $10 an hour, paid in ½ hour increments using contract funds.

Apparatus

A variety of equipment was evaluated both prior to ordering and then using bench tests once the equipment had arrived. After initial evaluation, additional equipment was ordered with the idea of filling out the configurations to be tested. With extremely careful planning and hardware design, 17 configurations were evolved. These covered the gamut from complex to simple, and represented some highly attention-getting devices. The 17 configurations are variants of the recommendations made in the Task 1 report (light bar, strobes, and additional simpler attention-getting systems) as well as baseline systems (constant on, flashing, and single/dual devices). Technology adapted from police interceptor lighting made it unnecessary to design power supplies, switching equipment, and lighting units. Lenses of various colors were also available. As indicated, Experiment 1 was conducted using white lights and clear lenses. This provided a fair comparison across all configurations. To do otherwise would have created a confound because color/hue changes the luminance (and therefore the apparent brightness) of the device.

A test rig incorporating the lighting equipment was designed and fabricated by the principal investigators and by VTTI Hardware Engineering Laboratory personnel. A manually-operated switchboard controlled 13 lights on a movable lighting assembly that allowed all 17 test configurations to be displayed and centered. The upper row consisted of eight medium-intensity halogen lamps and the bottom row consisted of four standard strobes, one high-intensity halogen lamp, one Viper strobe and one Traffic Clearing Light. Lamp parameters are presented in Appendix B. Clear lenses were used for all the lights.

White mask boards were created to fit the configurations so only the active lights could be seen. The main purpose of the mask boards was to eliminate any distraction of the subject by unlighted/unused elements of the test apparatus. The mask boards made it possible to display only those lamps in the specified configuration to be tested. To accomplish both on- and off-center use, each mask had a center section finished in white. There was also an outer section in dark gray on each side of the white section. The center section was roughly the width of a car, and the outer sections hid the lamps not used in the off-center applications. To use the masks in an off-center application, the lighting assembly was moved laterally so the lights were on a center line. Then the mask was applied on the centerline. The result was a centered display using lamps that were off-center with respect to the main test-bench. Figure 8 shows how this procedure worked for a specific application, namely, alternating strobes.

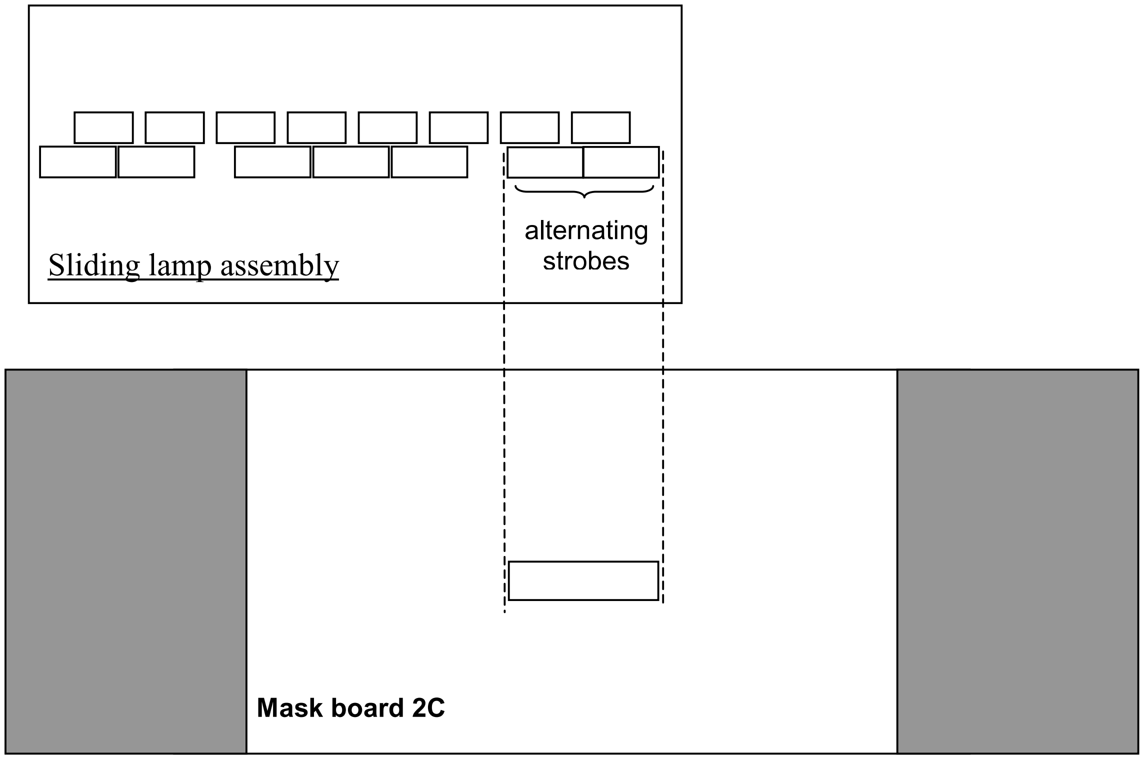


Figure 8. Use of the mask board to centrally locate the alternating strobes, even though they were not centrally located on the test bench.

Photographs of the test setup are shown in Figures 9 through 14. Specifically, Figure 9 shows the lighting rig with the mask board purposely removed to show the lighting assembly. Figure 10 shows the vehicle in which the subject sat, relative to the lighting rig and the spare mask boards. Note that the sun was always off to the right during data gathering. The vehicle is parked at the discomfort-glare rating distance of 40 feet (12.2m). Figure 11 shows the inside of the research vehicle in which the subject sat. The colored stickers on the windshield were used in the peripheral detection task. Note that the lighting rig is at the left (the picture was taken at a diagonal angle). Figure 12 shows the D lighting configuration in which all eight medium-output lamps in the light bar were illuminated. The lights actually appeared to be "brighter" to the subject than what was captured in the photo. Figure 13 shows the confederate experimenter changing the mask boards, while Figure 14 shows her operating the equipment from behind the lighting displays (with the mask board removed for purposes of explanation).

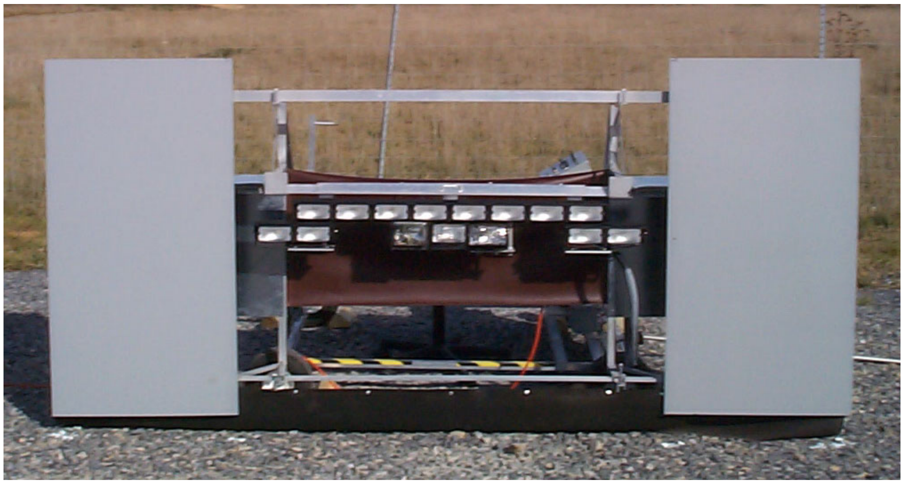


Figure 9. Test rig with mask board removed. Note that lights were attached to a frame assembly that could be moved back and forth along a rail to keep the configuration of interest centered in the mask board.

Figure 10. Subject vehicle parked at an eye distance of 40 feet from the test rig. Discomfort glare was measured at this distance, while attention getting and peripheral detection were measured at an eye distance of 150 feet. Notice the cart with spare mask boards to the left of the test rig.

Figure 11. View of the stickers used in the peripheral detection task.

Figure 12. Test configuration D: eight lamp bar with all eight lamps on continuously. (Note that actual brightness was greater than it appears in this photo.)

Figure 13. View of the confederate experimenter sliding a mask board into place.

Figure 14. Confederate experimenter operating the control panel for the experiment. With the mask board in place, the subject could not see the confederate experimenter sitting at the control panel.

The regulated power source was monitored via a digital voltmeter to insure a range of 13.8V ± 0.1V (corresponding to the voltage supplied by the electrical system of a running passenger vehicle). The rig was marked with center marks and sight lines to assist in the vertical and horizontal alignment of the vehicle at 150 feet (45.7 m) and 40 feet (12.2 m). Wooden chocks were placed at the wheels to prevent the rig from moving accidentally when mask boards were changed. Figure D3 (in Appendix D) provides a close-up view of the confederate experimenter's apparatus.

Configuration detail for Experiment 1

Seventeen configurations were tested using the test rig. All lamps were mounted on a test bench, as shown in Figure 15. All 17 configurations are described in Table 1. A section providing more detail on each configuration follows Table 1.

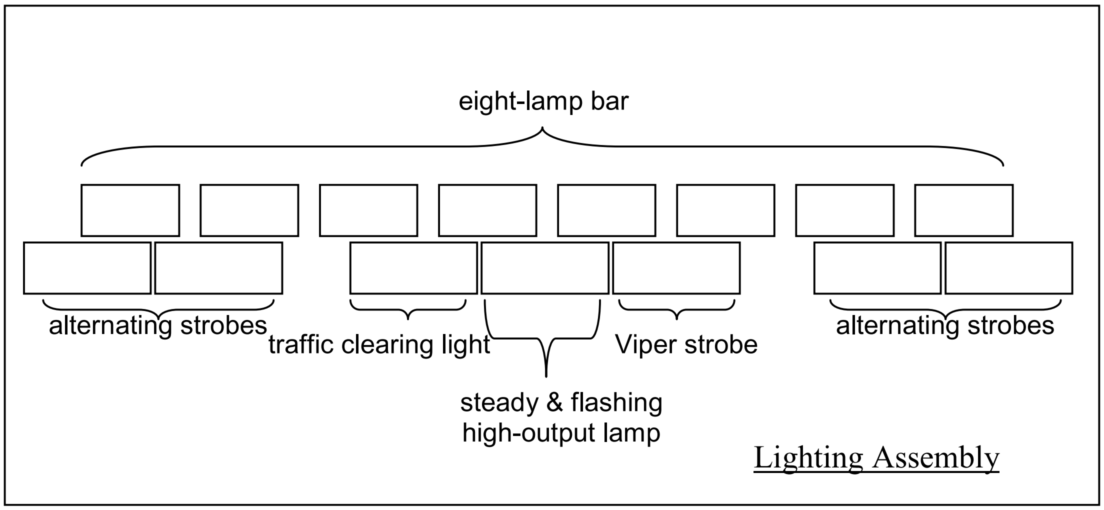


Figure 15. Lighting assembly apparatus with all lights installed for Experiment 1.

Table 1. Descriptions of 17 configurations tested in Experiment 1.

Name	Description	Type of lamps used
A. eight-lamp bar, pattern A	Produces a pattern in which the light bar lights up from the inside out, with each sequential light pair staying illuminated until the entire bar is illuminated. The cycle is approximately 1.2Hz.	Medium-output halogen
B. eight-lamp bar, pattern B	Produces a pattern in which the light bar lights up sequentially from the inside out, with each sequential light pair extinguishing as the next pair is illuminated. The outer pair flashes twice before the cycle starts again. The cycle is approximately 1.0Hz.	Medium-output halogen
C. eight-lamp bar, pattern C	Produces a pattern of four inner lights followed by four outer lights with a cycle of approximately 2Hz.	Medium-output halogen
D. eight-lamp bar, steady, undimmed	All eight lamps are illuminated and remain on during the testing.	Medium-output halogen
E. eight-lamp bar using 4 outer lamps only	The second and seventh lamps in the eight-lamp bar illuminate at the same time, then are extinguished as the first and eighth lamps are illuminated. The cycle is approximately 1.0Hz.	Medium-output halogen
F. eight-lamp bar using two outer lamps only	The two outer lamps of the eight-lamp bar flash alternately with a cycle of approximately 2Hz.	Medium-output halogen
G. eight-lamp bar using two alternating innermost lamps	The two innermost lamps of the eight-lamp bar flash alternately with a cycle of approximately 2Hz.	Medium-output halogen
H. eight-lamp bar using a flashing single center light	One of the innermost lamps of the eight-lamp bar flashes at a 2Hz rate.	Medium-output halogen
I. eight-lamp bar using a steady burning single center light	One of the innermost lamps of the eight-lamp bar burns steadily during testing.	Medium-output halogen
J. Center high-output lamp, steady	A dispersive lens is used, and the lamp burns steadily during testing.	High-output halogen
K. Center high-output lamp, flashing	A dispersive lens is used, and the lamp flashes during testing at a 2 Hz rate.	High-output halogen
Note that L, M, and N are reserved at present		
O. Quad outboard strobe	The two inner strobes flash first, followed by the outer strobes.	Moderate-output strobe
P. Dual outboard strobe	The two outermost strobes use an alternating flashing pattern.	Moderate-output strobe
Q. Dual center strobe	Two inner strobes use an alternating flashing pattern (left followed by right).	Moderate-output strobe
R. Single center strobe	The center mounted strobe flashes during testing.	Moderate-output strobe
S. Viper strobe	This programmable strobe is set to the 4-flash/off/3-flash/off pattern during testing. A nondispersive lens is used.	High-output strobe
T. Traffic clearing light (TCL)	The TLC has an “M-sweep” pattern (up and down at the same time it moves back and forth). This is center mounted. A nondispersive lens is used.	High-output halogen

Nine of the 17 configurations used the eight-lamp bar, with 4 configurations using all eight lamps and 5 using fewer than eight lamps. Three of the eight-lamp patterns follow the results of Task 1 for Concepts 5A and 5B, that is, lamps that illuminate from the center outward. Figure 16 depicts the three sequential illumination patterns used with the eight-lamp configurations. In addition, a steady burning eight-lamp pattern was tested. One four-lamp pattern, two two-lamp patterns, and two single lamp patterns were also used. The mask boards used for the eight-lamp light bar configurations are shown in Figures 17 through 21.

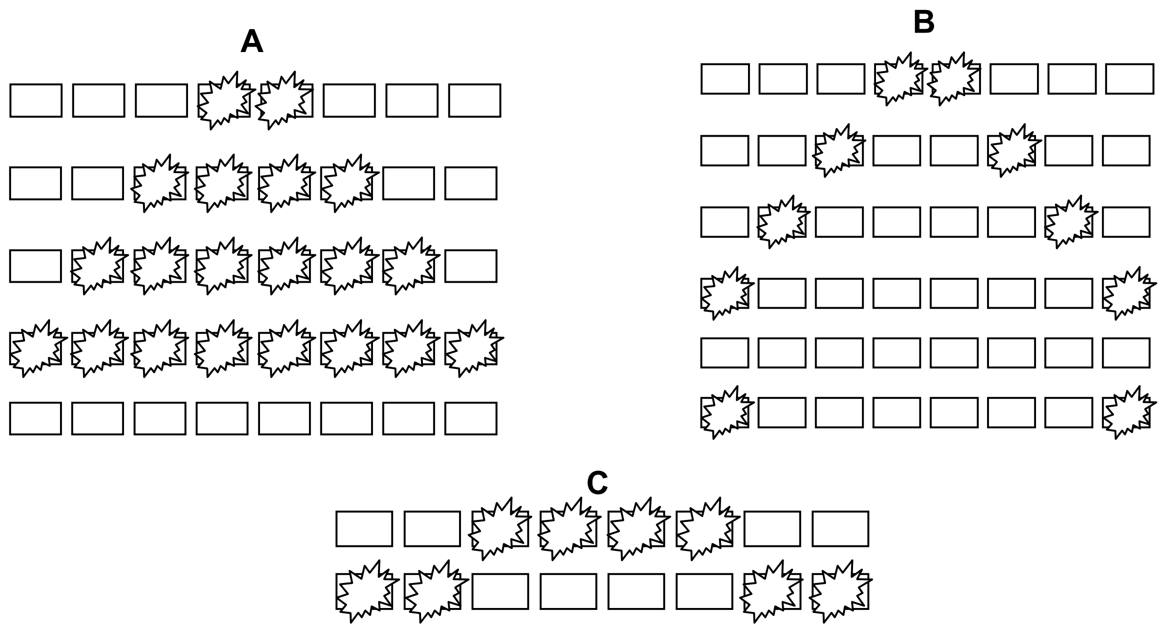


Figure 16. Three light bar patterns using inner to outer activation pattern with all eight lamps (configurations A, B, and C).

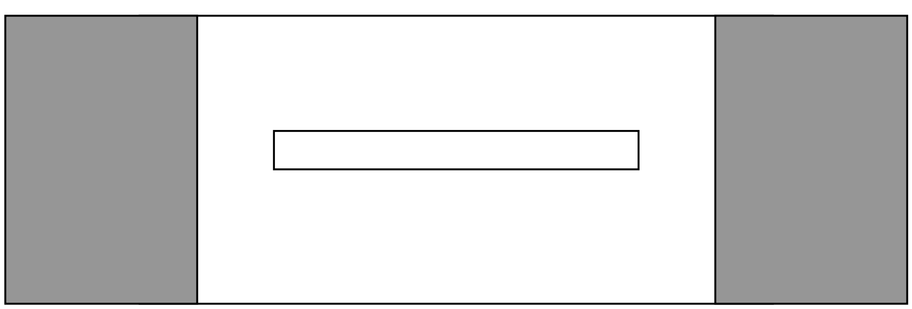


Figure 17. Mask board 1A, used with lighting configurations A to D (all eight-lamp configurations). All lamps except for the eight-lamp bar were concealed behind the mask.

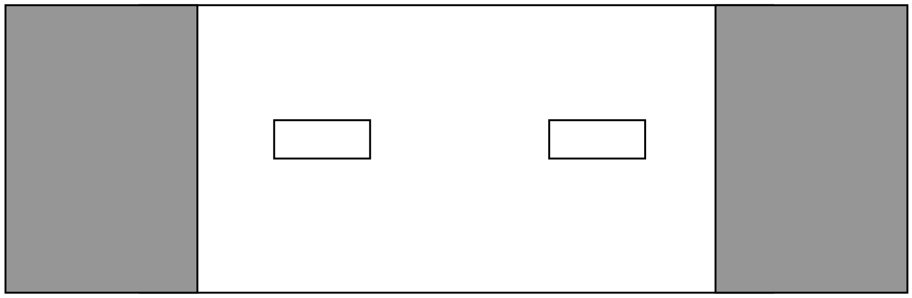


Figure 18. Mask board 1B, used with lighting configuration E, which used the four outer lamps of the eight-lamp bar.

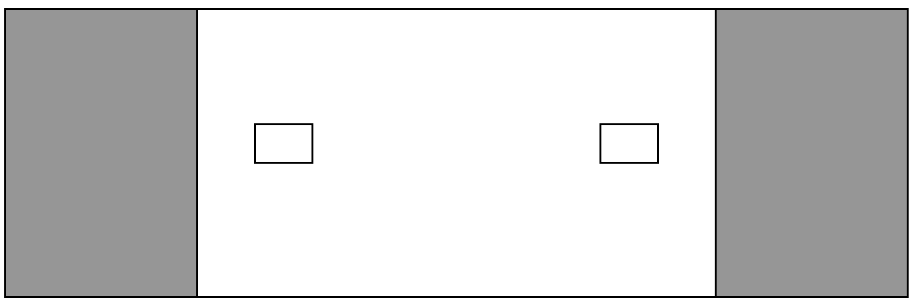


Figure 19. Mask board 1C, used with lighting configuration F, which used the two outer lamps of the eight-lamp bar.

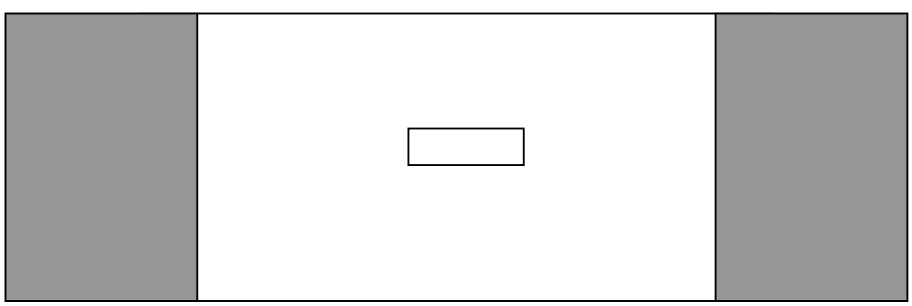


Figure 20. Mask board 1D, used with lighting configuration G, which used the two inner lamps of the eight-lamp bar.

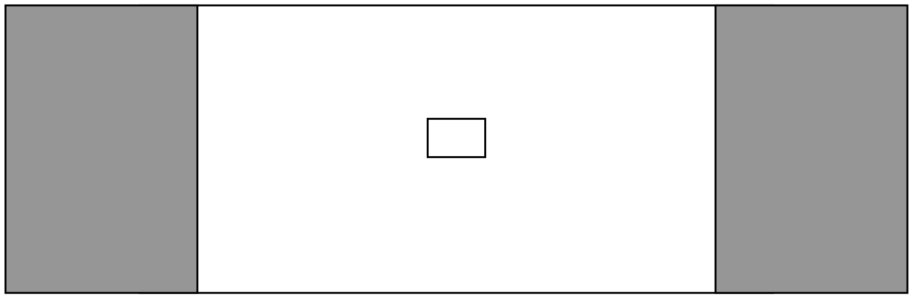


Figure 21. Mask board 1E, used with lighting configurations H and I, which both used a single inner lamp of the eight-lamp bar.

Eight other configurations were tested using the seven lamps below the eight-lamp array on the test apparatus. There were four outer strobes, arrayed according to Concept 1 of the Task 1 report. Each strobe flashed four times (in very rapid succession) and then was off for four similar timing intervals. The effect was that of a 50% duty cycle strobe. As shown in Figure 2, the two inner strobes flashed (1) followed by the outer strobes (2).

A center array was positioned between the four outer strobes. The middle device was a high-output halogen lamp and reflector with a dispersive lens. This fixed lamp was tested both in a steady mode and in a flashing mode. The traffic clearing light (TCL) was on the left, and used a high-output halogen lamp and a parabolic mirror that oscillated left-right and up-down in an "M-sweep" pattern. The beam output was very narrow and the resulting intensity was high. The "Viper" on the right was a single high-output strobe having greater than 50% duty cycle. This device had multiple patterns from which to choose. The pattern selected for testing was a 4-flash/off/3-flash/off pattern, in which the off times were short. This produced a flash pattern with greater than 50% duty cycle and the appearance of a slightly irregular pattern. The three devices in the center array were selected because they are simpler and appear to have the best chance of successfully competing with the more complex configurations. The steady burning lamp also provided a baseline condition for comparison. The mask boards for the lower array are depicted in Figures 22 through 25. (The concept of using a mask board to present a centered display for configurations that are not centrally located on the test rig lighting assembly was depicted earlier in Figure 8.)

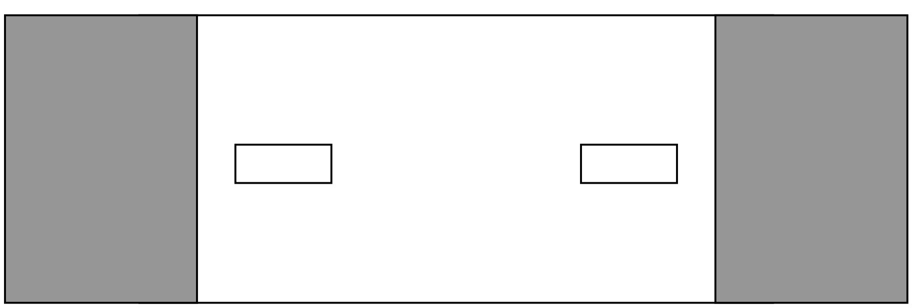


Figure 22. Mask board 2A, used with lighting configuration O, which used an outboard quad strobe.

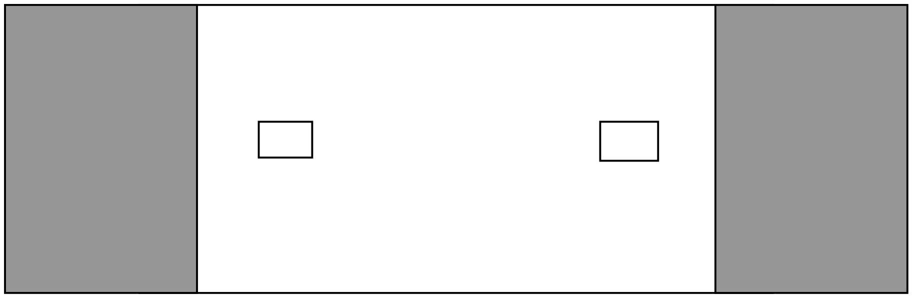


Figure 23. Mask board 2B, used with lighting configuration P, which used an outboard dual strobe.

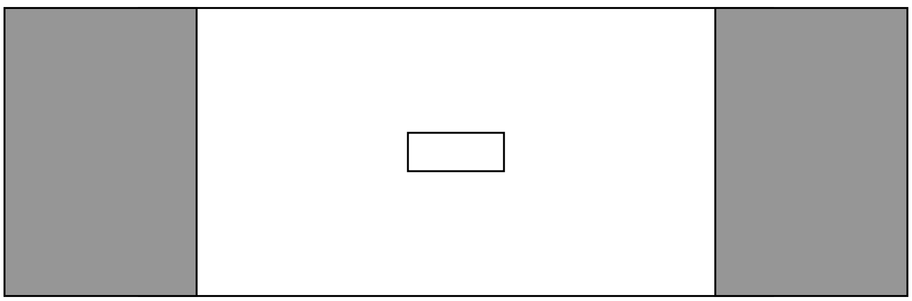


Figure 24. Mask board 2C, used with lighting configuration Q, which used a centrally located dual strobe.

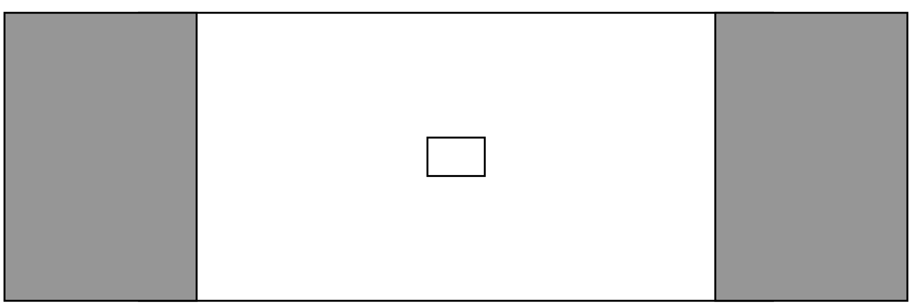


Figure 25. Mask board 2D, used with lighting configurations J, K, R, S, and T, which were all centrally located single lamp or strobe configurations.

The vehicle used for the experiment was a stationary 1997 Ford Taurus. The internal peripheral detectability test points were marked with colored translucent stickers. The experiments were conducted at VTTI in an empty parking lot paved with uniform grey gravel. Note that data were only taken when there were distinct shadows. Visual and auditory distractions were kept to a minimum; the experiment was paused to prevent interference by distractions that could not be controlled, such as a cloud passing over the sun.

Data Collection Protocol

Participants were recruited for the experiment as described previously. Data collection occurred between 9:30 am and 2:00 pm on days chosen according to participant availability and clear weather. Data collection had to be canceled and rescheduled several times because of overcast conditions and insufficient sunlight to cast visible shadows.

The experiment required two people: one to work with the subject (the experimenter) and one to operate the equipment (the confederate). The experimenter first cleaned the outside windshield of the Taurus while the confederate set up the test rig and verified the power supply to be 13.8V ± 0.1V. After greeting the subject, the experimenter explained the procedure and had the subject read and sign the Informed Consent Form. The experimenter explained the rating scales and answered any questions while driving to the designated testing area. The experimenter parked at the 150 foot mark, communicating with the confederate via 2-way radio to align the car horizontally and uniformly perpendicular to the rig.

The experimenter directed the subject to sit in the driver's seat. The experimenter adjusted the seat horizontally (fore and aft) to approximate the subject's normal driving position and then vertically so the subject's eye height was in the specified range. The experimenter made sure the sun position and cloud cover were such that distinct shadows were present. The experimenter and the confederate then presented each configuration with its corresponding mask board, using the predetermined configuration order for that subject. The subject made a preliminary rating for each configuration according to the visual attention-getting rating scale.

After all 17 configurations had been presented, the experimenter moved the vehicle to the 40 foot mark and realigned it with the help of the confederate. The confederate then presented the subject with each configuration, which the subject rated according to the discomfort-glare rating scale.

After a 20-minute break, the experimenter and the confederate realigned the vehicle at the 150 foot mark. The confederate presented each configuration for a final time while the subject provided revised ratings according to the visual attention-getting rating scale. After each rating, the experimenter directed the subject to perform the horizontal and diagonal peripheral detection tasks before going on to the next configuration. For the horizontal task, markers had been placed on the interior of the vehicle every 10° horizontally from forward center to 90° on the passenger side. Throughout the horizontal and diagonal detection tasks, the confederate used a timer to display the signals for 5-second increments, waiting 3 to 5 seconds between presentations.

For the horizontal detection task, the subject focused on the 90° marker and said "OK" if the signal was seen on the first presentation and "No" if it was not. If not, the subject repeated the task while focusing on the 80° marker, continuing to descend in this way until the signal was correctly identified. The experimenter recorded the angle at which the signal was seen. The subject then focused on the marker at 20° less than the final angle and repeated the task, this time ascending in increments of 10° until the subject could not see the signal any more. The experimenter recorded the greatest angle at which the signal had been seen and directed the subject to repeat the descending trial, with one final repetition if a discrepancy of 20° or greater occurred between trials. For the diagonal detection task, the experimenter and the subject followed the protocol for the horizontal task, this time focusing on a set of markers placed diagonally down from the center forward mark.

After the tasks had been completed, the experimenter drove the subject back to the main building and answered any questions. The subject filled out the necessary paperwork and was paid. Total time ranged from 3 to 4 hours per subject.

EXPERIMENT 1 RESULTS

As mentioned in the discussion of the experimental design, there were four dependent variables for this experiment: 1) attention-getting rating, using an 8-point scale with half-point increments; 2) discomfort-glare rating, using a heavily modified DeBoer 9-point scale with half-point increments; 3) horizontal peripheral detectability using the psychophysical method of limits to determine the absolute threshold; and 4) diagonal peripheral detectability using the same method as for horizontal peripheral detectability. The results associated with each of these measures will be discussed in this section.

Attention-Getting Rating

The first analysis performed for the attention-getting rating was an analysis of variance examining the between-subjects effects of age and gender and the within-subject effect of lighting configuration. Configuration was the only significant main effect ($F_{16,128} = 13.19$; $p<0.0001$), and there were no significant interactions. A Student-Newman-Keuls (SNK) post-hoc test was then performed to determine which configurations were significantly different from the others at $\alpha = 0.05$. The results of these analyses are portrayed in Figure 26, while the ANOVA summary table can be found in Appendix C, Table C1.[1]

[1] It could be argued that because the attention-getting scale used was ordinal, the resulting data do not strictly meet the assumptions associated with parametric analysis of variance. Therefore, a one-way Kruskal-Wallis (K-W) nonparametric test with configuration as the independent variable was also run. These results indicated significance (K-W Chi-Square$_{16\ df}$ = 96.07; $p<0.0001$).

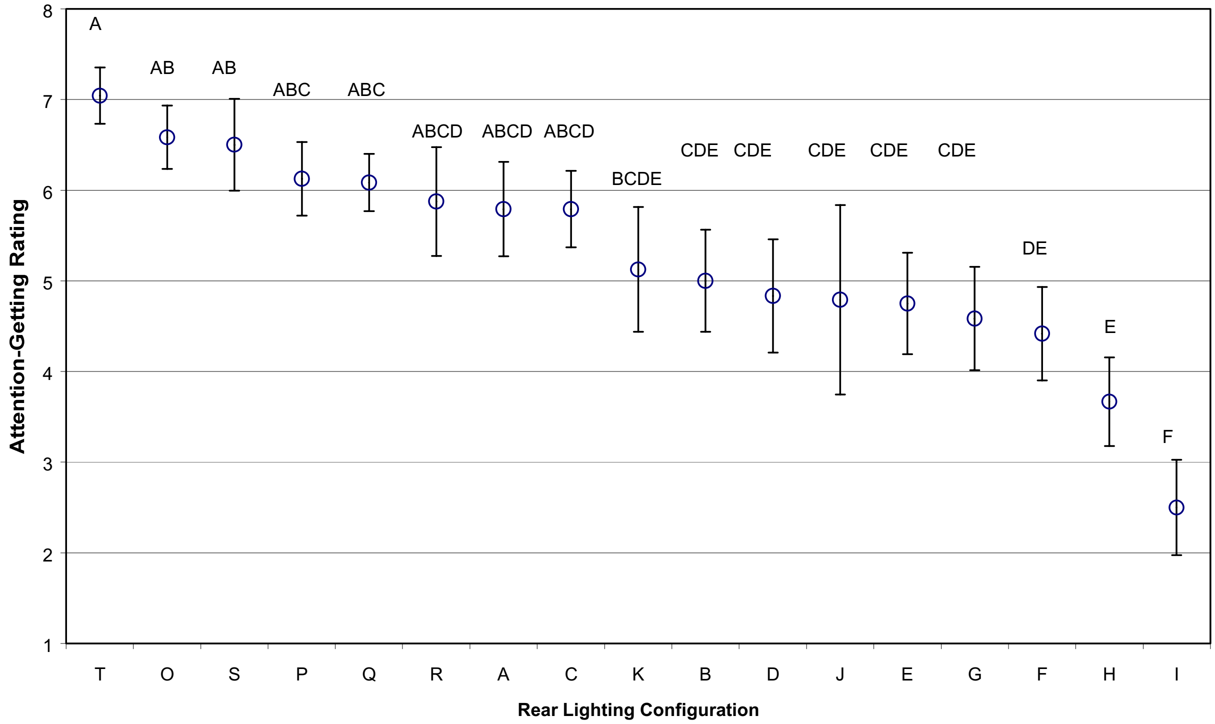


Figure 26. Mean final attention-getting ratings for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.)

Recall from the description of the protocol that subjects were asked to provide two attention-getting ratings: a preliminary rating while they were being initially exposed to all configurations and a final rating after they had seen all configurations twice (once for the preliminary attention-getting rating and once for the discomfort-glare rating). The preliminary and final ratings were compared using a simple linear regression, which showed that the two ratings were highly correlated (r = 0.944; $p < 0.0001$). This finding suggests that even during the preliminary exposure to the configurations, subjects were rating each configuration on an absolute rather than a comparative basis. That is, they did not change their ratings significantly between the first and second ratings, even though by the time of the second rating they had seen the remaining configurations, and could have then switched to a comparative rating. The experimenter took all notes as to ratings and the subjects were not allowed to see their preliminary ratings when providing their final ratings.
The order of presentation of the configurations was counterbalanced to the degree possible across subjects. The mean attention-getting rating was not significantly correlated to the order of presentation (r = 0.272; $p = 0.529$).

In the interest of maximizing the attention-getting qualities while minimizing system complexity, several other comparisons were performed to determine whether attributes such as steady versus flashing and high versus medium-output lamps differed significantly. The first comparison was for single halogen lamp configurations, of which there were four: high-output steady (configuration J), high-output flashing (K), medium-output steady (I), and medium-output flashing (H). As can be seen in Figure 27, the medium-output steady lamp was significantly less attention-getting than the other three configurations, which did not differ significantly from one another. In this comparison, the Newman-Keuls results of Figure 26 are simply transposed to the new figure, and of course remain valid for purposes of comparison.

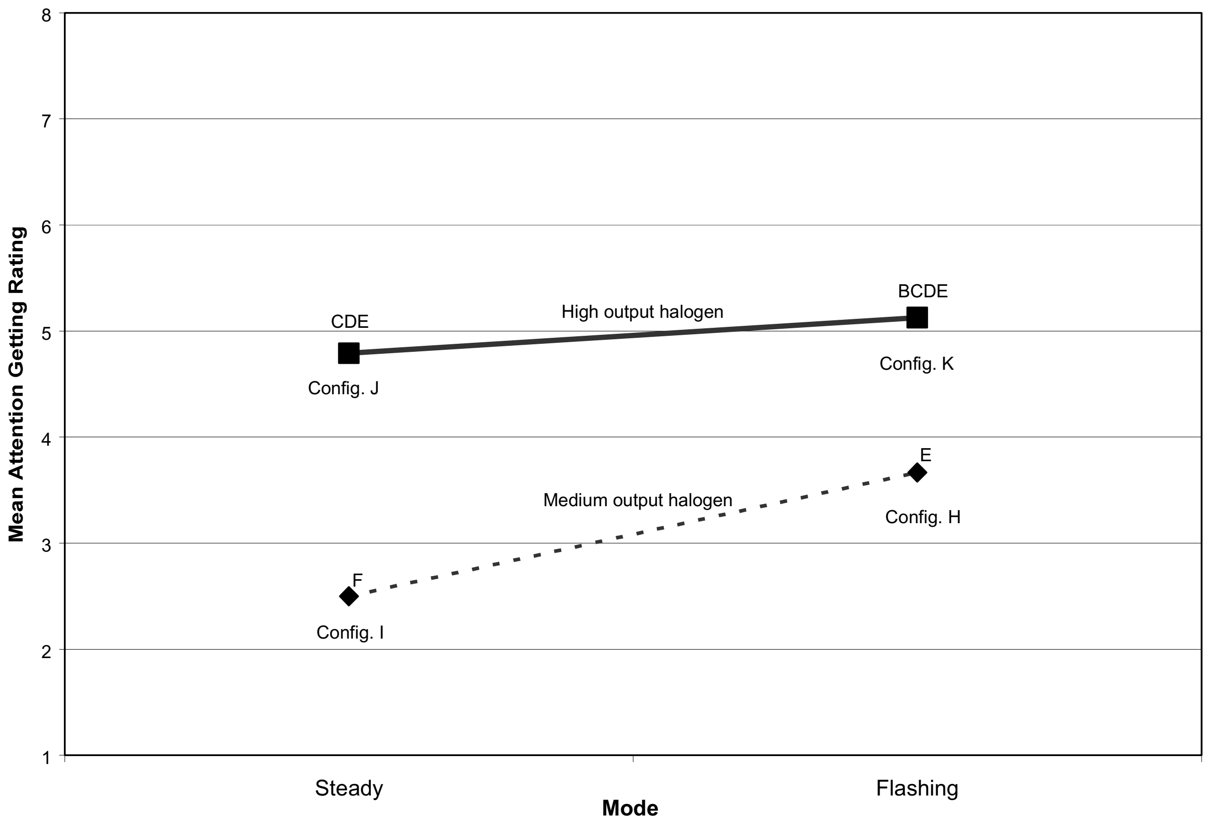


Figure 27. Mean attention-getting ratings for steady/flashing and medium/high-output single halogen lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

The next analysis compared the four eight-lamp configurations (A, an inward to outward fill; B, an inward to outward sequential pattern ending with a double flash; C, four inner lamps followed by four outer lamps; and D, all eight lamps on steadily). Figure 28 shows that there were no significant differences among any of the eight-lamp configurations.

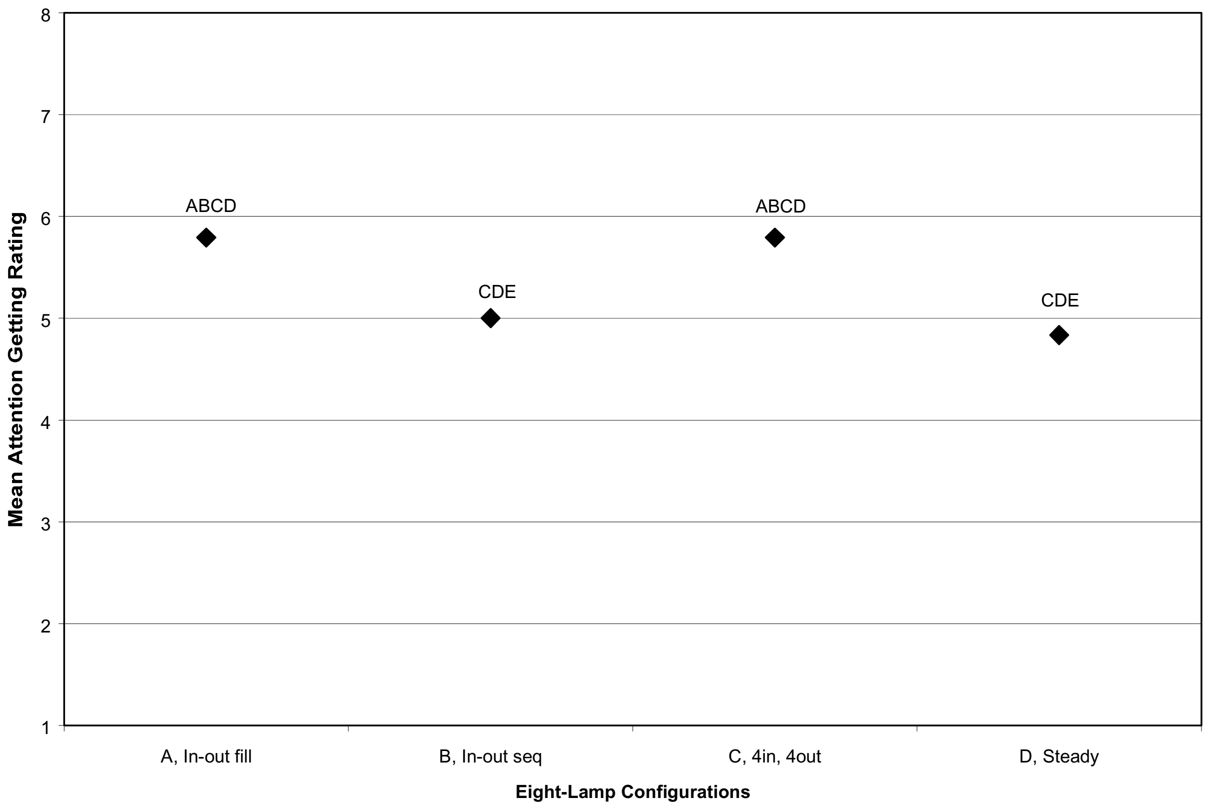


Figure 28. Mean attention-getting ratings for eight-lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

Several configurations made use of flashing medium-output halogen lamps. The issue of interest for this analysis was whether adding more lamps significantly increased the attention-getting properties of the configuration. As can be seen in Figure 29, the only significant difference was between the eight-lamp bar, configuration C, and the single flashing lamp. In other words, a two-lamp system did not differ significantly from a four-lamp system or an eight-lamp system, while a one-lamp system did not differ significantly from two-lamp or four-lamp systems.

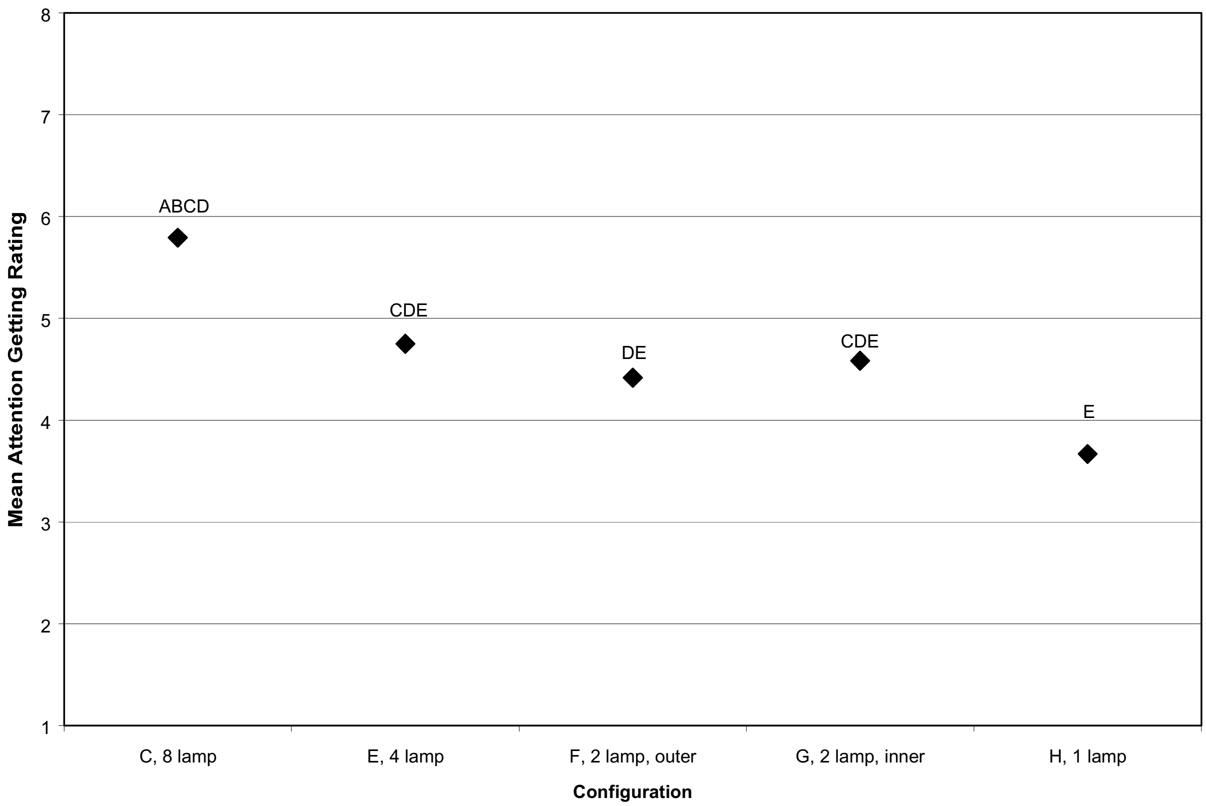


Figure 29. Mean attention-getting ratings for eight versus fewer lamps using medium-output halogen lamps. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

There were also seven single lamp configurations. Two were steady (high and low output halogen), two were flashing (high and low output halogen), two were strobes (standard and Viper high-output), and one was the Traffic clearing light (TCL). A comparison of these showed several significant differences in attention-getting properties, as shown in Figure 30. The TCL and strobes were the most attention getting, followed by the high-output halogens and then the medium-output halogens.

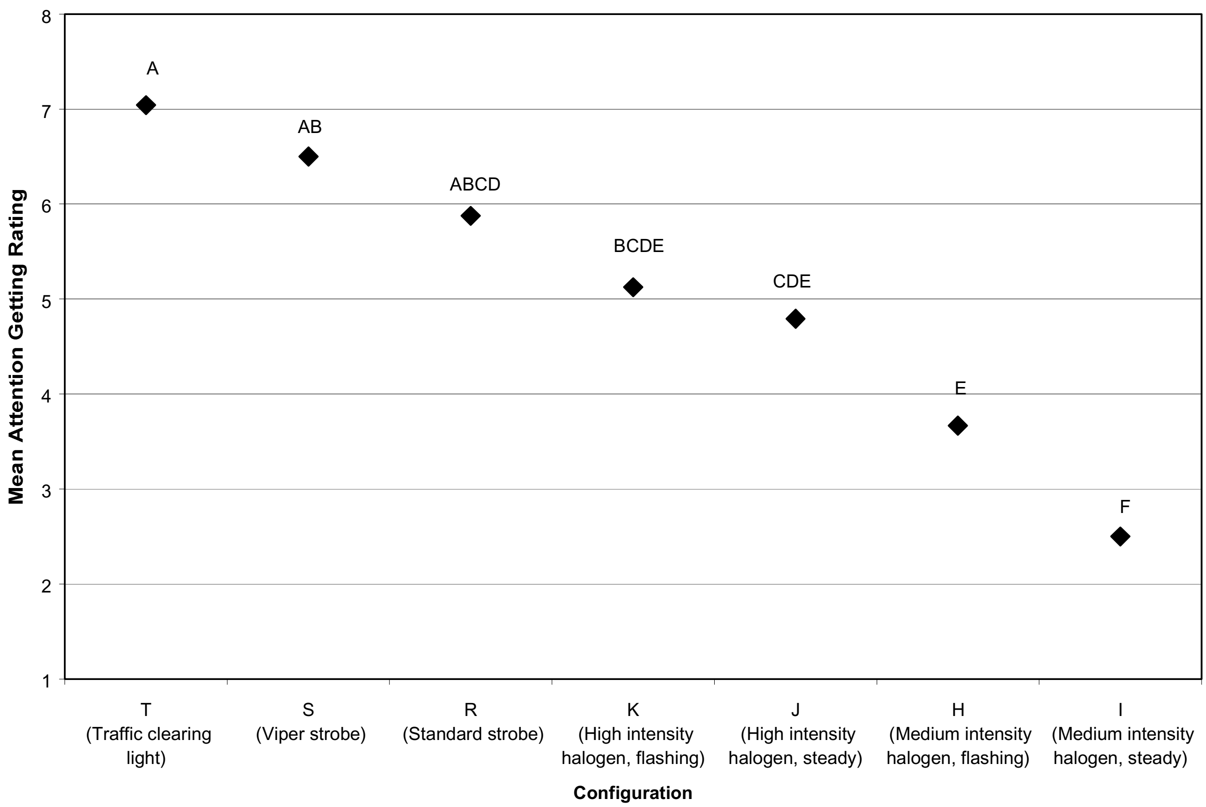


Figure 30. Mean attention-getting ratings for all single lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

The next comparison was for the five configurations using strobe lamps. Besides the Viper (high output) single strobe and the standard single strobe, there were dual alternating center strobes, dual alternating outboard strobes, and a quad outboard strobe using an inner-outer pattern. As seen in Figure 31, there were no significant differences among any of the strobe configurations.

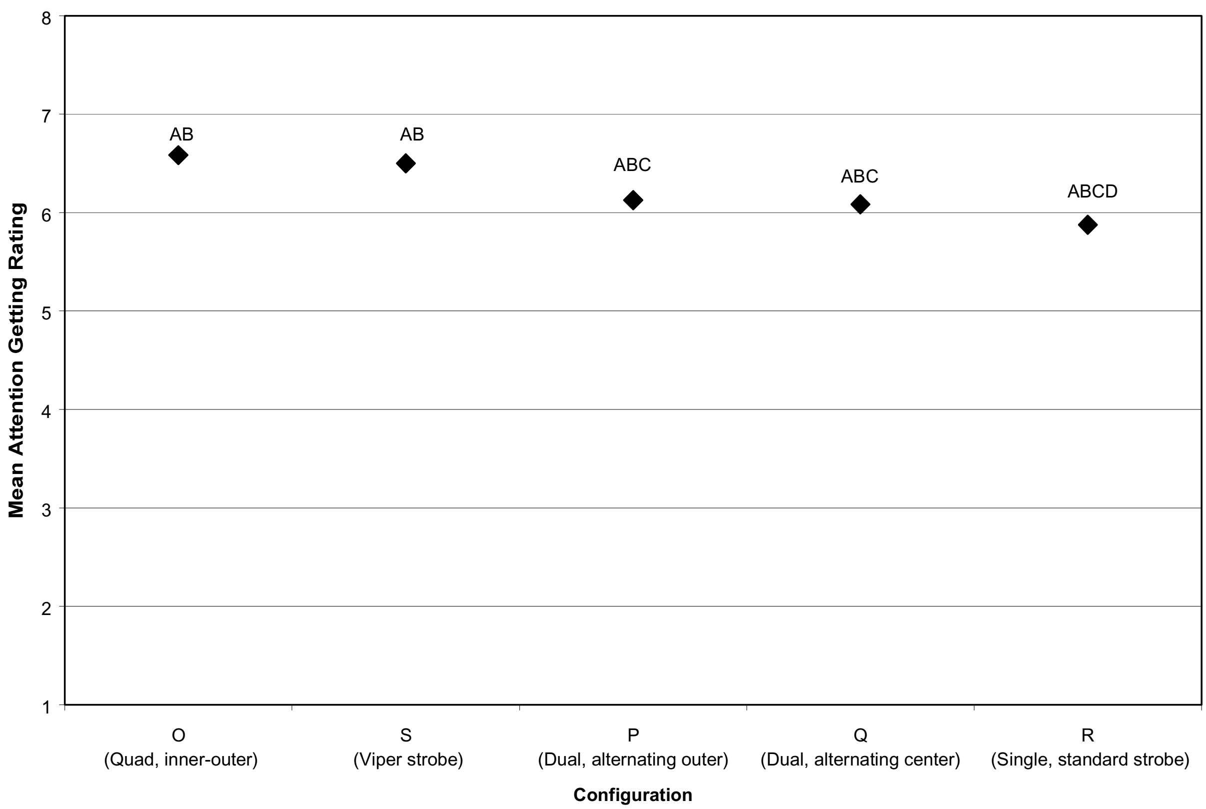


Figure 31. Mean attention-getting ratings for all strobe lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

The final comparison was for all steady burning configurations, of which there were three: eight medium-output halogen lamps, a single high-output halogen lamp, and a single medium-output halogen lamp. As seen in Figure 32, a single high-output halogen lamp was as attention getting as eight medium-output halogen lamps, while both were significantly more attention getting than the single medium-output halogen lamp.

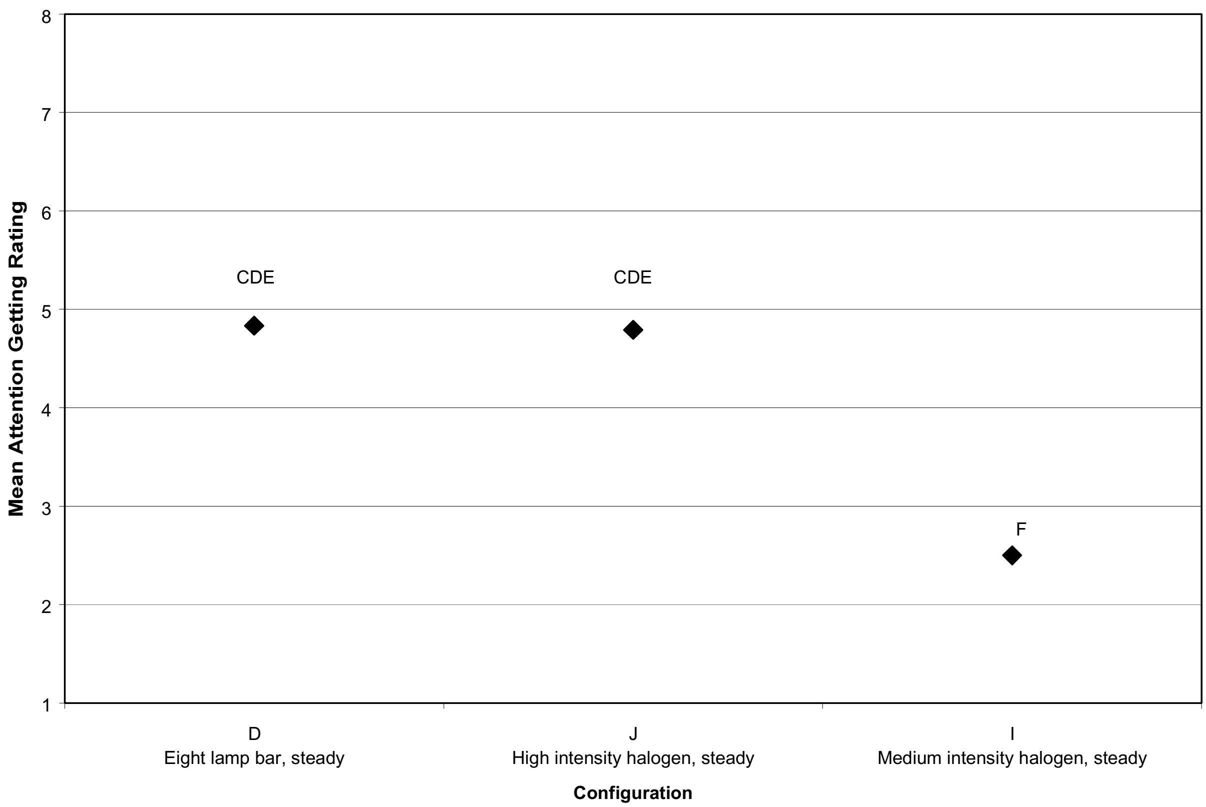


Figure 32. Mean attention-getting ratings for all steady lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

Discomfort-Glare Rating

The first analysis performed for the discomfort-glare rating was an analysis of variance examining the effects of age and gender (both between subjects) and the effect of lighting configuration (within-subject). Configuration was the only significant main effect ($F_{16,128} = 11.65$; $p<0.0001$),[2] and there were no significant interactions. An SNK post-hoc test was then performed to determine which configurations were significantly different from the others at $\alpha = 0.05$. The results of these analyses are portrayed in Figure 33, while the ANOVA summary table can be found in Appendix C, Table C2.

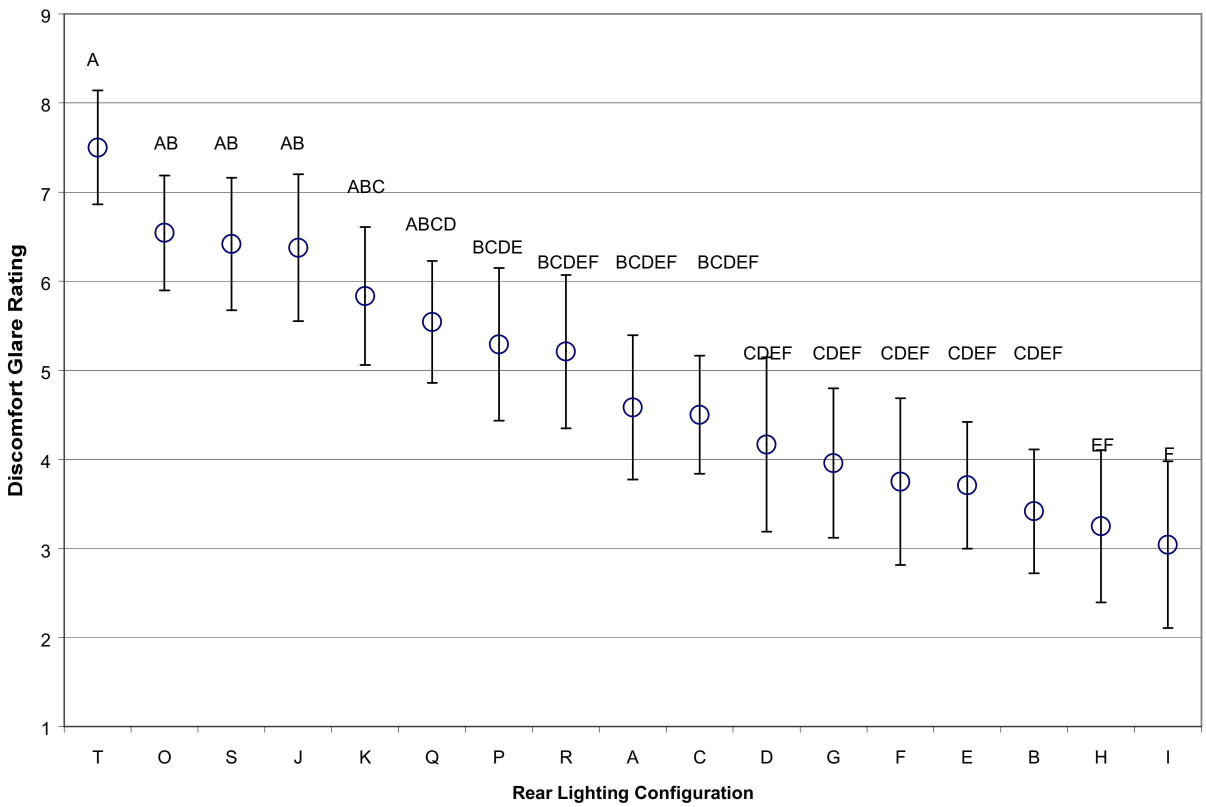


Figure 33. Mean discomfort-glare ratings for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.)

[2] Confirmed by a one-way K-W nonparametric test with configuration as the independent variable (K-W Chi-Square$_{16\ df}$ = 79.01; $p<0.0001$).

As for the attention-getting ratings, a number of comparisons were made to determine the discomfort-glare properties associated with parameters of interest. The first comparison was a 2x2 comparison of light output (medium/high) and mode (flashing/steady) for single halogen lamps. As seen in Figure 34, the medium-output halogen lamps exhibited significantly less discomfort glare than did the high-output halogen lamps, while within each lamp type, there was no significant difference between the flashing and steady modes.

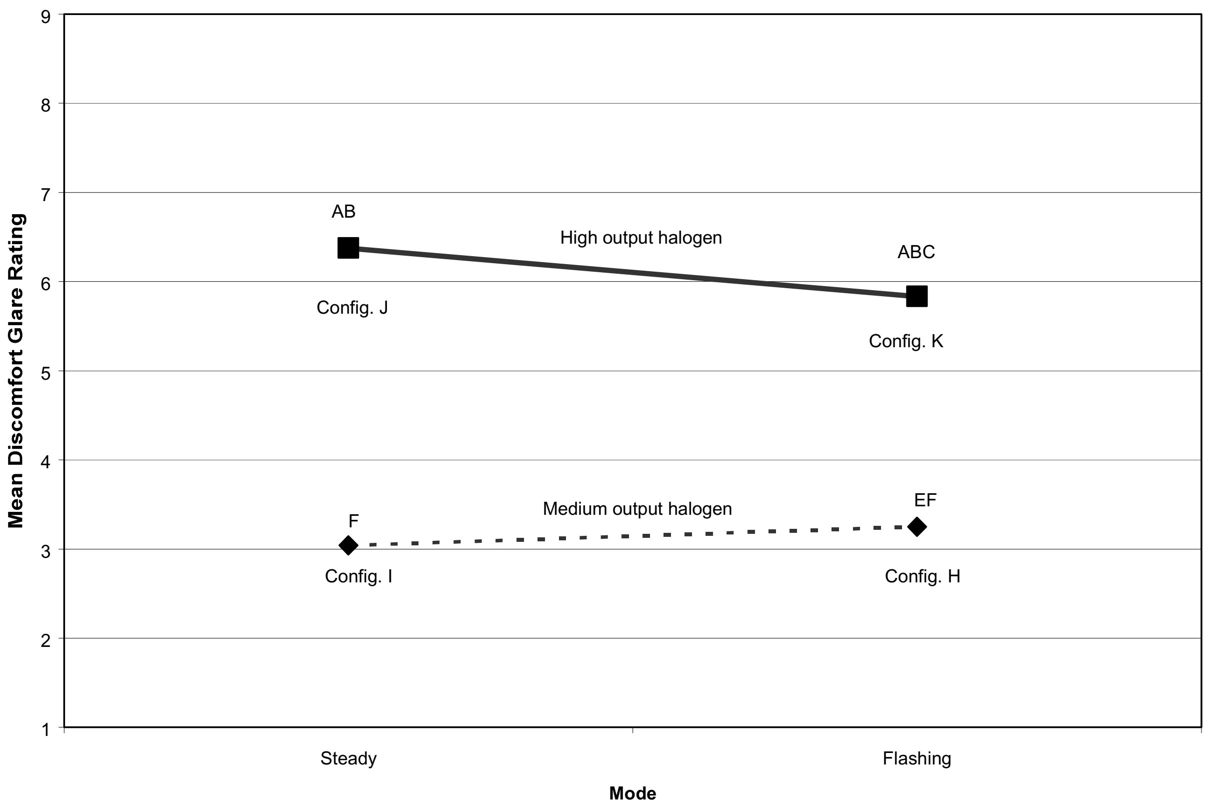


Figure 34. Mean discomfort-glare ratings for steady/flashing and medium/high-output single halogen lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

Another comparison examined the four eight-lamp configurations (A, an inward to outward fill; B, an inward to outward sequential pattern ending with a double flash; C, four inner lamps followed by four outer lamps; and D, all eight lamps on steadily). Figure 35 shows that none of the differences was statistically significant.

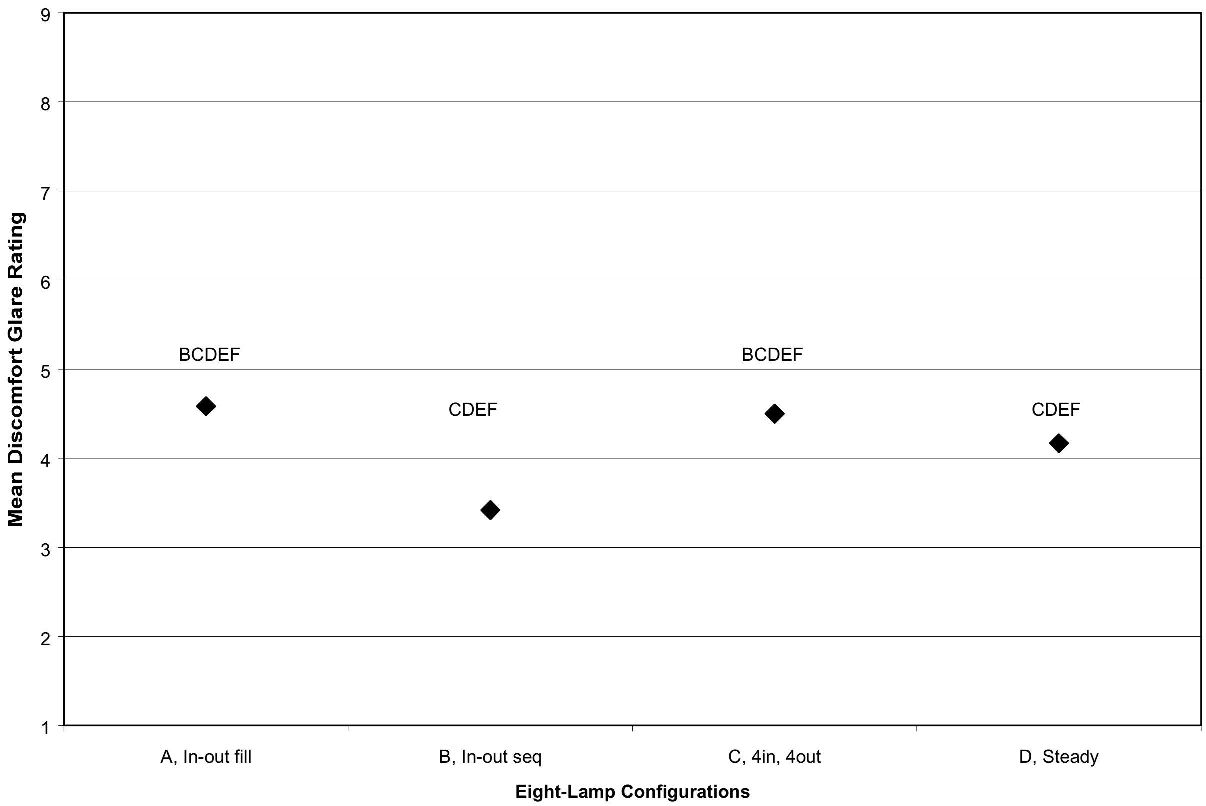


Figure 35. Mean discomfort-glare ratings for eight-lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

As seen in Figure 36, there were no significant differences in discomfort-glare ratings among the medium-output halogen configurations, no matter the number of lamps used in the configuration (one-, two-, four-, and eight-lamp configurations were compared).

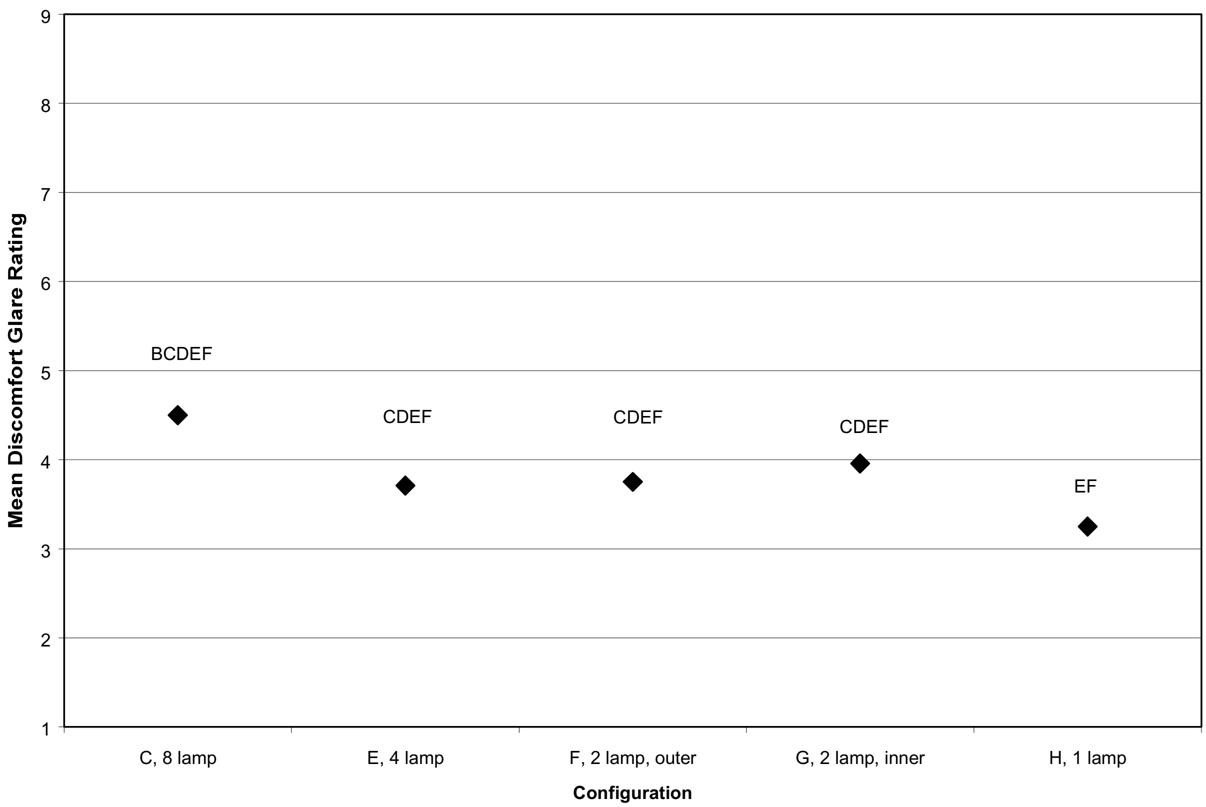


Figure 36. Mean discomfort-glare ratings for eight versus fewer lamps using medium-output halogen lamps. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

A comparison of the seven single lamp configurations used in Experiment 1 showed several significant differences as displayed in Figure 37. The Traffic Clearing Light was rated as having significantly more discomfort glare than the standard strobe and the two single lamp medium-output halogen configurations. The two single lamp medium-output halogen configurations were rated as having significantly less discomfort glare than every other single lamp configuration except for the standard strobe.

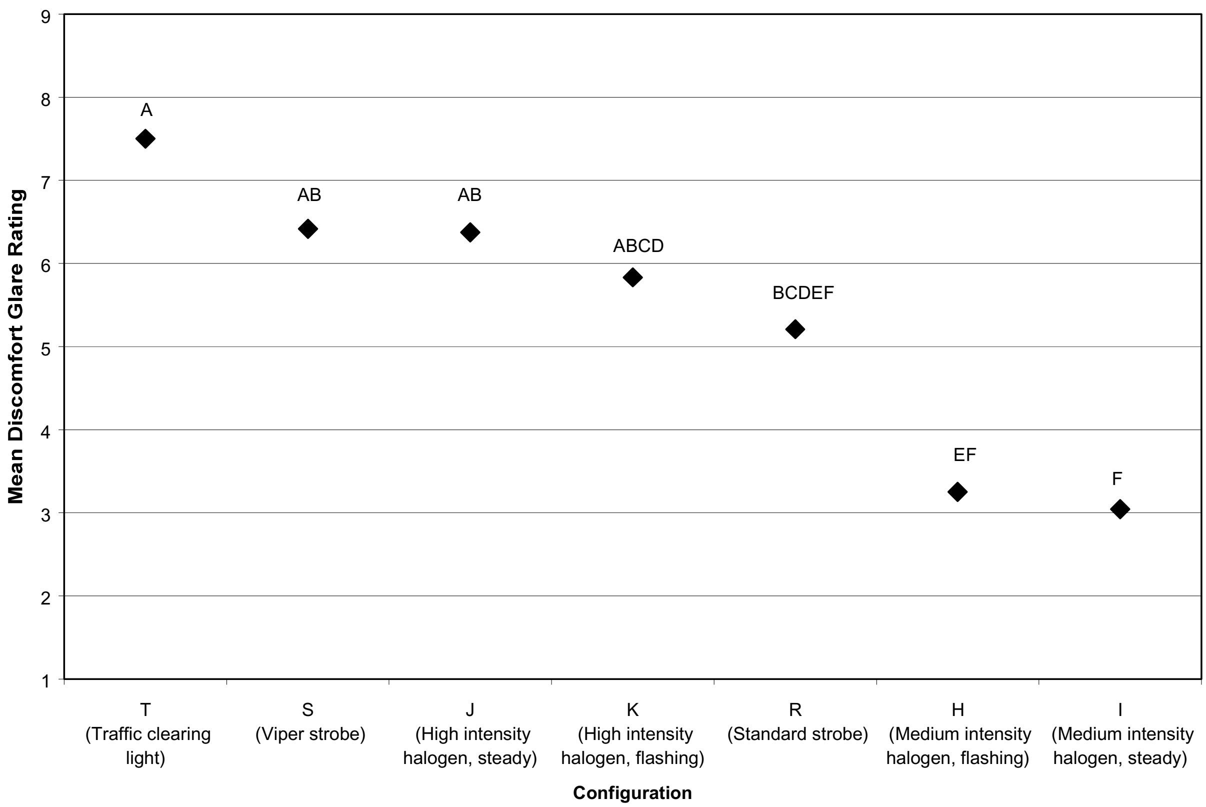


Figure 37. Mean discomfort-glare ratings for all single lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

The next comparison concerned the discomfort glare associated with the five strobe lamps used in Experiment 1. As can be seen from Figure 38, none of the strobe lamp configurations differed significantly from one another in terms of discomfort glare. Discomfort glare tended to be rated rather highly for the strobe lamps, ranging from 5.2 (Just Acceptable) for the single, standard strobe to 6.5 (Bordering on Disturbing) for the quad, standard strobe.

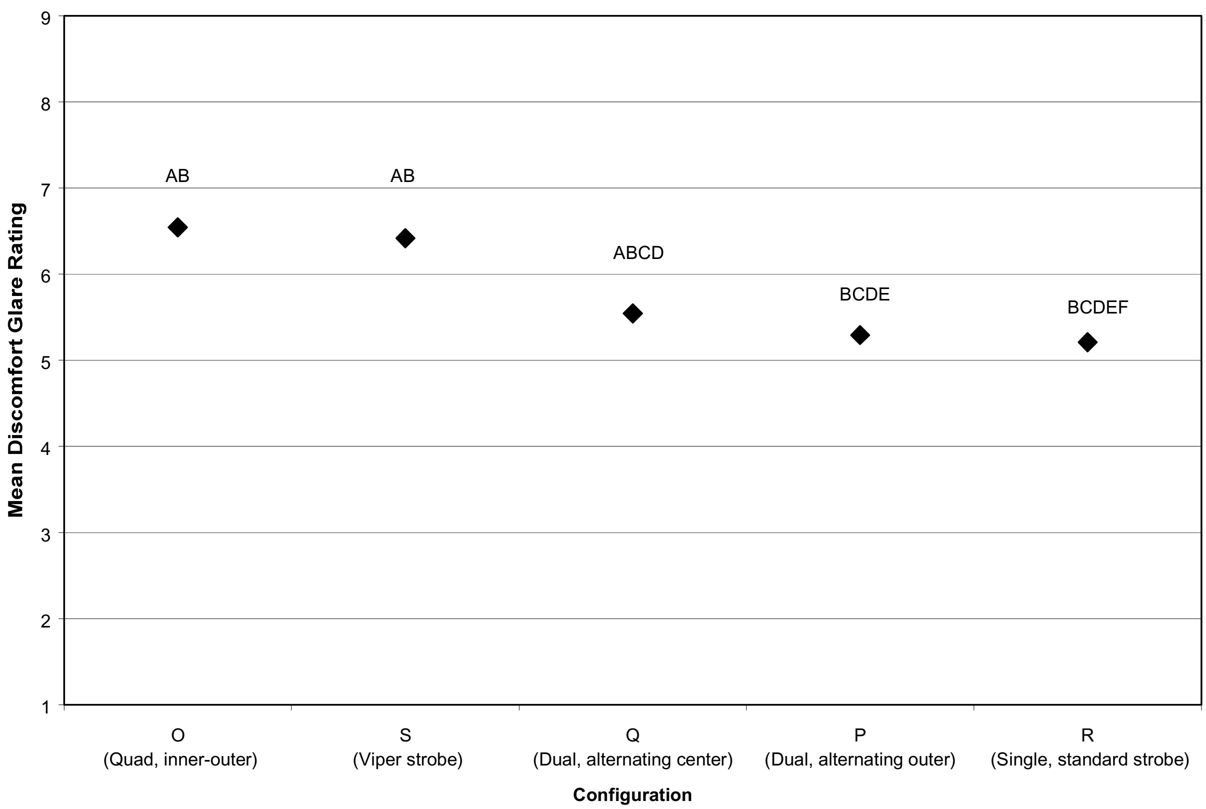


Figure 38. Mean discomfort-glare ratings for all strobe lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

There were three steady burning configurations tested in Experiment 1. The high-output single halogen was rated as having significantly more discomfort glare than either the eight-lamp configuration or the medium-output single halogen, which did not different significantly from one another. The 6.4 rating for the high-output halogen lamp was rated slightly above "Bordering on Disturbing." This comparison is shown in Figure 39.

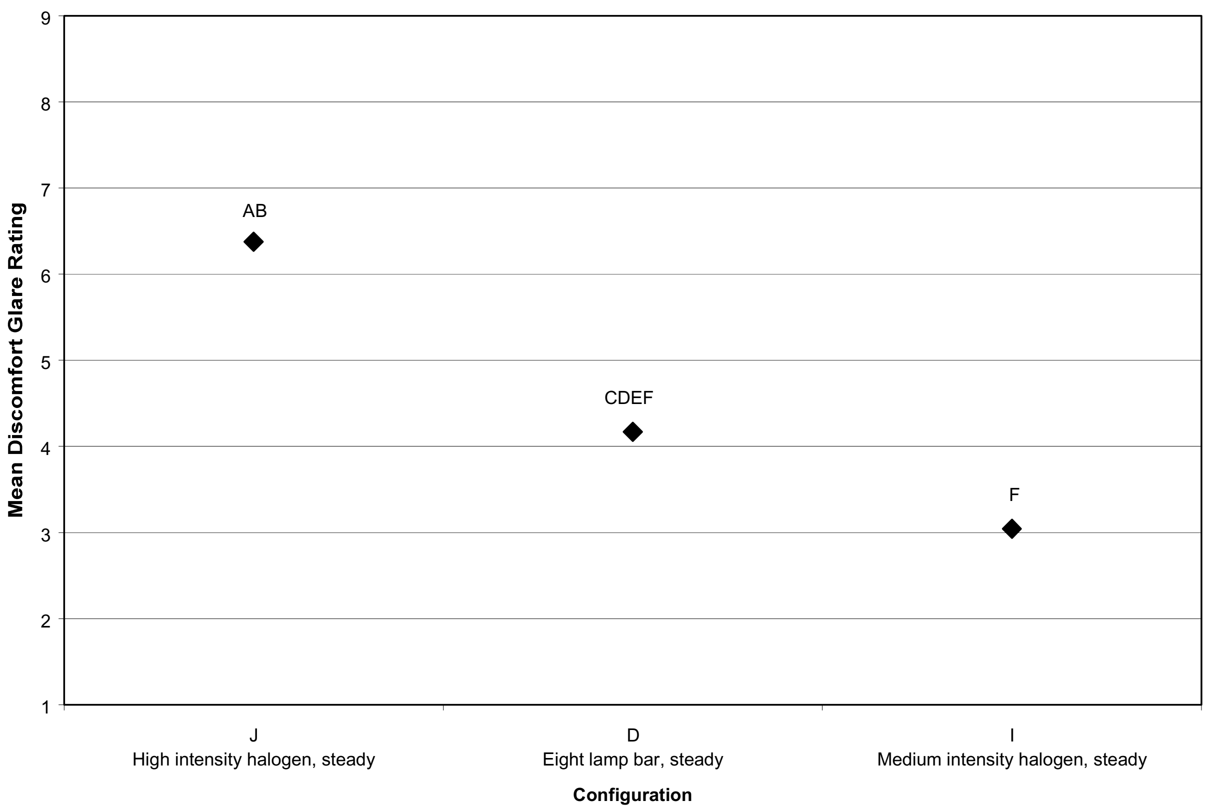


Figure 39. Mean discomfort-glare ratings for all steady lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

Horizontal Peripheral Detection

The ANOVA for horizontal peripheral detection showed that the main effect of configuration (within-subject) was highly significant ($F_{16,128} = 14.09$; $p<0.0001$),[3] while the main effect of age (between-subjects) approached significance ($F_{1,8} = 4.89$; $p=0.058$). The main effect of gender (between-subjects) was not significant. There were also two significant interactions for horizontal peripheral detection: an age by configuration interaction ($F_{16,128} = 2.32$; $p=0.0049$) and a gender by configuration interaction ($F_{16,128} = 2.15$; $p=0.01$). These interactions are plotted in Appendix C, Figures C1 and C2, and indicate that males and younger subjects could detect the halogen lamp configurations further into the horizontal periphery than could the females and older subjects, and that these differences were small for the strobe and TCL configurations. For the main effect of configuration, an SNK post-hoc test was performed to determine which configurations were significantly different from the others at $\alpha = 0.05$. The results of these analyses are portrayed in Figure 40, while the ANOVA summary table can be found in Appendix C, Table C3.

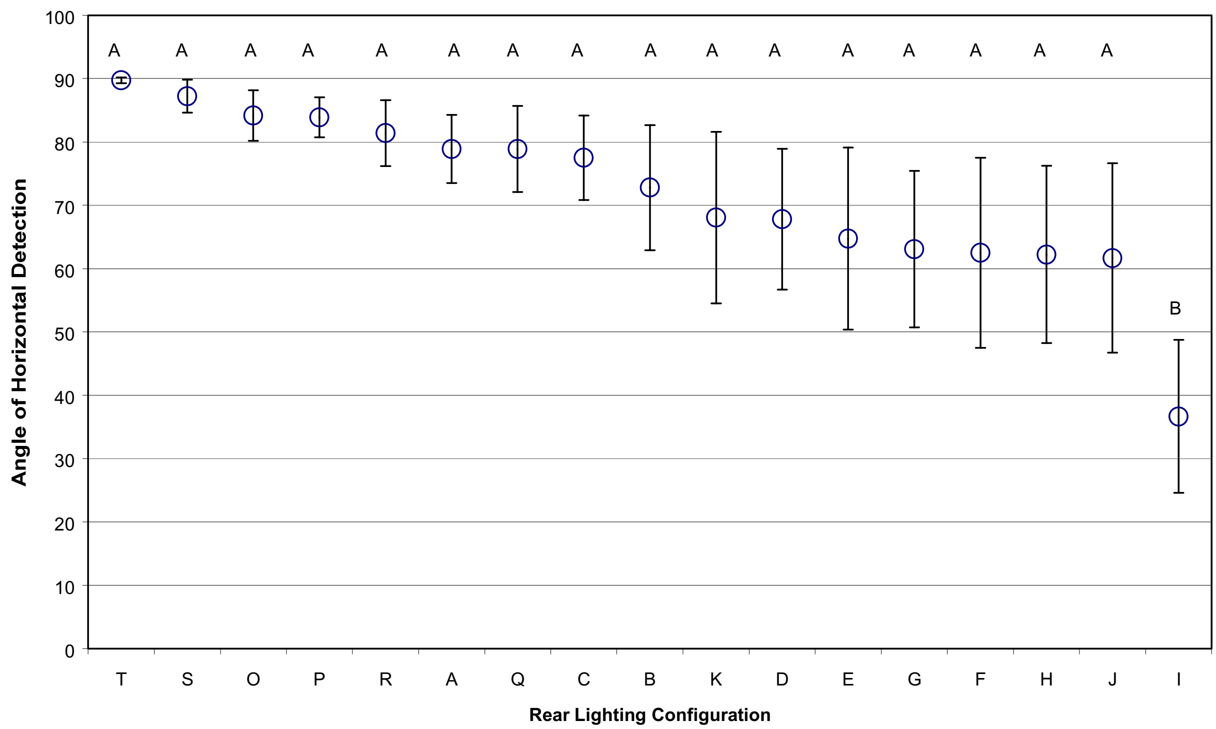


Figure 40. Mean horizontal peripheral detection angles for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.)

[3] Confirmed by a one-way K-W nonparametric test with configuration as the independent variable (K-W Chi-$Square_{16\ df} = 57.13$; $p<0.0001$).

As can be seen in Figure 40, the only significant difference among the 17 configurations in terms of horizontal peripheral detectability was that configuration I (single, steady medium-output halogen) was significantly less detectable in the horizontal field of view than any of the other configurations. The comparisons among various configurations performed for other dependent measures are not provided for horizontal peripheral detection since they do not provide any additional insight for the selection of configurations for further testing.

Diagonal Peripheral Detection

The ANOVA for diagonal peripheral detection showed that the main effect of configuration (within-subject) was significant ($F_{16,128} = 7.63$; $p<0.0001$),[4] and there was also a significant gender by configuration interaction ($F_{16,128} = 2.42$; $p=0.003$). There were no other significant main effects or interactions for diagonal peripheral detection. The discussion of results will be limited to the main effect of configuration. An SNK post-hoc test was performed to determine which configurations were significantly different from the others at $\alpha = 0.05$. The results of these analyses are portrayed in Figure 41, while the ANOVA summary table can be found in Appendix C, Table C4. The gender by configuration interaction is plotted in Appendix C, Figure C3, and indicates that males could detect both medium and high-output halogen lamp configurations at greater diagonal angles than could females, while both genders detected the strobe and TCL configurations equally well in the diagonal direction.

[4] Confirmed by a one-way Kruskal-Wallis nonparametric test with configuration as the independent variable (K-W Chi-Square$_{16\ df} = 50.11$; $p<0.0001$).

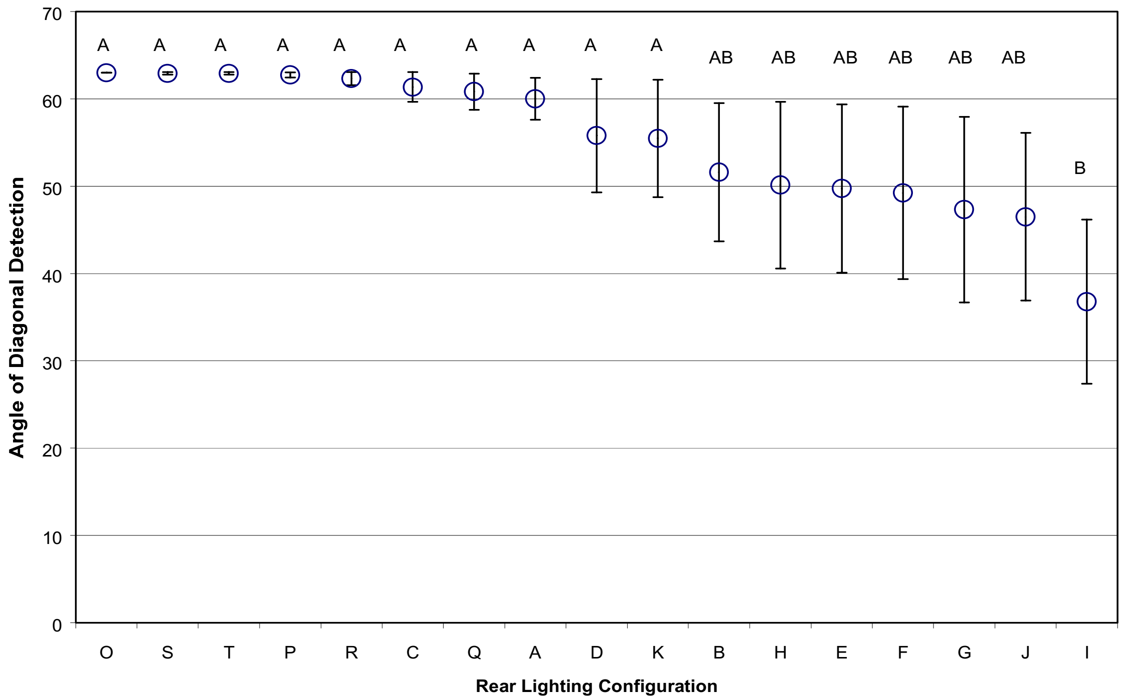


Figure 41. Mean diagonal peripheral detection angles for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$. Bars represent 90% confidence intervals.)

As can be seen from Figure 41, there was a greater degree of spread among the configurations for diagonal detection than for horizontal detection. Those comparisons among systems with similar parameters showing significant differences will thus be presented for this dependent measure. The first comparison is for single medium-output halogen lamps (steady/flashing) and single high-output halogen lamps (steady/flashing). As can be seen in Figure 42, the high-output flashing halogen lamp could be seen significantly further into the diagonal peripheral visual field than the medium-output steady halogen lamp.

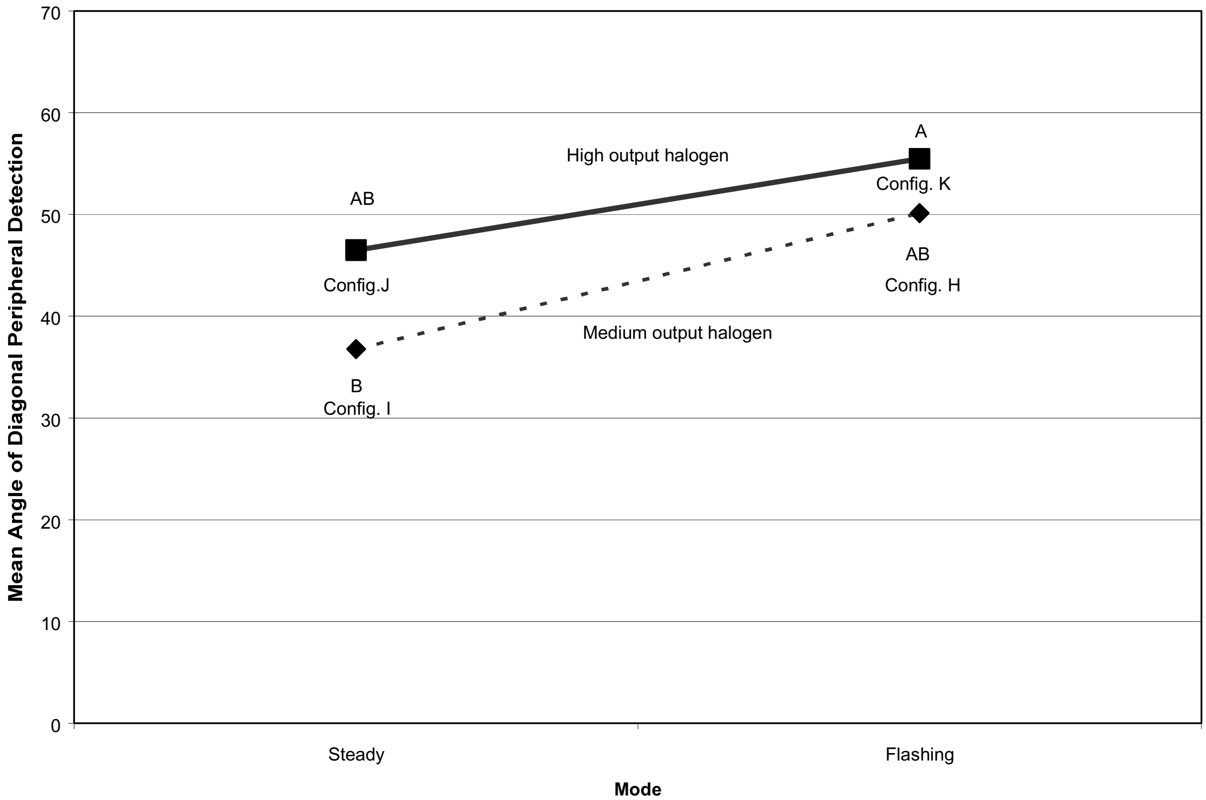


Figure 42. Mean diagonal peripheral detection angles for steady/flashing and medium/high-output single halogen lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

The next significant comparison was for all single lamp configurations. All of the other six single lamp configurations were significantly more noticeable in the diagonal peripheral direction than the single steady medium-output halogen lamp; there were no significant differences for this dependent measure among any of the other single lamp configurations. This comparison is shown in Figure 43.

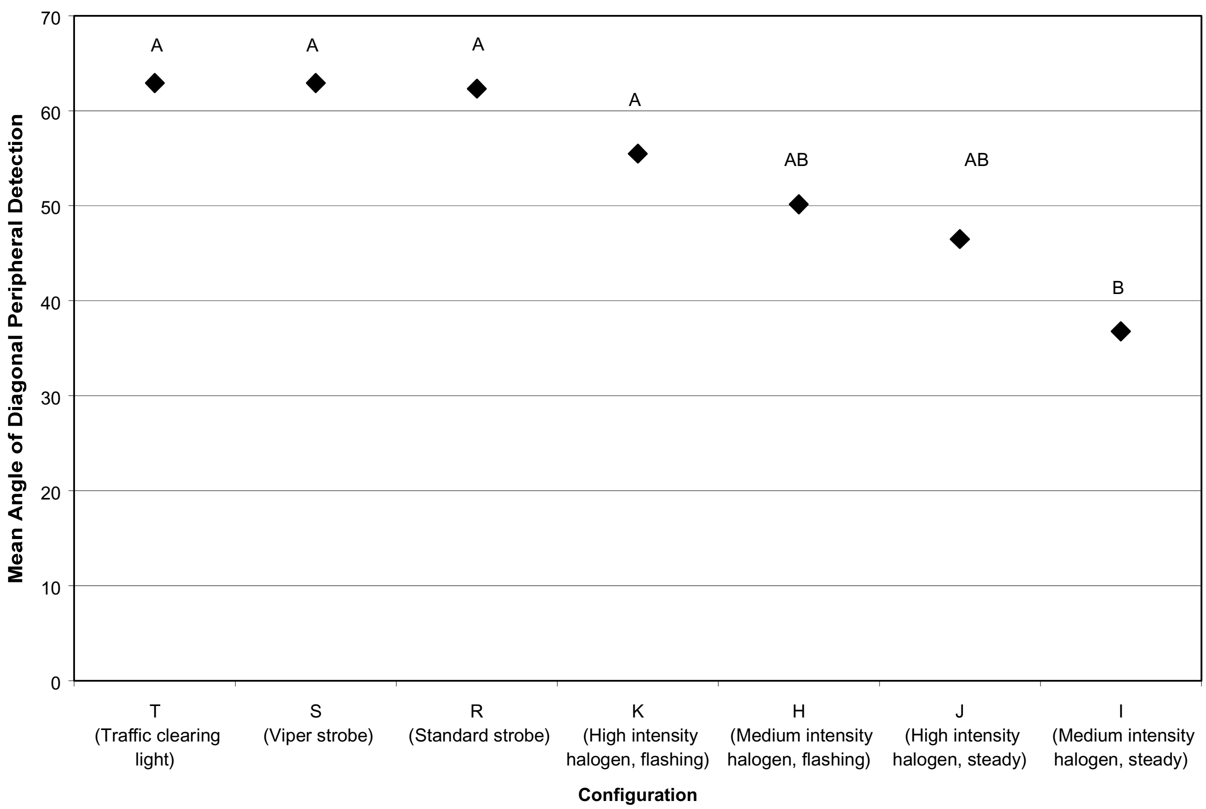


Figure 43. Mean diagonal peripheral detection angles for all single lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

The final significant comparison was for all steady lamp configurations. As can be seen in Figure 44, the steady eight lamp bar could be seen significantly further into the diagonal peripheral field of view than the single steady medium-output halogen lamp, but neither differed significantly from the single steady high-output halogen lamp.

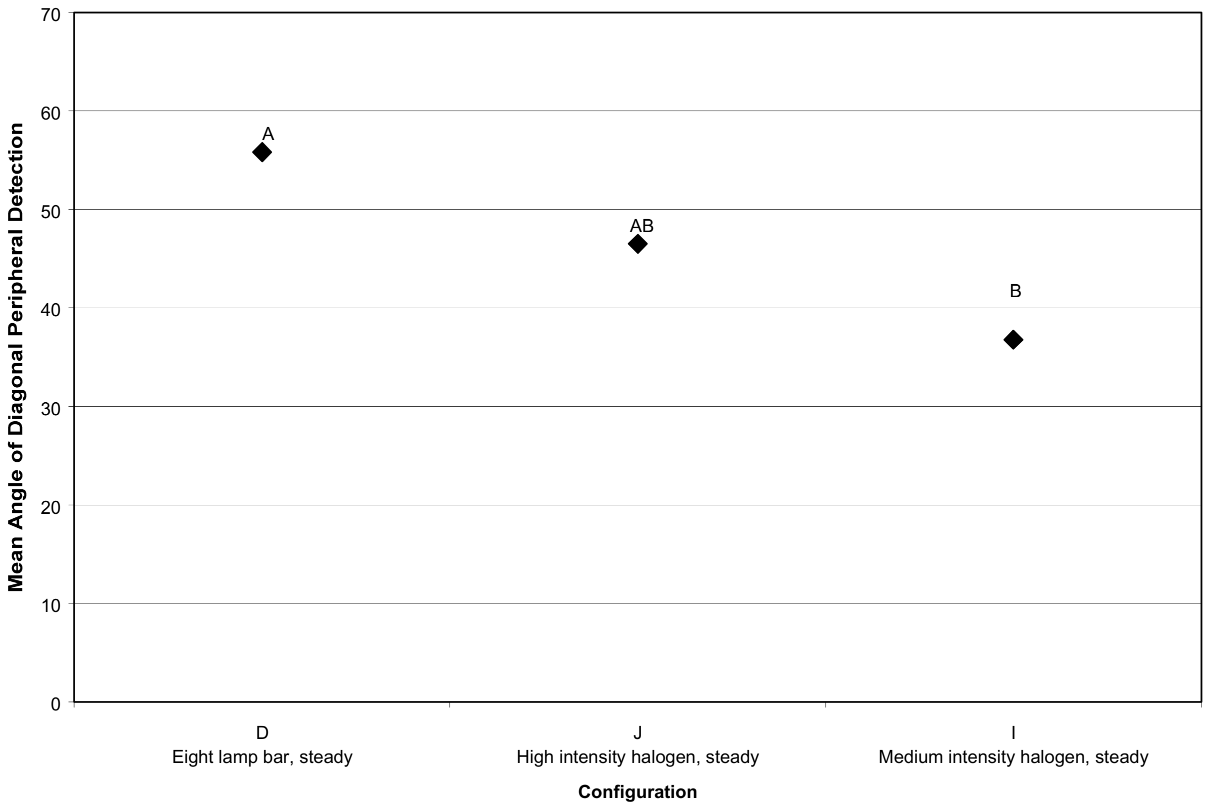


Figure 44. Mean diagonal peripheral detection angles for all steady lamp configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

Note that there were no significant differences for the comparisons among the eight-lamp configurations, among the eight versus fewer medium-output halogen lamp configurations, or among the strobe configurations.

System Complexity Evaluation

In addition to the four independent measures already discussed and assessed in Experiment 1, it was also deemed desirable to consider the relative complexity of each configuration. The reason for including this consideration was that complexity is closely associated with cost to implement, and expensive configurations should only be recommended if they show a substantial demonstrated advantage over less complicated configurations. Thus, in making any recommendations, it was considered important to include complexity.

The research team developed four measures of complexity for evaluation and assessment by technical experts, that is, individuals familiar with electrical, electronic, and mechanical design in automotive systems. The four measures selected and their descriptions are as follows:

1. Complexity of the Drive Electronics. This measure assesses the complexity of the electronic and electrical circuits required to drive the lighting. This form of complexity usually increases with the number of lighting units, the use of high-voltage discharge units, and complexity of switching and timing circuitry.

2. Complexity of Vehicle Redesign to Accommodate. This measure assesses the difficulty of incorporating the design into present-day vehicles. This form of complexity usually increases with the number of lighting units, any conflicts with existing lighting and other rear hardware items, and aspects such as required amount of inside depth.

3. Power Use Requirements. This measure assesses how much power is required to drive the lamp units used, including losses in generation.

4. Reliability and Maintainability. This measure assesses the likelihood of equipment failure and the corresponding amount of maintenance required to keep the lighting configuration fully operational.

Rating process

A simple rating process was also developed using a five point scale. The purpose was to make it possible to discriminate differences in lighting configurations so that relative complexities could be assessed. The scale values were: 1 = very low, 2 = low, 3 = medium or moderate, 4 = high, and 5 = very high.

Two experts, each of whom had expertise in all of the design issues listed above, rated each lighting system on each criterion. The experts worked together to evolve a single rating for each configuration along each of the four dimensions of complexity measures. The reason for using this approach was to allow discussion between the experts, which was believed to allow better resolution of issues. There were several points of discussion that involved subtleties not likely to have been resolved had there been no discussion. The experts seemed to have little trouble reaching a consensus on appropriate ratings for the configurations and dimensions of complexity, once the subtleties were resolved.

Table 2 shows the results of the rating process. The specific lighting configurations are designated in the first column, and the corresponding complexity ratings along the four dimensions (and for the various configurations) appear in the next four columns. The last column contains the sums of ratings for the configurations, and thus, provides an overall indication of the complexity of the configurations. Of course, summing the dimensional ratings in effect weights them equally. However, all four dimensions appear to be important, and in the absence of other information, equal weighting ensures that they are taken into account in the overall rating. Thus, the last column is believed to provide a usable relative assessment of overall complexity. The data in the table have been arranged from highest overall complexity at the top to lowest overall complexity at the bottom. Note that for the rating process used, the highest possible overall rating would be 20 and the lowest would be 4. It could be assumed that configurations near the top of the table would be much more difficult and expensive to integrate into production vehicles than configurations near the bottom of the table.

Table 2. Complexity ratings for the 17 configurations used in Experiment 1 (ranked in order of overall complexity from most to least complex).

Configuration	Complexity of Drive Electronics	Complexity of Vehicle Redesign to Accommodate	Power Use Requirements	Reliability & Maintainability Difficulty	**Sum of Ratings**
A	5	5	4	4	**18**
O	5	4	4	5	**18**
B	5	5	3	4	**17**
C	3	5	4	3	**15**
D	1	5	5	3	**14**
P	4	3	3	4	**14**
S	5	2	3	4	**14**
Q	4	2	3	4	**13**
E	2	4	3	3	**12**
R	3	2	2	3	**10**
T	1	2	3	3	**9**
F	1	3	2	2	**8**
G	1	2	2	2	**7**
J	1	2	2	1	**6**
K	2	2	1	1	**6**
H	1	2	1	1	**5**
I	1	2	1	1	**5**

Key:

A. Eight medium-output halogen: pairs light up and fill in from center outward, one pair at a time, ending with all eight lamps lit.
B. Eight medium-output halogen: pairs light up sequentially from center outward, one pair at a time, ending with a double flash of the outer pair.
C. Eight medium-output halogen: center four light up followed sequentially by outer four.
D. Eight medium-output halogen: steady.
E. Four medium-output halogen: outboard, inner two followed by outer two.
F. Two medium-output halogen: outboard, alternating.
G. Two medium-output halogen: center mounted, alternating.
H. One medium-output halogen: center mounted, flashing.
I. One medium-output halogen: center mounted, steady.
J. High-output halogen: center mounted, steady.
K. High-output halogen: center mounted, flashing.
O. Four standard strobes: outboard, inner two followed by outer two.
P. Two standard strobes: outboard, alternating.
Q. Two strobes, center, alternating.
R. One strobe, center.
S. Viper strobe.
T. Traffic clearing light.

SELECTION OF THE HIGH-LEVEL LIGHTING SIGNAL BASED ON RESULTS OF EXPERIMENT 1

The main purpose of the high-level lighting signal is to attract the following driver's attention to 1) high-level deceleration and potential short stopping distances to the lead vehicle in the open-loop case and 2) an impending rear-end crash in the closed-loop case. To accomplish this, the signal must have a high level of attention-getting capability as well as good detectability in peripheral vision. Since this signal would be transient in nature, probably not lasting more than seven seconds under any circumstances, and since the signal would be used sparingly, discomfort glare is not a major consideration.

Figure 45 shows the attention-getting ratings obtained from the first experiment in which 17 different configurations were tested (this is the same as Figure 26, and is repeated here for convenience). The results are presented in descending order, along with 90% confidence limits and SNK comparison results. The SNK results suggest that the first eight configurations are high in attention-getting capability.

The results for horizontal and diagonal peripheral detection are shown in Figures 46 and 47 respectively (these are similarly repeats of Figures 40 and 41). As can be seen, ordering the mean values produces results that are similar to Figure 45. However, the Newman-Keuls tests suggest that there is not a reliable statistical difference among the more salient rear-lighting configurations.

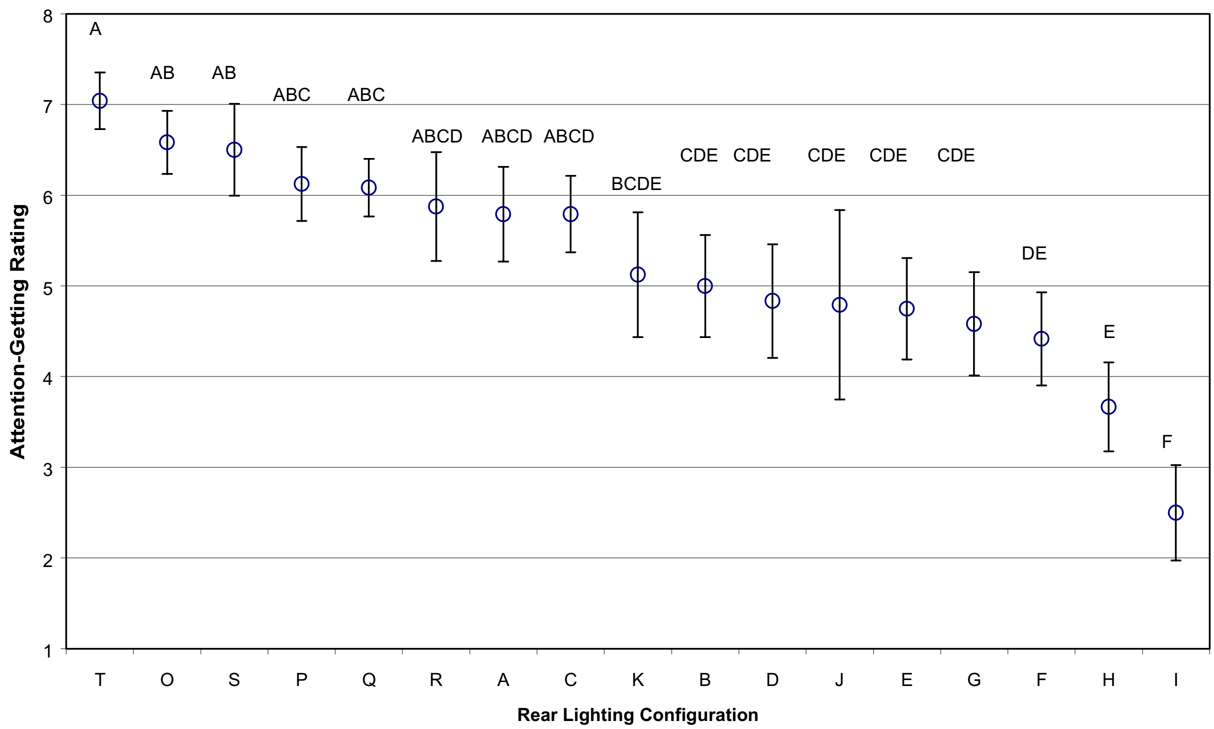


Figure 45. Mean final attention-getting ratings. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.) (This is a repeat of Figure 26.)

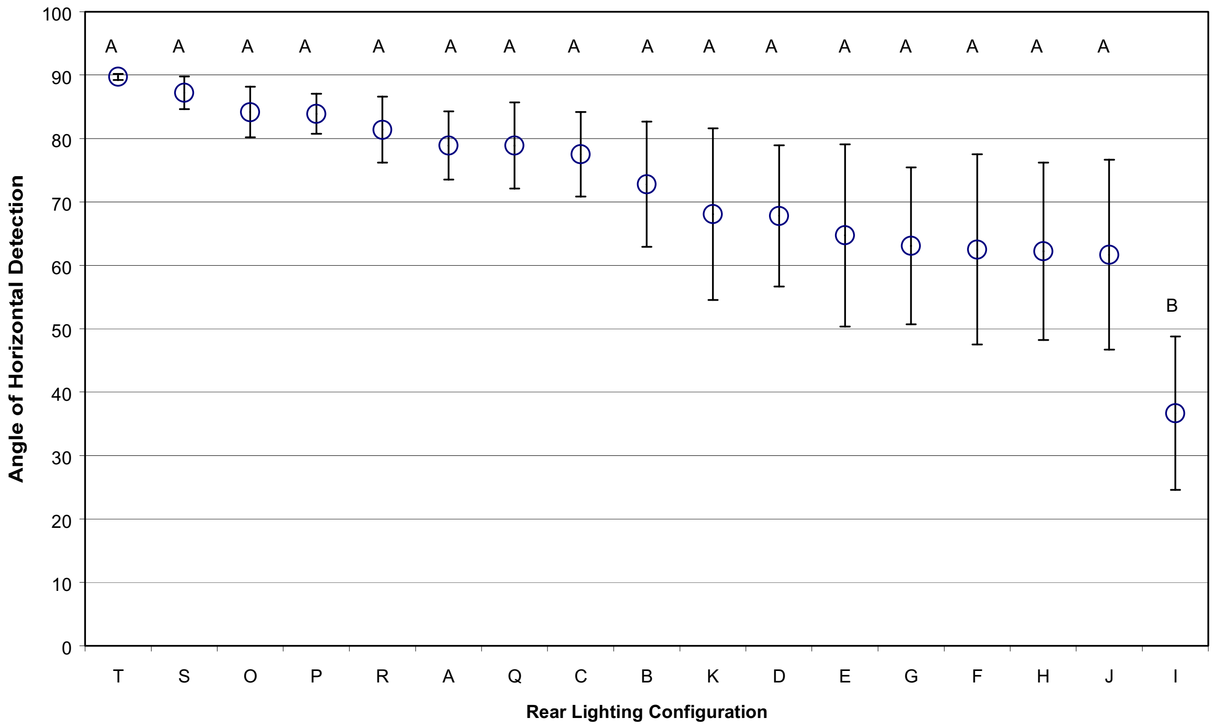


Figure 46. Mean horizontal detection angle for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.) (This is a repeat of Figure 40.)

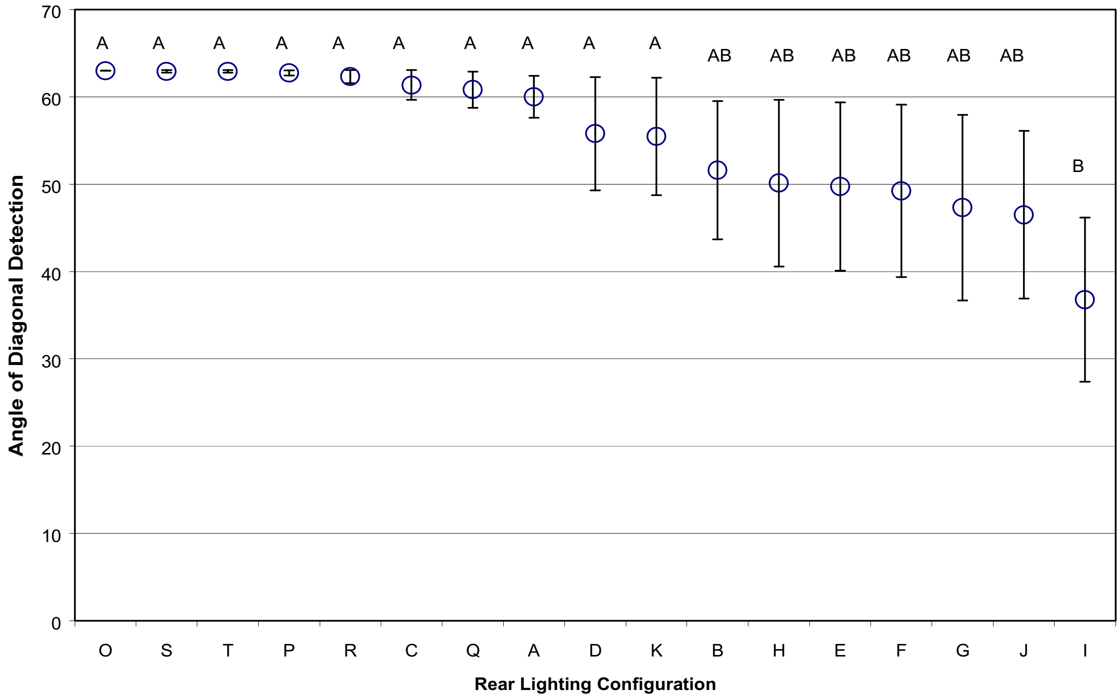


Figure 47. Mean diagonal detection angle for 17 rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05. Bars represent 90% confidence intervals.) (This is a repeat of Figure 41.)

Table 3 summarizes the attention-getting and peripheral detection results for the top eight attention-getting configurations. In the table, when the attention-getting means are the same, the configurations are given the same rank. Total peripheral detection is the sum of the horizontal and diagonal means for each given configuration. Note that the top three attention-getting configurations also provide the best peripheral detection when mean values are considered. Based on available data, these results suggest that, from the standpoint of attention-getting, one of the top three configurations should probably be selected. Of course, the cutoff rank is arbitrary, but the break in mean attention-getting ratings drops by a magnitude of 0.4 between the third and fourth ranked candidates, which is substantial (although not significant).

To further eliminate candidates for the high-level signal, the overall complexity ratings can be taken into account. Additionally, the discomfort-glare ratings might be considered, but only secondarily. These values appear in Table 4; the values are extracted from Table 2, presented earlier. Note that both complexity and discomfort-glare are “reverse” scales, with low values indicating more desirable characteristics.

Table 3. Attention-getting properties and peripheral detectability of the top eight configurations.

Configuration	Attention-getting Rank	Attention-getting Mean rating	Total peripheral detection mean value (degrees)
T	1	7.0	152.6
O	2	6.6	150.1
S	3	6.5	147.2
P	4	6.1	146.6
Q	4	6.1	143.7
R	5	5.9	139.7
A	6	5.8	138.9
C	6	5.8	138.9

Table 4. Complexity and discomfort-glare ratings for the top-ranked attention-getting configurations.

Configuration	Attention-getting Rank	Complexity rating	Discomfort-glare rating
T	1	9	7.5
O	2	18	6.5
S	3	14	6.4

The results show that configuration T is much less complex than O or S. However, it does create a bit more discomfort glare. A rating of 7.5 on the discomfort-glare scale corresponds to a level that drivers would not want to look at for more than perhaps 5 to 15 seconds. Since it is anticipated that the maximum exposure time would be about 7 seconds, configuration T would probably be acceptable.

To summarize, configuration T has several desirable attributes. According to the available data, it has the highest attention-getting rating and the highest peripheral detectability. Furthermore, it is far less complex than the other two top-rated configurations. It does border on the limits of acceptability for discomfort glare, but that is not unexpected, considering that attention-getting and discomfort glare are highly correlated, as shown in Figure 48.

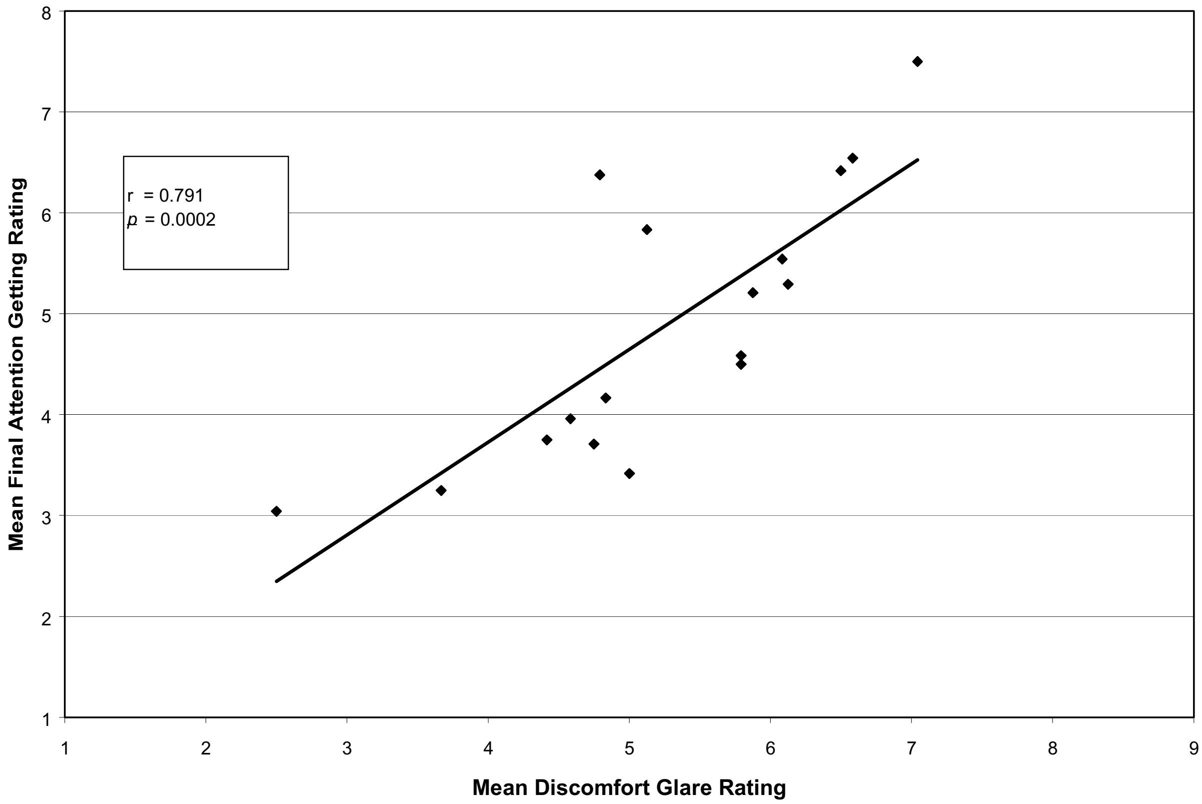


Figure 48. Regression plot of mean glare rating vs. mean final attention-getting rating.

In regard to discomfort glare, remember that Experiment 1 used clear lenses only and therefore produced white light. It is probable that the final form of a high-level signal would employ a tinted lens. Such a lens would likely reduce the light output somewhat, which would reduce the discomfort glare. There may also be a slight reduction in attention getting. Of course, all of the configurations would probably exhibit similar reductions for tinted lenses.

Configuration T is the so-called "traffic clearing light" (TCL). This is a single high-output halogen lamp unit with a motorized parabolic reflector that sweeps horizontally and vertically to produce an "M" pattern. Being compact, the unit can be embedded in the center of the trunk or hatch of a vehicle without major redesign of the rear of the vehicle. The unit is relatively simple and inexpensive. Power requirements are low and there are *no* electronic drive circuits. Figures 49 and 50 show the construction of the TCL.

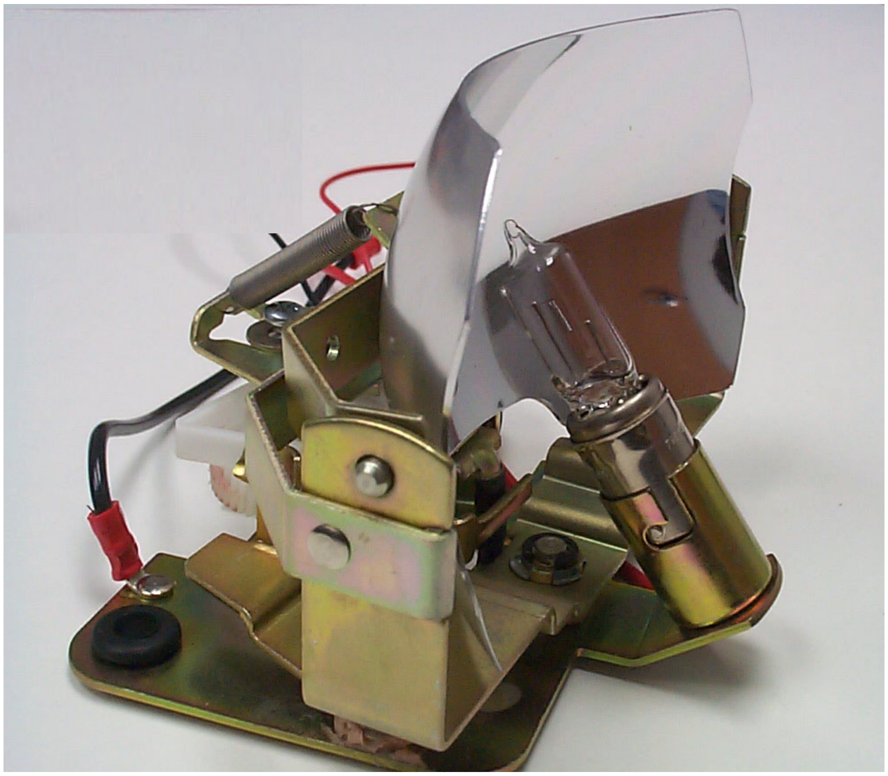


Figure 49. The TCL showing its bulb, reflector, and part of the reflector movement mechanism. The TCL is 11.9 cm wide, 8.8 cm high, and 9.6 cm deep.

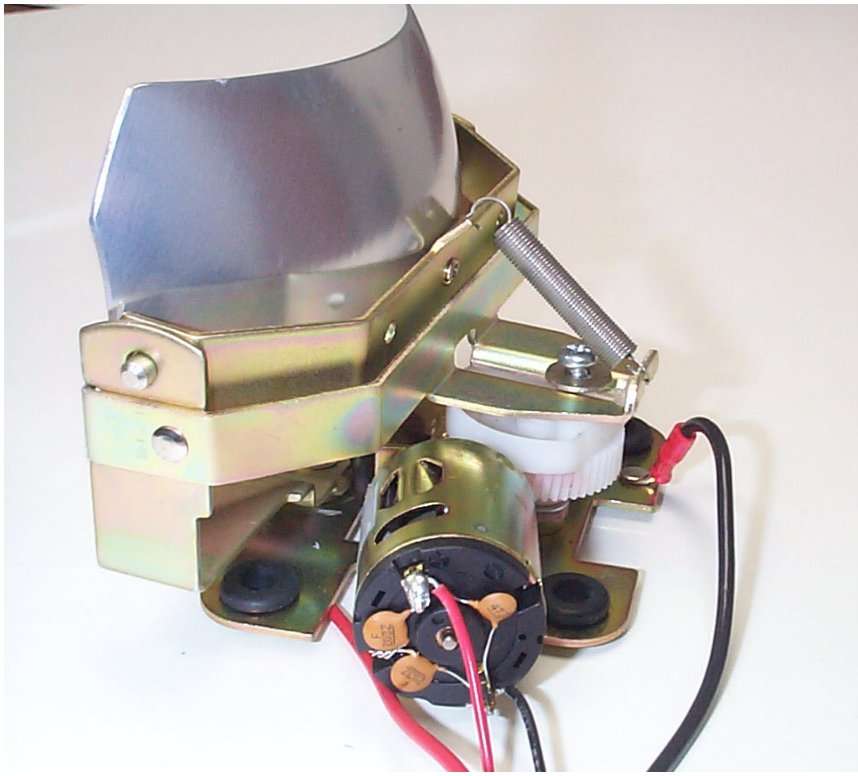


Figure 50. The TCL showing its drive motor, part of the reflector movement mechanism, and back of the reflector.

SELECTION OF THE STOPPED/SLOWLY-MOVING VEHICLE SIGNAL BASED ON RESULTS OF EXPERIMENT 1

The purpose of the stopped/slowly-moving vehicle signal is to warn/inform the following driver that the vehicle ahead is either stopped or nearly stopped. This signal should be a blend of moderate attention-getting and moderate-to-low discomfort glare.

Discomfort glare is an important consideration in the selection of this signal because there will be many occasions when a following driver will be behind a standing lead vehicle. In such cases the following driver will be forced to look at the vehicle in front from close range.

The stopped/slowly-moving vehicle signal represents a tradeoff. On the one hand it must signal the following driver of the stopped/slowly-moving vehicle condition. On the other, it must not be so high in discomfort glare that the following driver is uncomfortable when stopped behind the lead vehicle.[5]

To select candidate stopped-vehicle configurations, the 17 test configurations are listed in order of discomfort glare from highest to lowest, as shown in Table 5. Also shown are the corresponding visual attention-getting ratings.

[5] There is the possibility of using a rear-facing sensor to detect a vehicle directly behind, at say less than 50 feet, but this is an additional complication that will not be considered here. The stopped/slowly-moving vehicle signal is intended for open-loop use as a supplement to the high-level deceleration signal.

Table 5. Discomfort-glare and visual attention-getting ratings showing limits on domain of acceptability for a stopped/slowly-moving vehicle signal.

	Configuration	Discomfort-glare rating	Visual attention-getting rating
Unacceptable discomfort glare	T	7.5	7.0
	O	6.5	6.6
	S	6.4	6.5
	J	6.4	4.8
	K	5.8	5.1
	Q	5.5	6.1
	P	5.3	6.1
	R	5.2	5.9
Initially acceptable on both discomfort glare and attention getting	A	4.6	5.8
	C	4.5	5.8
	D	4.2	4.8
	G	4.0	4.6
	F	3.8	4.4
	E	3.7	4.8
	B	3.4	5.0
Unacceptable attention getting	H	3.3	3.7
	I	3.0	2.5

The table shows what are believed to be the limits on the acceptable region for the stopped/slowly-moving vehicle signal. The region is bounded by configurations with unacceptable discomfort glare on the upper side and by unacceptable attention-getting ratings on the lower side. The discomfort-glare rating scale used by the subjects was presented earlier in Figure 4. The upper boundary on discomfort glare has been set initially at 5.0, below which the driver would be willing to look at the configuration for at least a minute.

In terms of attention-getting, there is a clear break between configurations that are the second and third from the bottom of the table. Therefore, this would seem to be a good place to set the lower boundary. In terms of visual attention getting, this leaves ratings between 4.4 and 5.8 in the acceptable region.

As is the case for the high-level signal, the stopped/slowly-moving vehicle signal can be further specified by considering additional and more stringent criteria. Table 6 shows these additional criteria. In the table, both discomfort-glare and attention-getting ratings appear first. Both are shown because there is not an identical ranking order for the two ratings. Thereafter, total peripheral detectability and complexity are shown. As the table shows, each criterion has a different rank ordering, making selection somewhat of a dilemma.

Table 6. Discomfort-glare and visual attention-getting ratings showing limits on domain of acceptability for a stopped/slowly-moving vehicle signal.

Configuration	Discomfort-glare rating	Visual attention-getting rating	Total peripheral detectability	Complexity
A	4.6	5.8	138.9	18
C	4.5	5.8	138.9	15
D	4.2	4.8	123.6	14
G*	4.0	4.6	110.4	7
F*	3.8	4.4	111.8	8
E	3.7	4.8	114.5	12
B	3.4	5.0	124.4	17

* G and F are configurations with low complexity and other characteristics deemed acceptable.

In making the final selection, it should be remembered that discomfort glare is lower going down in the table. Thus, the upper values in the table are not optimum. A ranking of 4.0 or less for discomfort glare is probably desirable under all circumstances. This value moves the upper bound to between the third and fourth entries in the table. To complete the selection, it should be noted that the next two entries have the lowest complexity ratings by a wide margin. They do, however, have slightly lower peripheral detectability. Considering the substantial reduction in complexity of configurations G and F and that the other characteristics are all acceptable, these seem to be the optimal choices.

Configuration G uses two alternating, center-mounted medium-output lamps placed next to one another, while configuration F uses the same alternating lamps placed apart, similar to the positioning of the current taillights on vehicles. The characteristics of F are just slightly less favorable than those of G, and thus, the recommended configuration is G.

Configuration G uses a relatively small footprint and would be mounted at the center of the trunk or hatch. It would have the advantage of requiring very simple drive electronics or could use a thermal switching driver for the two lamps. While medium-output halogen lamps have been used in the test configuration, equivalent LED array lamps or possibly other technologies could also be used. Furthermore, closely spaced alternating lights are not used in any other known signaling application; thus, there is a uniqueness associated with this pattern.[6]

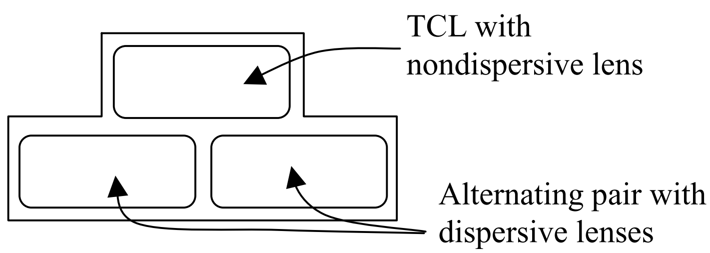
[6] There has been some transit bus use of an alternating amber pair of lamps spaced 12 to 24 inches apart. The lamps appear to be used to help following drivers determine that the transit vehicle is moving slowly or stopping.

COMBINING THE SELECTED HIGH-LEVEL AND STOPPED/SLOWLY-MOVING VEHICLE SIGNALS

Until now, the selected configuration for the high-level signal and that for the stopped/slowly-moving vehicle signal have been considered separately in the selection process. This leaves open questions of integration of the two configurations. Are they reasonably compatible, or do they conflict with one another? In this section, these questions will be considered.

There appear to be two ways in which the two signals could be combined: vertically and horizontally. As shown in Figure 51.a, one configuration could be placed over the other in a vertical arrangement. Here, the TCL has arbitrarily been placed over the alternating pair. Figure 51.b shows the lamps arranged horizontally. In this case, the alternating pair has been moved apart by one "cell" and the TCL placed at the center. This arrangement has been selected because it maintains symmetry about the vertical centerline.

a. vertical arrangement



b. horizontal arrangement

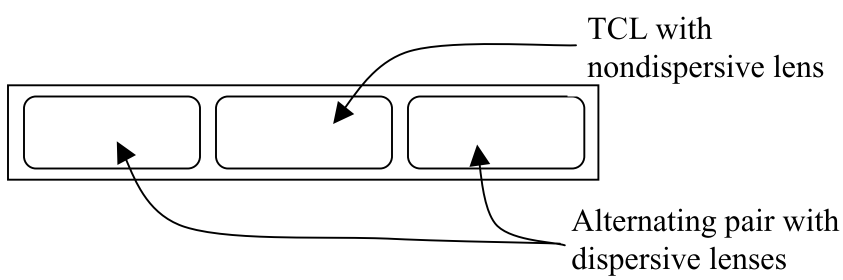


Figure 51. Candidate combined configurations for the high-level and stopped/slowly-moving vehicle signals.

It should be noted that the TCL uses a "nondispersive" lens, similar to a pane of glass. The lens therefore allows the lamp output (reflected off a parabolic mirror) to be concentrated in a beam that is directed where it is needed, that is, in an area directly behind the lead vehicle. This arrangement makes it possible for the high-output halogen lamp to compete and even provide slightly superior results over other high-output devices such as strobes. By directing the beam, drivers in adjacent lanes will not be in the path of the beam under ordinary circumstances.

On the other hand, the alternating lamp pair (as tested in Experiment 1) uses "dispersive" lenses that spread the light output over a greater area. These lenses are similar to taillight and backup lenses in present-day vehicles. Since the alternating lamp pair has less discomfort glare, there is no particular reason not to allow some portion of the output to be visible from adjacent lanes.

Because the lenses of the two types of devices may be different in the final configuration, the TCL probably should not be placed to the side of the contiguous alternating pair. Doing so would create an asymmetrical appearance for the three-lamp system. Also, under such circumstances, both the TCL and the alternating pair would be off-center, which could be confusing. Thus, it would seem that the symmetrical horizontal arrangement shown in Figure 51.b should be used.

There are additional ramifications associated with the configurations shown in Figure 51. From a styling and integration point of view, the vertical arrangement (51.a) would probably be slightly more difficult to integrate into current vehicles than the horizontal arrangement (51.b). On some vehicles there may not be sufficient vertical, central free space to include additional signals that are approximately 6 inches (15.2cm) high. However, most vehicles have a vertical expanse of around 3.5 inches (8.9cm) along the rear centerline and could also accommodate the larger horizontal dimension without difficulty. Thus, from the standpoint of integration into current-day vehicles, the horizontal arrangement would probably be preferred. While not a major consideration, the horizontal arrangement might also be preferred from the standpoint of aesthetics.

The horizontal arrangement as shown in Figure 51.b is *not* exactly the same as Configuration G (as it was tested), because it includes a separation between the two alternating lamps of one "cell." The question that arises is whether or not this separation matters. To answer the question, note that Configuration F, which uses a wide separation, produces only slightly different results. All other parameters associated with Configurations G and F are the same. Based on the similarity of the results of Configurations G and F, it is probably safe to say that a one-cell separation would not materially affect the performance of the alternating lamp arrangement, assuming the lamps were separated by about 6 inches (15.2cm). However, to be safe in making recommendations, the second phase of the testing (Experiment 2) should include this separation, so that the results are applicable with certainty to the configuration in Figure 51.b.

Another ramification involves integration with the existing rear lighting. Implicit in the candidate arrangements of Figure 51.b is an assumption that the conventional rear lighting would operate as it now does. Clearly, in the long run, a systems engineering study should be performed that would integrate all rear lighting, assuming demonstrated effectiveness of one or both of the new signals proposed in Figure 51.b.

A final question involves whether or not there would be any unexpected performance interactions when the two types of lighting are integrated. Would there be confusion and possible misunderstanding of the two signals? The answer appears to be no. There would be very few occasions when both would be activated. The TCL is intended to indicate rapid deceleration in the open-loop system and an impending crash in the closed-loop system. The alternating pair is intended to indicate that the vehicle is standing on the pavement or moving very slowly. Thus, the two lighting signals would generally not be activated at the same time, since a vehicle that is standing is not decelerating.

There are, however, two situations in which the two signals might be activated simultaneously (or overlap in time). They are as follows:

1. In the open-loop situation, after the lead vehicle decelerates rapidly to a stop, the high-level signal time-out feature might remain on for approximately three seconds to help prevent a rear-end crash. At the same time, the stopped/slowly-moving vehicle signal would be activated.
2. In the closed-loop situation, if the stopped/slowly-moving vehicle signal is used, it might be activated at the same time as the high-level signal to prevent a rear-end crash.[7]

There are two possible ways to handle the above situations. They are as follows:

1. The simultaneous activation could be checked experimentally, to see if it causes any untoward reactions by drivers. If not, then there is no problem.
2. The high-level signal could be given priority, so that whenever it is activated, the stopped/slowly-moving vehicle signal could not be activated. If untoward reactions do occur for solution 1 (above), this alternative should be used.

It should be mentioned that overlap might be helpful in that there is more light output for detection and in that the signals have precise meanings that are consistent. If so, then overlap should definitely be retained.

Thus, the final recommendation emanating from the first experiment and its related results is that the configuration shown in Figure 51.b should be further tested in the second experiment. This configuration appears to have maximum overall advantages. It includes a TCL in the center cell for high-level use and a flanking, alternating pair used as a stopped/slowly-moving vehicle signal.

[7] The decision as to whether to include a stopped/slowly-moving vehicle signal in the closed-loop situation has not yet been made.

PROCEDURES FOR EXPERIMENT 2 OF TASK 2

The results of the first phase of testing (the first experiment) suggested that the straightforward arrangement shown in Figure 51.b should be further examined. This arrangement appeared to have many advantages in terms of desired driver response characteristics and in terms of low complexity. The recommended arrangement includes a high-level signal for use in attracting the following driver's attention (to rapid deceleration in the open-loop case and to an impending crash in the closed-loop case). The recommended arrangement also includes an alternating pair of lamps to indicate to the following driver that the vehicle ahead is stopped or moving very slowly. Considering the substantial promise that the combined configuration had, there seemed to be little reason to investigate alternatives further. Thus, resources in the second phase of experimentation (the second experiment) were devoted to refinements of the recommended configuration.

What experiments appeared warranted? First, all previous testing was done using white lighting. The reason for initially limiting testing to white lighting was to avoid the confounds and additional variables (dimensionality) associated with the simultaneous introduction of color. Color and "apparent brightness" are known to interact (Boff and Lincoln, 1988, sections 1.303 and 1.304). Thus, to obtain a fair comparison of various configurations, a common color had to be used. To avoid bias associated with slight variations in color and specific color sensitivity of various drivers, it seemed prudent to use white lighting for all testing because of its broadband energy. However, white lighting differs from the colors ordinarily used in rear lighting, and thus the second phase of experimentation was planned to include the effects of color. Since the number of configuration elements had been reduced to two, other dimensions (independent variables, such as color) could then be tested.

As mentioned, apparent brightness is affected by color. Therefore, it was hypothesized that because the human eye is differentially sensitive to colored light (as evidenced by the photopic and scotopic response characteristics; Boff and Lincoln, 1988, section 1.301), it was considered possible and perhaps even likely that drivers would give lower rating values for both attention getting and discomfort glare when color lenses were substituted. Also, colored lenses would be expected to suppress light wavelengths that are well away from the predominant passband. This would result in lower light energy reaching the subject's eyes. Offsetting these phenomena is color contrast. Driver-subjects might be expected to increase their ratings for attention getting and discomfort glare because of improvements in contrast due to the use of colors that are different from the surround. Color contrast might offset somewhat the lower levels of light reaching the driver's eyes. Thus, overall, introduction of color would be likely to result in some reduction of both attention-getting and discomfort-glare ratings.

What ramifications did these complex color phenomena have for the second experiment? To answer this question, the research team considered the high-level signal (the TCL) and the stopped/slowly-moving vehicle signal (the alternating lamps) separately. In the case of the TCL, the mean rating for attention getting was 7.0 and the mean rating for discomfort glare was 7.5. These ratings are quite high; in fact, they are the highest ratings attained in the first experiment. With the introduction of tinted lenses it was hypothesized that both ratings would be reduced somewhat. Small reductions could be tolerated and might even be desirable. Therefore, the TCL was tested without modification using both clear (as a baseline) and tinted lenses (amber and red). Information on performance would then be available for the final design process.

In the case of the stopped/slowly-moving vehicle signal (the alternating lamp pair), the ratings in the first experiment were 4.6 for attention getting and 4.0 for discomfort glare. These values were deemed to be in the correct range for the signal. However, if the introduction of colored lenses reduced the values appreciably, the resulting attention-getting rating might be too low.

The alternating vehicle signal tested in the first experiment used medium-output halogen lamps and dispersive lenses. There were two possible ways to increase the attention getting characteristics (essentially, the light output) of the alternating vehicle signal when colored lenses were introduced: use higher output bulbs or use nondispersive (though tinted) lenses. Since high-output halogen lamps were available, it was decided that both medium and high-output halogen lamps should be tested. There were no nondispersive lenses available to fit the medium-output halogen casings, so hybrid lenses were fabricated using nondispersive lenses intended for the Viper strobe unit fused to the front of the standard medium-output lenses (after the dispersive front portion had been removed).

Thus there were nine conditions tested for the stopped/slowly-moving vehicle signal: a medium-output alternating pair using dispersive lenses in clear, amber, and red; a high-output alternating pair using dispersive lenses in clear, amber, and red; and a medium-output alternating pair using nondispersive lenses in clear, amber, and red. This set of conditions would make selection possible based on more comprehensive information. Specifically, it would be possible to determine the most efficient way to increase the attention-getting properties of the medium-output alternating lamp when colors are added: increasing the light output by using more powerful bulbs, or increasing the light output by using nondispersive lenses.

A high-output alternating pair of lamps was not tested in the first experiment, and provisions had not been made to perform such testing. It therefore became necessary to develop modifications to the original test apparatus to accommodate the high-output alternating pair. In addition, as discussed earlier, both the medium-output alternating pair and the high-output alternating pair were to be separated by one cell or lamp distance. This required some reprogramming and the fabrication of a new mask board for each of the alternating pairs. Figure 52 depicts the changes to the lighting rig for the second experiment, and Figure 53 portrays one of the new mask boards used for the alternating signal pair. In addition, Appendix D shows three photos of the lighting assembly as it was used for Experiments 1 and 2.

Independent Variable (Conditions) in the Second Experiment

As per discussions above, four lighting configurations were tested in the second experiment (with three colors tested for each configuration):

1. The high-level signal or TCL, with clear, amber, and red nondispersive lenses, without any modifications.
2. The medium-output alternating pair with dispersive lenses of clear, amber, and red, and separated by a single lamp distance.
3. The medium-output alternating pair with nondispersive lenses of clear, amber, and red, and separated by a single lamp distance.
4. The high-output alternating pair with dispersive lenses of clear, amber, and red, and separated by a single lamp distance.

These four conditions were deemed adequate to provide the necessary information for the final design.

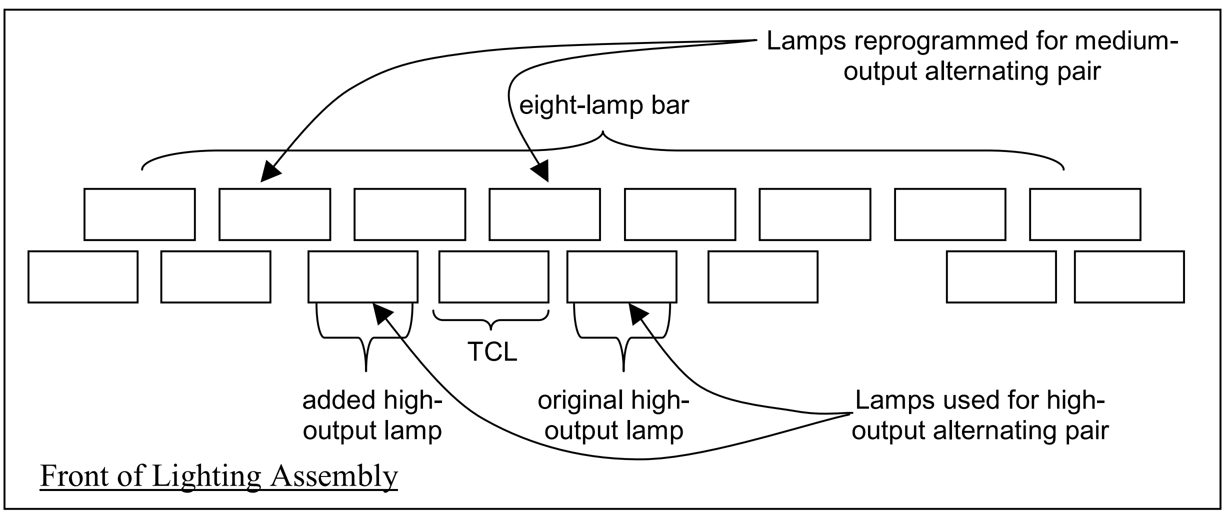


Figure 52. Depiction of modifications to the lighting rig for the second experiment.

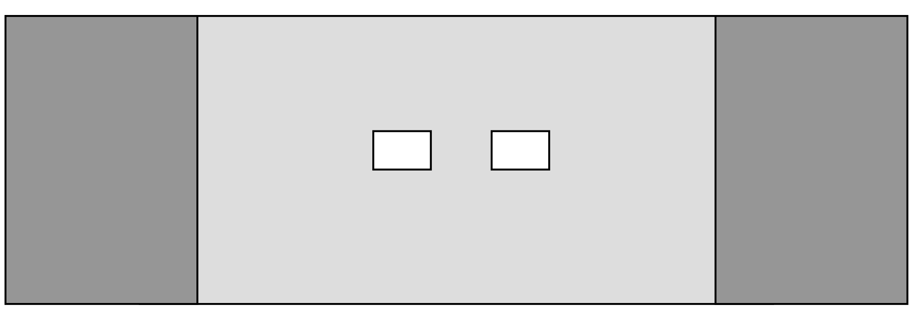


Figure 53. Portrayal of one of the new mask boards used in the second experiment for the alternating signal conditions.

Additional Lens Considerations

Three sets of lenses were obtained when the lighting rig was fabricated: clear (producing white light), amber, and red. Two other available colors were considered and rejected for the following reasons:

- Blue was rejected because of its prevalent use on police cruisers and because of low transmissivity.
- Green was rejected because of its possible association with green traffic signals, which conflict in meaning with bringing a vehicle to a stop or slowing to avoid a collision with a vehicle ahead.

Thus, the initial lens tint candidates were as follows: clear, amber, and red.

The research team had concerns about the transmissivity of red lenses. This concern centered on the problem that if the red lenses suppressed the light output by a large factor, the attention-getting ratings would be much lower. Also, sensitivity to red light is lower than to most other colors. On the other hand, red is definitely associated with stopping, and thus it is quite appropriate from an information coding point of view. It was desired to retain the coding properties of red while at the same time improving the transmissivity. The research team experimented with a variety of thin, red plastic filters placed over the clear lenses. This approach did not yield a satisfactory solution, and upon reflection, the research team concluded that transmissivity concerns were only applicable to the medium-output lamps. Furthermore, the transmissivity concerns with the medium-output lamps were applicable to all colors, not just red. Thus the decision was made, as discussed previously, to test hybrid nondispersive lenses in all three colors (clear, amber, and red) for the medium-output lamps in addition to the dispersive lenses already scheduled for testing. Dispersive lenses of clear, red, and amber were used for the high-output lamps, while nondispersive lenses of clear, amber, and red were used with the TCL. In all, 12 conditions were tested in the second experiment: four configurations (1, 2, 3, and 4) by three tints (C, A, and R) in all factorial combinations. Appendix E presents the lens parameters in terms of light transmissivity and color coordinates.

Table 7 provides a description of each configuration, while Table 8 shows the counterbalancing scheme used. For data gathering, the subject was presented with all four configurations in a given tint before moving on to the next tint. Both tint and configuration were counterbalanced across the 12 subjects who participated.

Table 7. Configuration descriptions for the 12 configurations used in Experiment 2.

Configuration	Description
1C	Nondispersive lenses, clear, two-lamp, medium-output halogen, alternating, separated by one lamp width
1A	Nondispersive lenses, amber, two-lamp, medium-output halogen, alternating, separated by one lamp width
1R	Nondispersive lenses, red, two-lamp, medium-output halogen, alternating, separated by one lamp width
2C	Dispersive lenses, clear, two-lamp, medium-output halogen, alternating, separated by one lamp width
2A	Dispersive lenses, amber, two-lamp, medium-output halogen, alternating, separated by one lamp width
2R	Dispersive lenses, red, two-lamp, medium-output halogen, alternating, separated by one lamp width
3C	Dispersive lenses, clear, two-lamp, high-output halogen, alternating, separated by one lamp width
3A	Dispersive lenses, amber, two-lamp, high-output halogen, alternating, separated by one lamp width
3R	Dispersive lenses, red, two-lamp, high-output halogen, alternating, separated by one lamp width
4C	Nondispersive lens, clear, Traffic clearing light
4A	Nondispersive lens, amber, Traffic clearing light
4R	Nondispersive lens, red, Traffic clearing light

Table 8. Counterbalancing scheme used for the second experiment. Presentation order was by row from left to right.

		Order											
		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**	**11th**	**12th**
	1	1C	2C	3C	4C	1A	2A	3A	4A	1R	2R	3R	4R
	2	2C	4C	1C	3C	2A	4A	1A	3A	2R	4R	1R	3R
	3	3C	1C	4C	2C	3A	1A	4A	2A	3R	1R	4R	2R
	4	4C	3C	2C	1C	4A	3A	2A	1A	4R	3R	2R	1R
Subject	**5**	1A	2A	3R	4R	1R	2R	3C	4C	1C	2C	3A	4A
	6	2A	4A	1R	3R	2R	4R	1C	3C	2C	4C	1A	3A
	7	3A	1A	4R	2R	3R	1R	4C	2C	3C	1C	4A	2A
	8	4A	3A	2R	1R	4R	3R	2C	1C	4C	3C	2A	1A
	9	1R	2R	3A	4A	1C	2C	3R	4R	1A	2A	3C	4C
	10	2R	4R	1A	3A	2C	4C	1R	3R	2A	4A	1C	3C
	11	3R	1R	4A	2A	3C	1C	4R	2R	3A	1A	4C	2C
	12	4R	3R	2A	1A	4C	3C	2R	1R	4A	3A	2C	1C

<u>Experiment 2 Methods</u>

The experimental procedure used in Experiment 2 was quite similar to Experiment 1. However, because of the very high correlation between the first attention-getting ratings and the final attention-getting ratings, the initial practice/familiarization session was limited to four configurations that were counterbalanced across subjects. The configurations used were 1A, 2R, 3A, and 4C. These four were selected as representative of the entire set. In Experiment 2, configuration settings, mask boards, *and* lenses had to be changed. As a result, there was concern that subjects might become fatigued if the experiment dragged on too long. This represented a second, important reason for curtailing the practice session.

The procedure thus became the following. Each subject first provided initial attention-getting ratings (for the four selected configurations) while sitting in a vehicle at an eye distance of 150 feet (45.7 m). The purpose was to expose the subject to typical conditions, as well as to provide practice in using the attention-getting rating scale. Thereafter, the vehicle was moved to an eye distance of 40 feet (12.2 m), where all twelve configurations were presented. The subject provided discomfort-glare ratings at this distance. After a break, the vehicle was returned to the 150 foot eye distance position. From there the subject provided final attention-getting ratings, horizontal peripheral detection angles, and diagonal peripheral detection angles for each condition. The presentations were repeated in exactly the same order as for the discomfort-glare ratings. All three measures were obtained for each condition before moving on to the next condition.

It is important to note that the diagonal peripheral detection task was modified slightly for Experiment 2. In Experiment 1, the subject was directed to particular landmarks (small stickers) inside the vehicle and then asked if he or she could detect the signal which was presented for five seconds. Checks were made to insure consistency, and ascending and descending trials were used as described earlier. Precisely the same procedures were used for the second experiment. However, the positions of the landmarks for the diagonal peripheral detection tasks were changed.

In the first experiment, the landmarks progressed diagonally down and to the right across the lower edge of the instrument panel. The three landmarks with the highest peripheral slant angles, however, were somewhat compressed in angular position because of the particular form of the dash of the research vehicle used. In the second experiment, the points were reselected to emphasize slant angles that might be used when the driver would be attending to interior displays or controls along the centerline and console. The first landmark was on the windshield, at the centerline of the vehicle. The next four landmarks were below this first landmark and followed the dash vertically along the instrument panel centerline, while the remaining two landmarks were arranged longitudinally along the console. Thus, the slant angles increased by first going down along the instrument panel and then going back along the console for a total of seven landmarks.

As a final note, it should be mentioned that data were gathered during December, January, and early February. To offset the limited brightness and daylight, each subject was run during the maximum daylight interval from 10:30 am to 3:00 pm. Only one subject was run per day. As before, data were only taken when there were distinct shadows.

Subjects

The subjects used in the second experiment were pre-selected based on age: younger (ages 18-35) and older (ages 50-70). There were an equal number of males and females in each age group. Presentation order was counterbalanced to prevent biases by age or gender.

As in Experiment 1, subjects in Experiment 2 had to present a valid driver's license and were required to wear glasses if the driver's license so indicated. They were also required to be no more than 6'1" in height so that their eyes could be properly positioned. None of the subjects in the second experiment had participated in the first experiment.

EXPERIMENT 2 RESULTS

As indicated in the discussion of protocol, there were four independent variables (4 configurations by 3 colors [hues] by 2 age groups by 2 genders) and four dependent variables (attention-getting rating, discomfort-glare rating, horizontal peripheral detection angle, and diagonal peripheral detection angle). A parametric analysis of variance was performed for each dependent variable. These appear in Appendix F. Where main effects were significant, one-way Kruskal-Wallis (K-W) nonparametric tests were also performed. When main effects involved more than two levels of an independent variable, Student-Newman-Keuls (SNK) tests were also performed to determine which levels differed significantly from one another.

Attention-Getting Ratings

The ANOVA for attention-getting ratings showed a main effect of configuration. This was the only significant main effect ($F_{3,24} = 70.36$; $p<0.0001$). An SNK post-hoc test was then performed to determine which configurations were significantly different from the others at $\alpha = 0.05$. The ANOVA and SNK results are shown in Figure 54. A one-way K-W nonparametric test with configuration as the independent variable was also run. These results also indicated significance (K-W $\text{Chi-Square}_{3\ df} = 66.09$; $p<0.0001$). The ANOVA summary table is presented in Table F1 of Appendix F.

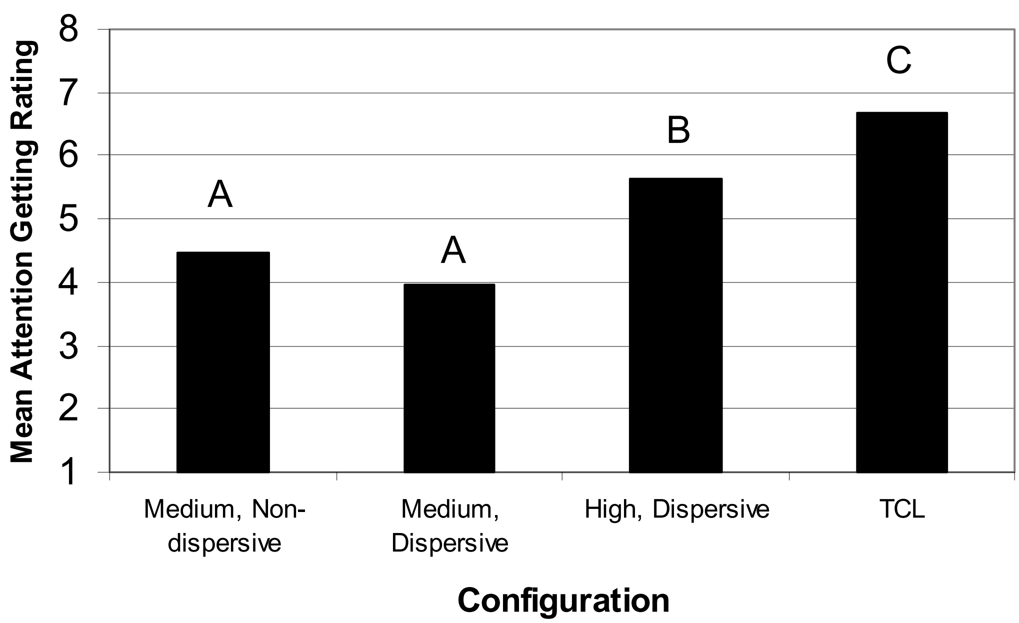


Figure 54. Mean attention-getting ratings for four rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

For information purposes, a plot of configuration by color is also shown (Figure 55). Note that neither color nor its interaction with configuration was significant. The results show that there is no straightforward trend in color for the various configurations. Three of the configurations (with clear lenses) shown in Figure 55 correspond closely to those used in Experiment 1. The corresponding results from Experiment 1 appear as dots, for purposes of comparison.

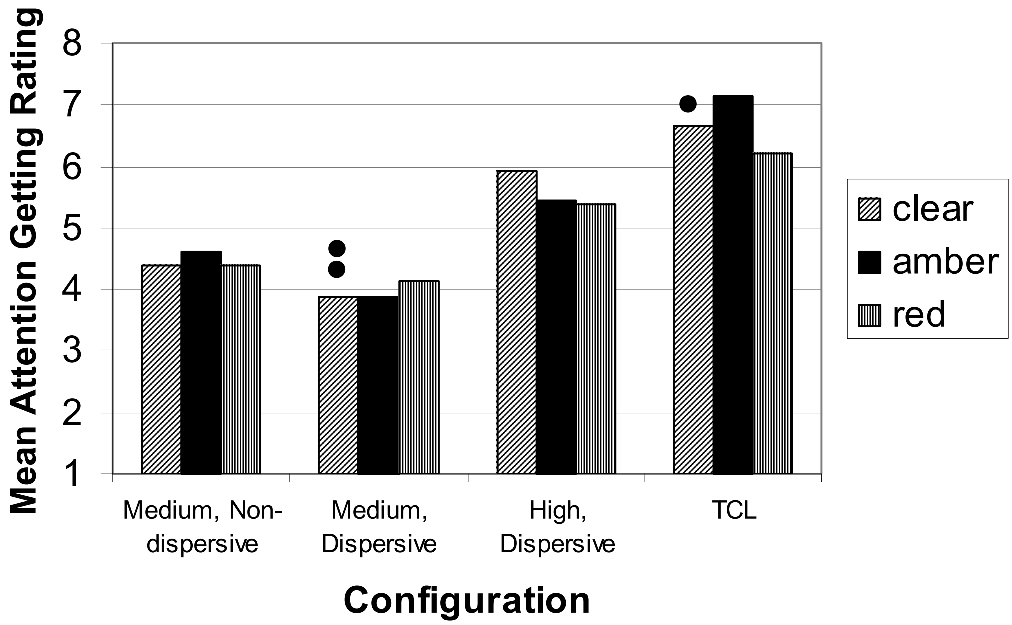


Figure 55. Plot of color by configuration for attention-getting ratings. The small dots represent data points from similar configurations during Experiment 1.

The only other significant effect for attention-getting was a three-way interaction of configuration by gender by age ($F_{3,24} = 4.92$; p=0.008). This result is plotted in Figure F1 of Appendix F.

Discomfort-Glare Ratings

Both configuration ($F_{3,24} = 55.57$; $p<0.0001$) and color ($F_{2,16} = 8.32$; $p=0.003$) main effects were significant for the discomfort-glare dependent measure. No other main effects or interactions were significant. A non-parametric K-W one-way test on configuration yielded significance (K-W $\text{Chi-Square}_{3\ df} = 79.10$; $p<0.0001$), as did a one-way K-W test on color (K-W $\text{Chi-Square}_{2\ df} = 9.44$; $p=0.009$). Figure 56 shows a plot of the configuration main effect. SNK values are also shown. Similarly, the color main effect is shown in Figure 57 with corresponding SNK test results. The ANOVA summary table for this analysis is presented in Table F2 of Appendix F.

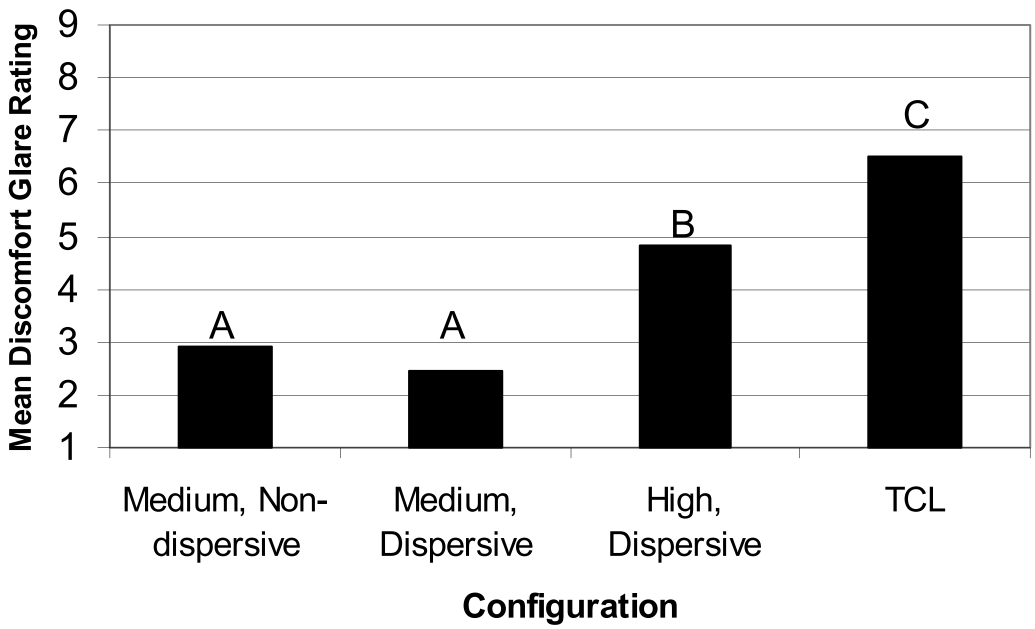


Figure 56. Mean discomfort-glare ratings for four rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

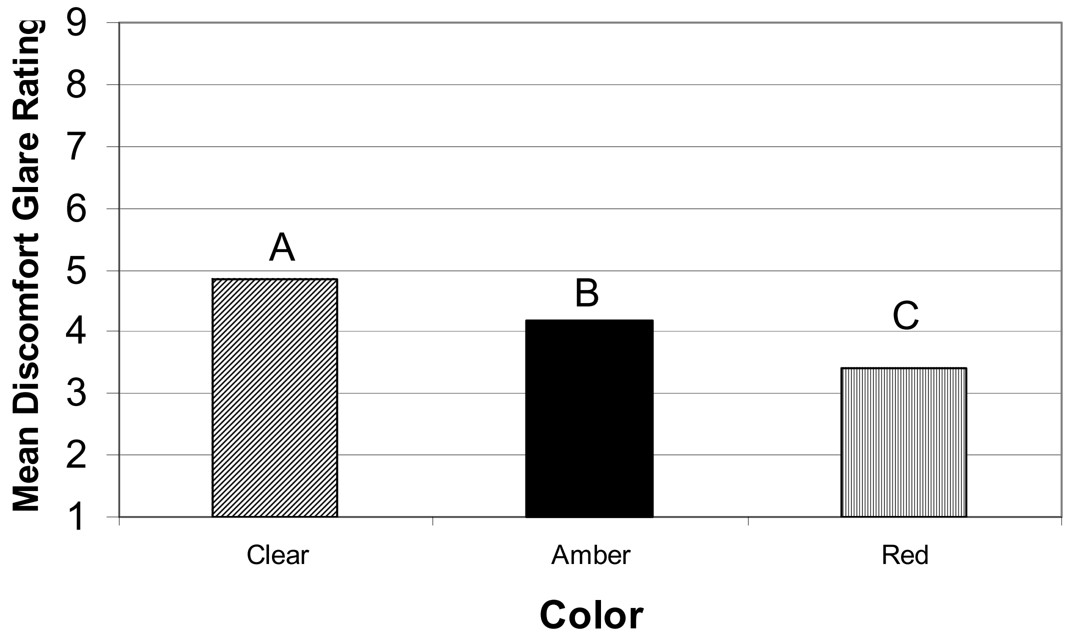


Figure 57. Mean discomfort-glare ratings for three lighting colors. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

For completeness, a plot showing configuration by color is presented in Figure 58. As can be seen, color has the same trend for each configuration. Again, the three closely corresponding (clear lens) results from Experiment 1 are plotted in Figure 58.

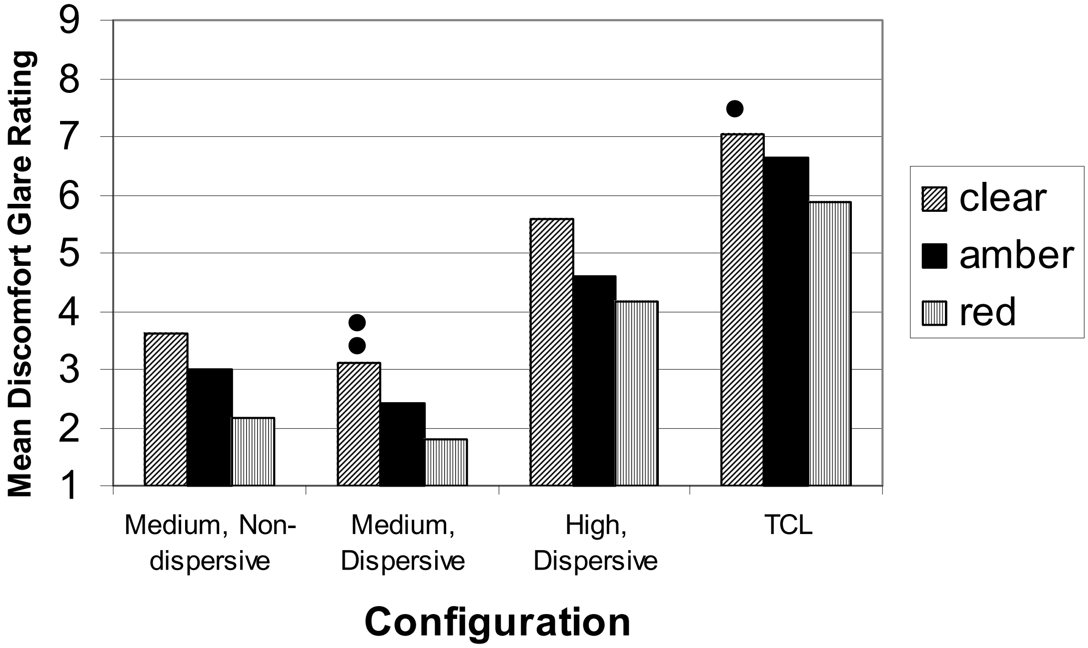


Figure 58. Plot of color by configuration for discomfort-glare ratings. The small dots represent data points from similar configurations during Experiment 1.

Horizontal Peripheral Detection

For horizontal detection, the main effects of configuration ($F_{3,24} = 54.92$; $p<0.0001$) and color ($F_{2,16} = 4.96$; $p=0.021$) were significant. These are plotted in Figures 59 and 60. The one-way K-W tests resulted in significance for configuration (K-W Chi-Square$_{3\ df} = 69.58$; $p<0.0001$), but not for color (K-W Chi-Square$_{2\ df} = 4.23$; $p=0.1208$). Nevertheless, both figures contain the results of SNK tests, which also demonstrate significant differences as a function of levels of the independent variables. The ANOVA summary table for this analysis appears in Appendix F, Table F3.

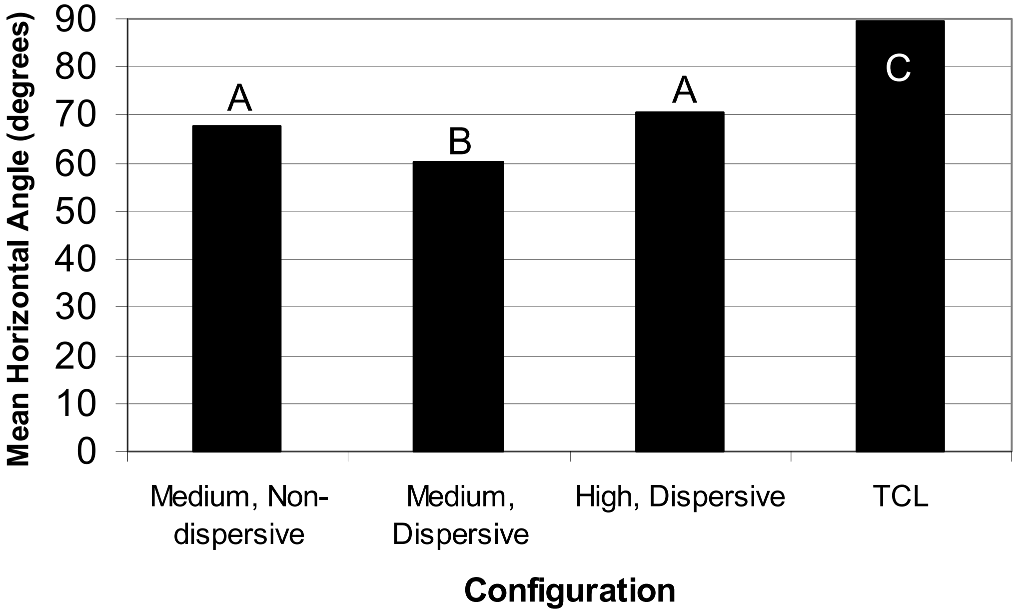


Figure 59. Mean horizontal peripheral detection angle for four rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

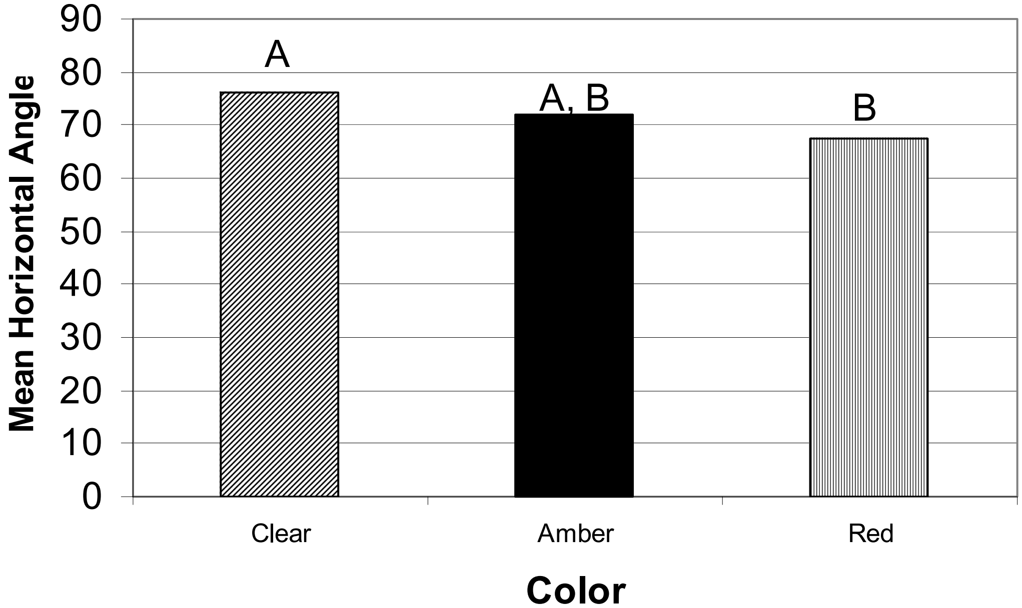


Figure 60. Mean horizontal peripheral detection angle for three lighting colors. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

For purposes of illustration, the results of configuration as a function of color are presented in Figure 61. As can be seen, the trends are similar as a function of color, except for the TCL, which provides nearly 90˚ of coverage for all three colors. For comparison purposes, the three results (using clear lenses) from Experiment 1 similar to those of Experiment 2 are plotted in Figure 61. Nearly perfect correspondence exists.

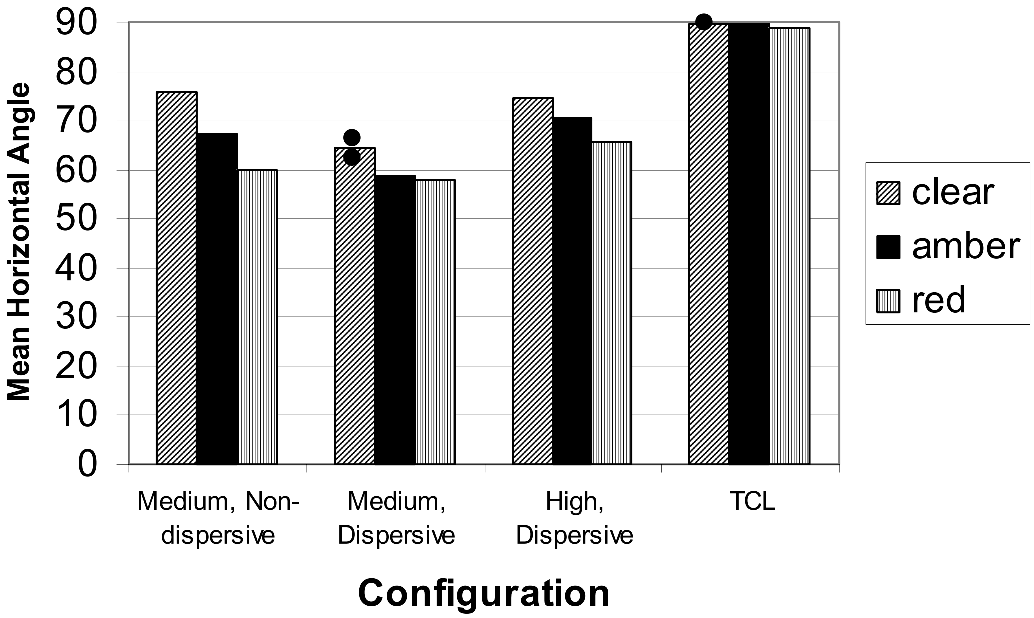


Figure 61. Plot of color by configuration for horizontal peripheral detection angle. The small dots represent data points from similar configurations during Experiment 1.

There were also four significant interactions for horizontal peripheral detection angle: age by gender ($F_{1,8} = 11.41$; p=0.0097), configuration by age ($F_{3,24} = 4.37$; p=0.014), configuration by gender ($F_{3,24} = 4.47$; p=0.013), and configuration by age by gender ($F_{3,24} = 10.18$; p=0.0002). These results are plotted in Appendix F, Figures F2 through F5 respectively. Two main conclusions can be drawn from these interactions: 1) the TCL appears to be immune to any effects of age or gender that are apparent for the other three configurations for horizontal detection; and 2) all four interactions appear to be driven by the fact that the three older females exhibited worse peripheral detection than did the other three age/gender groups. There is no apparent reason for this difference, which only appears in the horizontal detection task.

Diagonal Peripheral Detection

For diagonal detection, the analysis of variance revealed a significant main effect of configuration ($F_{3,24} = 2479$; p<0.0001) and a significant effect of color ($F_{2,16} = 8.45$; p=0.003). The main effects are plotted in Figures 62 and 63 along with the SNK results. As can be seen, the TCL could be detected at a significantly greater diagonal angle than the other three configurations. Also, red did not provide as great a detection angle as either clear or amber. One-way nonparametric K-W tests similarly revealed significant effects of configuration (K-W $\text{Chi-Square}_{3\ df} = 3894$; p<0.0001) and color (K-W $\text{Chi-Square}_{2\ df} = 6.76$; p=0.034).

For purposes of comparison, the effects of configuration and color are again presented (Figure 64). There are no corresponding results from Experiment 1 for diagonal detection, because the test points were changed in Experiment 2, as explained earlier.

The only other significant effect in diagonal peripheral detection was an age by gender interaction ($F_{1,8} = 5.38$; p=0.049). This result is plotted in Figure F6 of Appendix F.

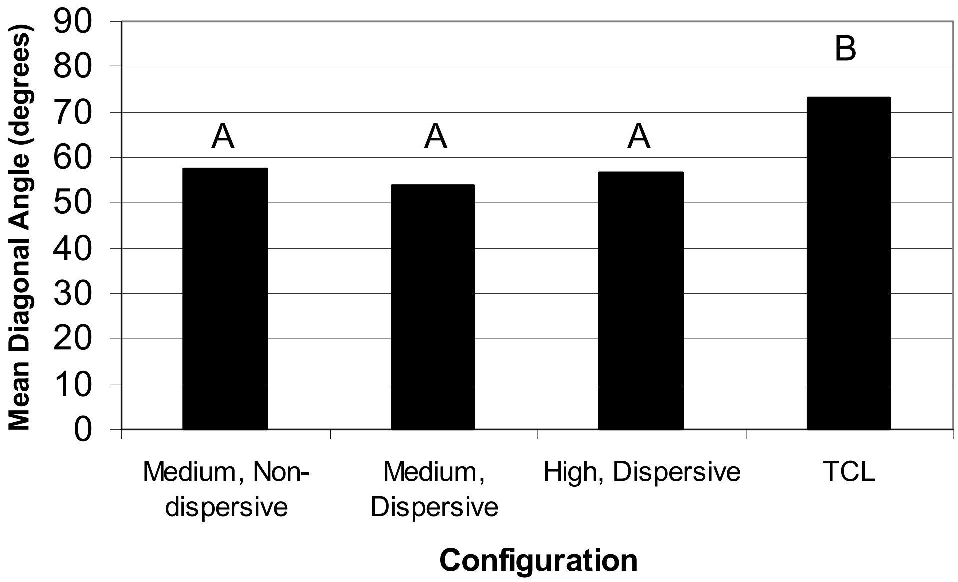


Figure 62. Mean diagonal peripheral detection angle for four rear-lighting configurations. (Means with the same letter are not significantly different using an SNK post-hoc test at α = 0.05.)

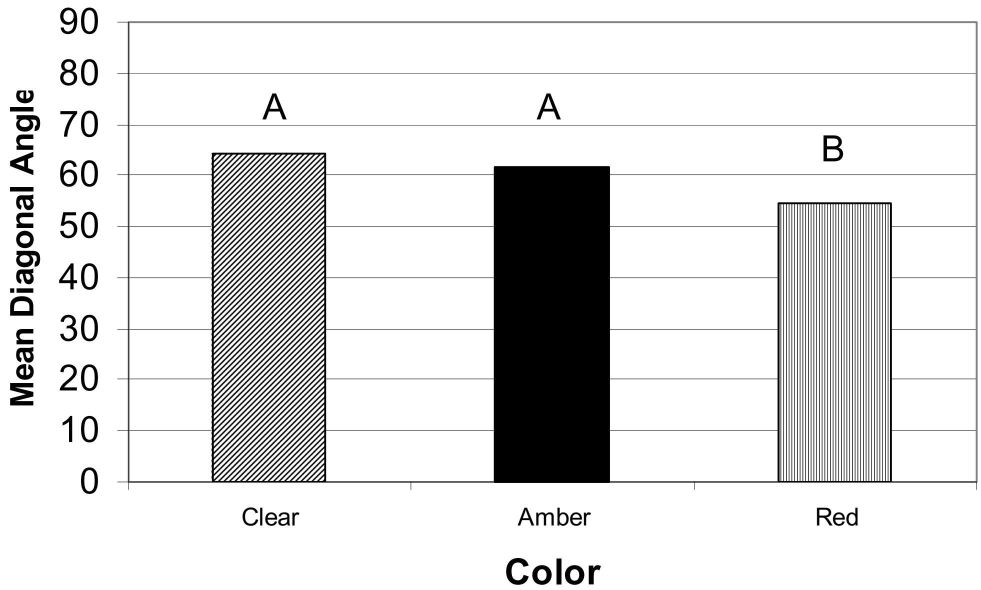


Figure 63. Mean diagonal peripheral detection angle for three lighting colors. (Means with the same letter are not significantly different using an SNK post-hoc test at $\alpha = 0.05$.)

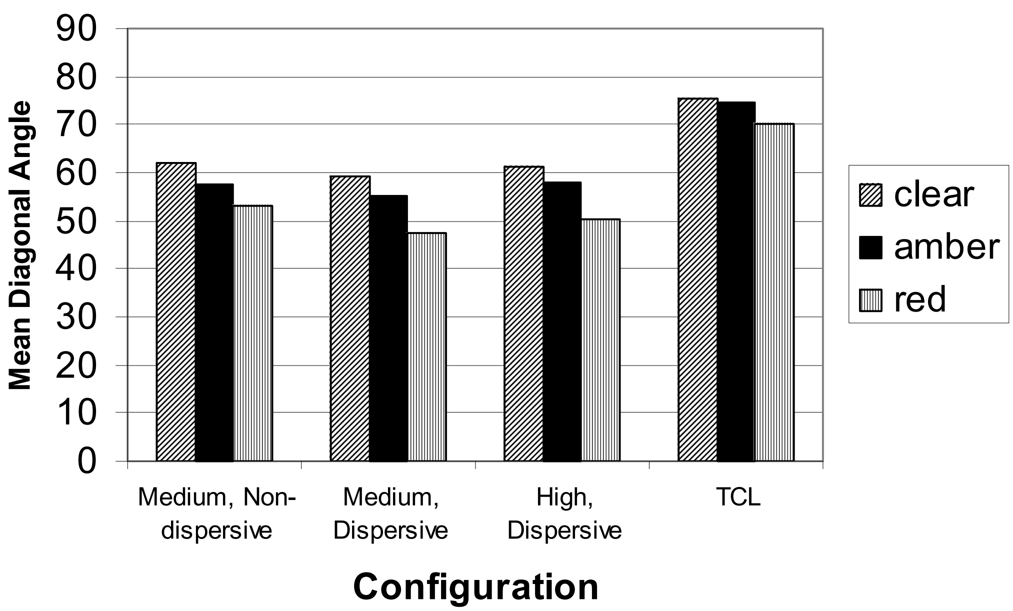


Figure 64. Plot of color by configuration for diagonal peripheral detection angle.

DISCUSSION OF RESULTS OF EXPERIMENT 2, AND CORRESPONDING RECOMMENDED LIGHTING CONFIGURATIONS

Overall, the results of Experiment 2 demonstrate that there are reliable (i.e., significant) configuration and color effects in the gathered data. These results suggest that the objectives of the experiment were attained, in that questions about color and final configuration selection could be answered. The results will be discussed first in regard to consistency between Experiments 1 and 2, then in regard to the high-level lighting signal, and finally in regard to the stopped/slowly-moving vehicle signal.

Comparison of Similar Conditions between Experiments 1 and 2

There were three conditions that were similar between Experiments 1 and 2. By examining these conditions, information on consistency can be attained.

In Experiment 1, configurations F and G involved an alternating pair of medium-output halogen lamps with clear dispersive lenses. In F the lamps were adjacent to one another and in G the lamps were separated by six "lamp distances." Nevertheless the conditions are similar to the clear dispersive lens, medium-output halogen alternating pair condition of Experiment 2. In Experiment 2, the lamps were separated by one lamp distance. Similarly, configuration T was the TCL in Experiment 1 that was tested with a clear nondispersive lens. The condition was identical to the clear lens TCL condition of Experiment 2.

Comparisons of the similar Experiment 1 and Experiment 2 conditions can be made by examining Figures 55, 58, and 61. Figures 55 and 58 demonstrate that both attention-getting and discomfort-glare were consistently rated slightly lower in Experiment 2. However, the test for the horizontal peripheral detection angle was virtually identical in the two experiments. (Diagonal peripheral detection was not compared because of changes in procedure from Experiment 1 to Experiment 2.)

What would cause the consistent, slightly lower values for the ratings in Experiment 2? Of course, the use of a different group of subjects could account for a difference of this magnitude. However, there is another factor that is more likely to be the cause: the time of year. Data for Experiment 1 were gathered during the months of September and October, whereas data for Experiment 2 were gathered during December, January, and early February. The sun angles were quite different for the two experiments.

In both experiments the subject faced approximately East Northeast (at a measured angle of 65 degrees from magnetic north). Because of the very low sun angle in Experiment 2, owing to the time of year, there was usually a great deal of illumination of the display board by the sun. Thus, contrasts may have been slightly lower in Experiment 2, resulting in slightly lower ratings for attention-getting and discomfort-glare. The fact that the ratings differences are so consistent suggests a systematic effect such as average sun angle. In regard to horizontal peripheral detection, this psychophysical test does not involve opinion ratings. Rather, it is likely to be more dependent on detection capabilities of the eye where peak lamp output might dominate the detection process. Also, the eye would tend to adapt to the surround luminance rather than to the display board luminance, since the driver was looking away from the display board during this test.

In general, there is good reason to believe that the research subjects were indeed providing consistent and accurate ratings for the conditions they experienced. Nothing in regard to the data appears suspect.

High-Level Lighting Signal

As will be recalled, the high-level lighting signal is intended to warn the following driver that a) in the open-loop case, the lead vehicle is decelerating rapidly (or has just completed decelerating rapidly), or b) in the closed-loop case, a rear-end collision is imminent. This signal must have high attention-getting capability and must be visible as far into the periphery as possible. Discomfort glare is a secondary consideration, because the signal will be transient and is not likely to be activated for more than an estimated 7 seconds. The results of Experiment 1 indicated that the TCL (Traffic Clearing Light) possessed superior high-level signal properties when compared to other configurations, and thus the TCL was the only high-level signaling device tested in Experiment 2. Therefore, it was only necessary to examine color, that is, hue or tint of the lens to be used.

Attention-getting for the high-level signal

Figure 54 of Experiment 2 demonstrates that the TCL produced significantly higher attention-getting than any of the other conditions tested (i.e., those associated with the stopped-vehicle signal). Thus, once again the TCL provided superior attention-getting results.

In regard to color, there was no significant main effect or interaction for attention-getting in Experiment 2. This result can be seen in Figure 55. However, the interaction of configuration and color had an F value of 1.91 and a p value of 0.099. Because of this "trend" in the data, the TCL data depicted in Figure 55 were extracted and separately submitted to a one-way analysis of variance. This was done to further examine any possibility that reliable color differences existed for TCL. The test indicated that the differences as a function of color for the TCL were not significant ($F_{2,33} = 2.35$, $p = 0.115$). These results further suggest that any differences in experimental data were not sufficient to overcome chance. Thus, it must be concluded, on the basis of the data available, that attention-getting for the three hues is about the same, at a value of 6.7 (the grand mean of the ratings for TCL attention-getting). For purposes of speculation, it could certainly be said that going from clear to an amber hue does not reduce attention-getting, while going from clear to red might reduce attention-getting slightly. It must be emphasized that these are speculations, pending verification by further data gathering.

Finally in regard to attention-getting, it is very clear that color-contrast plays a major role in rated attention-getting, since the measured outputs in candelas for the amber and red lenses were substantially lower than for the clear lens (see Appendix B showing equivalent on-axis lamp output). The perception of color must therefore be offsetting this reduction in light output, resulting in attention-getting ratings that are about the same as for a clear lens.

Discomfort-glare for the high-level signal

Figure 56 demonstrates that while the TCL had significantly higher attention-getting ratings, it also had significantly higher discomfort-glare than the other conditions tested. This result is the same as in Experiment 1. Figure 57 shows that there was also a significant color main effect, with amber producing a lower rating than clear, and with red producing a lower rating than amber. This result is demonstrated more clearly in Figure 58 for the TCL, where the magnitudes of the differences can be seen. Going from a clear to an amber lens reduces discomfort-glare ratings by about 0.4 rating point, and going from clear to red reduces the ratings by about 1.2 rating points. Thus color has the effect of reducing discomfort-glare, a desirable effect.

Horizontal peripheral detection for the high-level signal

Figure 59 shows that TCL horizontal peripheral detection was significantly superior to the other conditions tested, with an average of 89 degrees. As previously discussed, peripheral detectability is important because it should help redirect the driver's attention when looking away or when daydreaming/looking near, but not at, the lead vehicle.

Figure 60 shows the main effect of color on horizontal peripheral detection. However, this effect only borders on significance in the sense that post-hoc tests show a difference only between clear and red. Also, the corresponding K-W nonparametric test produced a non-significant result. Figure 61 demonstrates that color has a virtually negligible effect for the TCL. Clear and amber produce a full 90 degrees of horizontal detectability, and red produces only one degree less. Clearly, the three colors produce quite similar results.

Diagonal peripheral detection for the high-level signal

Figure 62 shows that the TCL had superior diagonal capability, reaching a full 72 degrees diagonally downward. As with horizontal peripheral detection, it would be difficult to find any reasonable light source that could do better in broad daylight. This statement is made recognizing that, as the driver looks downward into the vehicle, the eyelid and eyelashes begin to obstruct the light path to the pupil of the eye.

The color main effect is shown in Figure 63, demonstrating that red produces a slight reduction in diagonal peripheral detection. This result is further demonstrated for the TCL in Figure 64. As can be seen, there is a loss of about 5 degrees of detectability when a red lens is used. Nevertheless, diagonal detection is still excellent.

TCL lens discussion

Clearly, any rating or performance losses are small in going from clear to amber or from clear to red lenses. There is also a compensating effect of lower discomfort-glare. Table 9 summarizes the effects for the TCL. The amber lens produces virtually no reductions in desirable characteristics, while at the same time reducing discomfort-glare slightly. The red lens (relative to clear) produces a slight reduction in peripheral detection, but also reduces the discomfort-glare by about 1.2 rating points. Thus it trades a small bit of peripheral detection for lower discomfort-glare.

These results suggest that, by and large, either the clear, the amber, or the red lens could be used in the final recommended configuration, and the choice among the three can be made on the basis of other considerations such as consistency and driver interpretation. Since it is unlikely that white light would be used, both amber and red should be considered as final candidates.

Table 9. Effect of lens tint on four human response parameters for the High-Level (TCL) signal.

Property	**Amber Relative to Clear**	**Red Relative to Clear**
Attention-Getting Rating	No change	No change
Discomfort-Glare Rating	Lower by 0.4 rating point	Lower by 1.2 rating points
Horizontal Peripheral Detection	No Change	Lower by 1 degree
Diagonal Peripheral Detection	Lower by 1 degree	Lower by 5 degrees

<u>Stopped/Slowly-Moving Vehicle Signal</u>

In the way of review, this signal is intended to inform the driver of the following vehicle that the lead vehicle is stopped or moving slowly, say, under 5 mph. Because drivers are often stopped in traffic, this signal must have a discomfort-glare rating that is acceptable to the following driver. Specifically, the following driver must find the discomfort-glare acceptable for a period of about a minute. With this requirement as a constraint, the attention-getting and peripheral detection properties should be as high as possible.

Upon completion of Experiment 1, analysis suggested that an alternating pair of lamps with medium-output halogen bulbs and dispersive lenses provided the best tradeoff in terms of both human performance and hardware complexity factors. However, there was concern that with tinted lenses, the signal might not be quite sufficient in terms of attention-getting and peripheral detection. Therefore, in Experiment 2, not only was the original configuration tested, but so were two modified versions. One modified version used nondispersive lenses to increase on-axis light output, and the other version used high-output halogen lamps with dispersive lenses to increase light output. Thus, there were three test configurations, each with three lens colors: clear, amber, and red.

Attention-getting for the stopped/slowly-moving vehicle signal

Figure 54 shows that in Experiment 2, the attention-getting capabilities of the three stopped/slowly-moving vehicle signals (shown by the first three bars) differ significantly. In particular, the high-output halogen lamp with dispersive lenses produced higher attention-getting ratings than the other two configurations. As mentioned in the previous section, there was no reliable *color* effect in regard to attention-getting. Figure 55 shows the lack of a consistent effect of color for the three stopped/slowly-moving vehicle signals. Thus, the results suggest that attention-getting is better for the high-output halogen lamps with dispersive lenses, and color has no reliable effect.

Discomfort-glare for the stopped/slowly-moving vehicle signal

The discomfort-glare ratings demonstrate a reliable configuration effect in which the high-output halogen alternating pair with dispersive lenses produces higher ratings as compared with the other two stopped/slowly-moving vehicle signal configurations (Figure 56). In addition there is a reliable color effect (Figure 57) demonstrating that amber produces lower ratings than clear, and red produces lower ratings than amber. These results are shown very clearly in Figure 58. They suggest that color has the beneficial effect of reducing discomfort-glare.

Note also that mean discomfort-glare ratings in Experiment 1, as depicted in Figure 58, are higher than those obtained in Experiment 2. This result was explained earlier, but suggests also that, in regard to discomfort-glare, the high-output halogen pair with dispersive tinted lenses may be acceptable. The ratings are approximately 4.5 for amber and 4.2 for red. The discomfort-glare rating scale (Figure 4) shows that these values correspond to something in the range of "wanting to look away in about a minute." Assuming that the discomfort-glare would be acceptable to the average driver, then the higher output of these lamps provides greater attention-getting, as discussed earlier and depicted in Figure 55.

Horizontal peripheral detection for the stopped/slowly-moving vehicle signal

Figure 59 shows the reliable effect of configuration for the stopped/slowly-moving vehicle signal. In particular, the medium-output halogen pair with nondispersive lenses and the high-output halogen pair with dispersive lenses produce larger peripheral detection angles than the medium-output, dispersive pair. The color main effect shown in Figure 60 suggests that red provides less coverage than clear, and that possibly amber may produce less coverage also (but is not demonstrated in the post-hoc test). However, when examining color by configuration, as shown in Figure 61, it becomes clear that the TCL results are suppressing the color main effect somewhat. Thus, for the stopped/slowly-moving vehicle signals there is a trend as a function of color in which amber produces a small loss and red produces an additional small loss.

Diagonal peripheral detection for the stopped/slowly-moving vehicle signal

This coverage angle did not differ significantly for the three stopped/slowly-moving vehicle signals, as shown in the post-hoc test results depicted in Figure 62. However, there is a color main effect as shown in Figure 63, with red producing a smaller coverage angle than clear or amber. Examination of Figure 64 shows that once again the TCL is to some degree suppressing the color main effect, and it is probably safe to say that in regard to the stopped/slowly-moving vehicle signal, amber produces a small loss of coverage and red an additional loss. Nevertheless, the magnitudes of the losses are relatively small.

Stopped/slowly–moving vehicle signal discussion

The stopped/slowly-moving vehicle signal represents a tradeoff between detection capabilities and discomfort-glare. At the completion of Experiment 1, there was concern that the medium-output halogen alternating pair with dispersive lenses might not have sufficient attention-getting capabilities, especially when tinted lenses are used. For that reason Experiment 2 was planned to examine color and also to provide two alternative configurations having higher on-axis outputs.

As shown in Figures 54 and 55, the average attention-getting capability of the original alternating pair is modest, with a value of around 3.9. This corresponds on the rating scale (Figure 3) to "small level of attention-getting" and "I would probably notice this system, but only against an uncluttered background." Clearly, a higher attention-getting rating would be desirable.

The use of nondispersive lenses with moderate output halogen lamps does not improve the situation appreciably. As Figure 54 shows, there is no statistically reliable difference. Even if mean values are considered, less than a half-rating point increase is obtained.

In contrast, there is a definite increase in attention-getting capability when using high-output halogen lamps with dispersive lenses, as shown in Figure 54. Average ratings for this alternating pair are in the range of 5.6, a value that falls between "moderate" and "quite" attention-getting on the rating scale. There is no color main effect, suggesting that the three colors do not produce significantly different results. Even if one chooses to use the mean values in Figure 55, tinted lenses still produce ratings of 5.3 to 5.4. Thus, from the standpoint of attention-getting, the high-output halogen pair with dispersive lenses is recommended.

The corresponding discomfort-glare for the high-output dispersive pair is also increased. However, as discussed earlier, the amber and red lenses produce ratings of 4.5 and 4.2, which seem to be in the acceptable range.

Horizontal peripheral detection capabilities of the high-output dispersive pair are reliably better than those of the medium-output dispersive pair, and there is no appreciable difference for diagonal peripheral detection.

In general, the results suggest that the high-output halogen alternating pair with dispersive lenses represents the best available configuration for the stopped/slowly-moving vehicle signal. A summary of the color-related differences for this lamp pair is provided in Table 10. Note that once again, either amber or red appears satisfactory for use in a modified rear-lighting system.

Table 10. Effect of lens tint on four human response parameters for the High-Output Halogen Alternating Pair with Dispersive Lenses.

Property	Amber Relative to Clear	Red Relative to Clear
Attention-Getting Rating	No change	No change
Discomfort-Glare Rating	Lower by 1.0 rating point	Lower by 1.4 rating points
Horizontal Peripheral Detection	Lower by 4 degrees	Lower by 7 degrees
Diagonal Peripheral Detection	Lower by 3 degrees	Lower by 11 degrees

Answers to Specific Research Questions

As the test plan for Experiments 1 and 2 was developed, a group of research questions were posed.[8] The questions were intended to provide guidance in developing the plan and to provide results that would specify recommended configurations. In this section the questions are restated and answers provided either directly or by referring the reader to specific items in the report.

What is the subjective salience, given a uniform color (hue)?
The results for attention-getting ratings (for Experiment 1) using clear lenses (white light) are presented in Figure 26.

What is the subjective annoyance and/or glare, given a uniform color?
The results for discomfort-glare ratings (for Experiment 1) using clear lenses (white light) are presented in Figure 33.

How well can the configuration be detected in peripheral vision, given a uniform color?
The results for horizontal peripheral detection (for Experiment 1) using clear lenses (white light) are presented in Figure 40. Similarly, the results for diagonal peripheral detection are presented in Figure 41.

For two or three of the better configurations, what is the effect of (uniform) color on saliency, annoyance/glare, and peripheral detection?
Figures 55, 58, 61, and 64 show the effects of color (clear/white, amber, and red) for four configurations: the TCL and three types of alternating pairs (Experiment 2).

[8] These questions appear earlier in the report in the section entitled Task 2 Test Plan Detail.

Based on the experimental data, which configuration or configurations are recommended for testing in Task 3?
The experimental results indicate that the TCL should be used as the high-level signal. This signal should be used with a nondispersive clear, amber, or red lens. Because of considerations other than the results of Experiments 1 and 2, amber or red may be preferred over clear. Based on the results of Experiment 2, amber may have a slight overall advantage when compared to red. However, both hues are acceptable.

The experimental results indicate that a high-output halogen alternating pair should be used for the stopped/slowly-moving vehicle signal. This signal should be used with dispersive clear, amber, or red lenses. Because of considerations other than the results of Experiments 1 and 2, amber or red may be preferred over clear. Based on the results of Experiment 2, amber may have a slight overall advantage when compared to red; however, both hues are acceptable.

RECOMMENDED DESIGN FOR FUTURE TESTING

At the completion of Experiment 1, candidate designs were developed which combined the high-level and stopped/slowly-moving vehicle signal. Those are shown in Figure 51 of this report. It was suggested that the horizontal arrangement shown in Figure 51.b would be more acceptable for use in automotive applications because of its form factor, that is, its height of approximately 3.5 in (8.9 cm) and width of approximately 16 in (40.6 cm). Such an arrangement could be embedded in the trunk lid or hatch without major difficulty.

The center lamp would be the high-level signal and would consist of the TCL. The flanking signal pair would be the stopped/slowly-moving vehicle signal and would consist of the high-output halogen alternating pair, as determined by the results of Experiment 2. The TCL would use a nondispersive lens in clear, amber, or red, and the alternating pair would use dispersive lenses in either clear, amber, or red, in concordance with the results of Experiment 2. Figure 65 shows the arrangement as part of the typical rear lighting of automobiles.[9] The three-lamp system could be placed midway between the taillight assemblies or possibly a bit higher on the rear surface of the trunk lid. If so, it could be placed directly below the CHMSL (in terms of line of sight) from the rear. This latter alternative is shown in Figure 66. The arrangement has the advantage that the current styling trend of embedding the license plate in the trunk lid would not have to be modified, or would only have to be modified slightly. Furthermore, for the closed-loop case, the radar unit could be embedded in the center of the rear bumper and there would still be room on the trunk for the license plate.

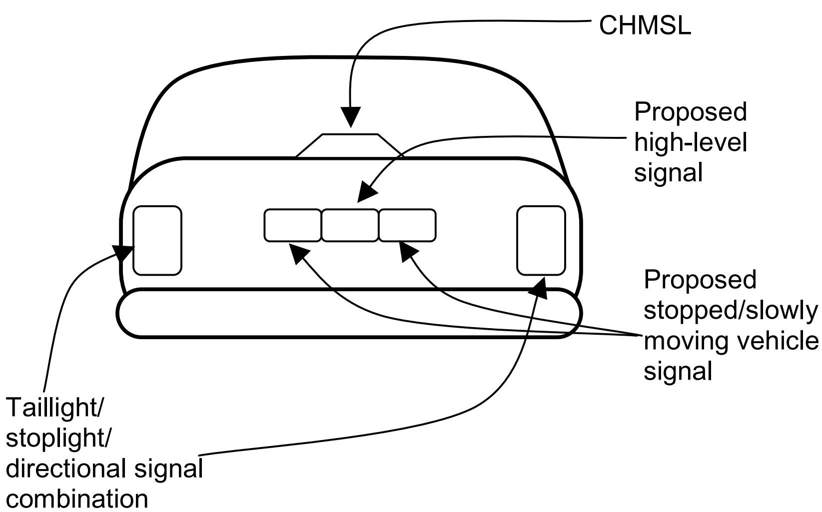


Figure 65. Proposed arrangement for signal lighting. License and backup lighting are not shown.

[9] In this section, hazard flashers and backup lights are not discussed because they are used very infrequently in normal highway traffic.

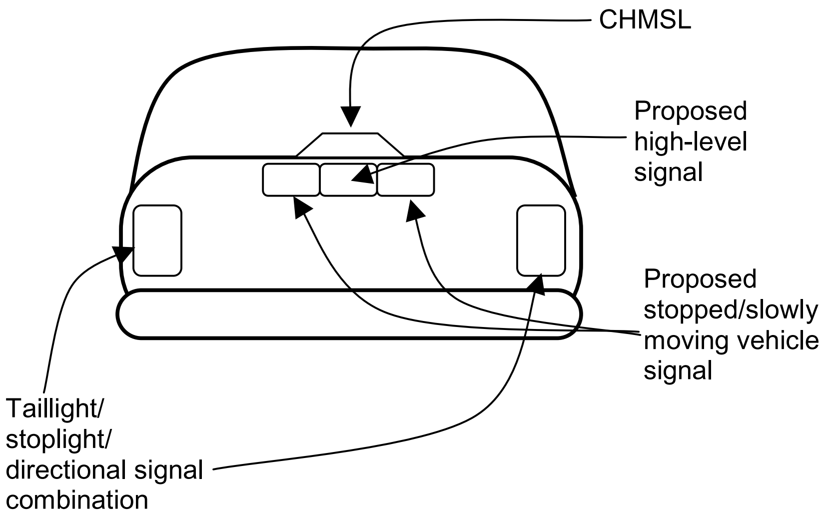


Figure 66. Alternative proposed arrangement for signal lighting. License and backup lighting are not shown.

Color Considerations

In the Task 1 report (Lee, Wierwille, & Klauer, 2001), there was a discussion of several researchers who have studied the coding aspects of rear lighting and arrived at various and mixed conclusions (e.g., Projector, Cook, & Peterson, 1969; Mortimer, 1970; Moore & Rumar, 1999). In some instances, they have proposed changes in current lighting standards that would change the colors or change how the colors are used. Unfortunately, such changes would probably violate NHTSA's policy of not proposing rulemaking changes to the existing regulations without strongly compelling scientific evidence of improvement. Since such evidence does not currently exist, it is unlikely that changes would be made.

The three lamp units proposed for the high-level signal and the stopped/slowly-moving vehicle signal can be envisioned as an addition to the current rear-lighting standards. No changes (or at least, no major changes) to the existing standards would have to be made. This approach might simplify the process of both further research and development, and later proposed rulemaking. In such a case, color selection of the additional lighting could be based on best compatibility/consistency with existing standards.

There are then really only two questions remaining in regard to color:

1) Should the high-level signal be white (clear), amber, or red?
2) Should the stopped/slowly-moving vehicle signal be white (clear), amber, or red?

The use of white is problematic in that white light is currently used for headlamps and some daytime running lamps. Thus, white could possibly be confusing, although such a hypothesis is by no means a certainty. A second possible reason for not using white is that daytime reflections off glass, chrome, and other polished surfaces usually appear as white light and are suppressed in the driver's perception. In other words, the driver learns to filter out or ignore such reflections. Similarly, at night, the driver may attempt, though unsuccessfully, to filter out oncoming headlights and streetlights. This type of response to white light might create problems when used for signaling purposes. For these reasons, it would seem that white should not be used for the new rear-signaling devices.

Overview of current conventions

Currently, rear-marker lamps (taillamps) are red. Stoplights are also red, and the CHMSL is red. Directional signal lamps are either red or amber, with amber slowly becoming more prevalent. What generalities are there in the current system?

1) Vehicle presence as viewed from the rear is a low-luminance red signal.
   - This signal is a constant signal that is used in low light and poor visibility conditions (when the headlights or parking lights are illuminated).
2) Vehicle braking is a high-luminance red signal.
   - This signal is activated when the driver's foot is on the brake pedal.
3) Vehicle intended change of direction is a high-luminance amber or red signal.
   - This signal flashes on one side of the vehicle when the turn signal stalk is deflected.

These conventions suggest that color is not being used as a unique form of coding. The only statement that can be made on the basis of color alone is that if a single lamp is amber, it represents a directional signal. The converse is not true, however, since some directional signals are red. A second, more general statement can also be made, namely, that if red lamps are observed, one is viewing the rear of the vehicle.

This discussion leads to the conclusion that rear signaling currently depends on geometric location, flashing, number of lamps illuminated, and intensity to provide unique signaling to the following driver. Color is used primarily as an enhancement.

Are there any general statements in regard to color coding at the rear of a vehicle that could be used as guideposts? There appear to be four:

1) Bright red in more than one lamp denotes braking and therefore possible slowing and stopping. This red is consistent with traffic signal use of bright red.
2) Subdued red denotes the rear of the vehicle.
3) Amber denotes directional changes as well as caution that slowing may take place. This is also consistent to an extent with the caution amber of traffic signals.
4) Flashing bright red on one side also denotes directional changes, and corresponding possible slowing.

These uses of amber and red clearly overlap, causing a lack of uniqueness.

Color selection for the high-level signal and for the stopped/slowly-moving vehicle signal

Because color coding is not being used to provide uniqueness in conventional rear signaling systems, there is no straightforward way of selecting color for the proposed new signaling devices. Both red and amber have advantages in their use, and there is overlap. To perform the selection, a table of advantages and disadvantages is presented for each of the two signals. Thereafter, the signal colors are selected based on the most compelling reasons.
Table 11 shows the comparison for the high-level signal. In reviewing the table it is important to understand that the high-level signal, whether used in an open-loop or closed-loop application, is almost certainly going to result in the following driver braking heavily when it is activated. Therefore, the signal can be thought of primarily as a heavy braking signal. When viewed from this perspective, the selection process is facilitated. The table shows that a red tint high-level signal is much more aligned with the idea of heavy braking than is an amber signal. The other advantages and disadvantages seem to suggest that red may have a slight advantage as well, owing mainly to the consistency of need for braking. Therefore, in the absence of any additional information, a red signal is recommended for the high-level signal, the TCL.

Similarly, Table 12 shows a comparison of the advantages and disadvantages of red and amber lenses for the stopped/slowly-moving vehicle signal. This signal is intended to inform the following driver that the lead vehicle is either standing still on the pavement or moving very slowly. This could be considered an advisory signal similar to the directional signals. It may require the following driver to brake, but if so, braking may be at almost any level from very mild to severe depending on closing rate. Thus, the signal is advisory, or in other words, it is a caution signal. When viewed from this standpoint, the table makes it relatively clear that the stopped/slowly-moving vehicle signal should be amber. The overriding consideration is that the signal is cautionary.

Table 11. Comparison of advantages and disadvantages associated with red and amber lenses for the high-level signal.

Lens Tint	Advantages	Disadvantages
Red	Consistent with the use of red associated with stopping/slowing. Consistent with the near certainty that the following driver must brake hard to avoid a collision. Compatible with CHMSL color while providing a deceleration cue not currently present in the CHMSL. Slightly lower discomfort-glare than amber.	Adds to the number of red signals at the rear, resulting in potential overuse of red and corresponding confusion. Slightly lower peripheral detection than amber.
Amber	Consistent with the notion of caution.	Inconsistent with the near certainty that

	Consistent with the notion of slowing. Does not add to the number of red signals at the rear of the vehicle and corresponding confusion. Amber is used very little in current rear lighting. Slightly greater peripheral detection than red.	the following driver must brake hard to avoid a collision. May suggest that the driver should use caution, when in fact hard braking is required. Inconsistent with CHMSL color. Slightly higher discomfort-glare than red.

Table 12. Comparison of advantages and disadvantages associated with red and amber lenses for the stopped/slowly-moving vehicle signal.

Lens Tint	Advantages	Disadvantages
Red	Consistent with the use of red for caution, as in presence or in light braking. Slightly lower discomfort-glare than amber.	Not consistent with the use of red for heavy braking. (This signal will usually not require heavy braking.) Lower peripheral detection than amber. Inconsistent with the concept of caution. Adds to the number of red lights at the rear, possibly resulting in overuse of red and corresponding confusion. Because the CHMSL and stopped/slowly-moving signal differ greatly in meaning, perhaps they should not be the same color.
Amber	Consistent with the notion of caution, that may require some braking. Better peripheral detection. Differs from CHMSL color, which has a different intended meaning. Does not add to the number of red signals at the rear of the vehicle and corresponding confusion. Amber is used very little in current rear lighting. There is some use of amber for an alternating signal in transit buses.	Slightly higher discomfort-glare. Same color as amber directional signal, but meaning is clear nevertheless because of alternating pair and location.

In conclusion, the available information is sketchy. If, however, one takes the viewpoint that the high-level signal will most likely require heavy braking and the stopped/slowly-moving signal is cautionary and may or may not require braking, then it seems that the high-level signal should be red and the stopped/slowly-moving vehicle signal should be amber.

Lastly, it should be mentioned that the decision of whether or not to include a stopped/slowly-moving vehicle signal in the *closed-loop* configuration has not been made. As discussed earlier, theoretically, such a signal should not be necessary, since the system would detect impending crashes with high reliability and then activate the TCL. If this does indeed turn out to be correct, it should only be necessary to have a single-cell signal containing the TCL. The three-cell signal with the alternating pair would then not be necessary.

Lamp Output Modulation

All of the experimental research in Task 2 has had the objective of optimizing lamp selection for broad daylight conditions. This condition was selected for testing because it represents the situation where most rear-end crashes seem to be occurring. Thus, the decision was made to test where improvements were most needed. In addition, this condition requires maximum lamp output. Of course, ambient light levels can range from this high level down to nighttime conditions without moonlight.

It is quite clear that the full output of the lamps selected should not be used under subdued lighting. Discomfort-glare is just within tolerable range under bright daylight conditions. Any substantial reduction in ambient light will most certainly cause unacceptable discomfort-glare for the following driver. Therefore, the output levels for the new signals must be reduced as a function of ambient light level.

There are two possible ways in which the output levels could be changed: by discrete steps, or continuously. Future research and development should deal with this problem using experimentation. However, continuous adjustment with ambient light level is preferred, because it offers the opportunity for maximizing lamp output while holding glare to just within acceptable limits. Use of discrete steps controlled by the headlamp switch (for example) would result in a compromise.

Regardless of the output level type, there are technical matters that must be considered, including lamp illumination onset. If an ordinary bulb is driven at a voltage below its rated voltage, it will reach its corresponding steady-state light output more slowly. A slow rise time for the lamps may result in longer detection time for the following driver. In addition, the *average* light level would be lower.

To solve the problem of slow rise-time, the lamps should initially be switched to full voltage, allowing the filaments to heat quickly. Thereafter, the voltage can be reduced to the level needed for the desired output level. This approach should produce rise-times that are about the same, regardless of the lamp output level programmed.

A second technique that could be very useful is to use fast switching to achieve the desired output, rather than a series-resistive circuit design. The switched approach would save power usage, whereas the resistive design is relatively simple but wasteful of power. The switching technique relies on pulse width modulation at a frequency above the response capabilities of the lamp. The result is a constant lamp output with the desired *level* of output.

The concepts of fast rise times and switching are easily combined, as shown in Figure 67. As the figure shows, the voltage applied is V_0, "full" voltage, initially, followed by a pulse width modulated voltage achieving the desired average level. To achieve lower output levels, the duty cycle (on) percentage is reduced. The numerical values shown in the figure are representative of a final design, but are not accurate values.

It should be mentioned that the TCL (high-level signal) and the alternating pair (stopped/slowly-moving signal) use the same bulb type, namely a number 795X. This use of the same bulb type occurred by coincidence and was not planned. However, as a result, the same design of switching modulator can be used for each of the three bulbs in the final recommended design.[10]

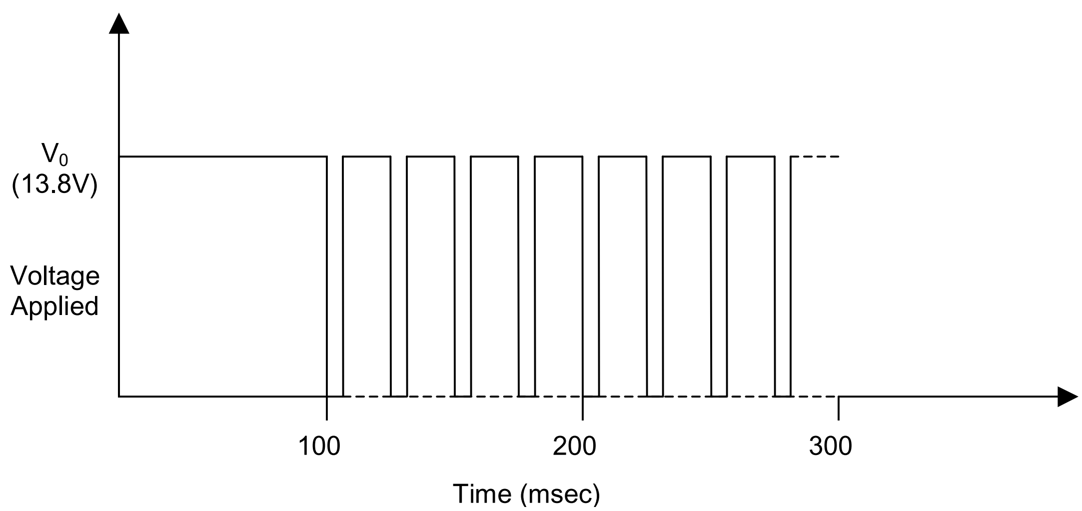


Figure 67. Example of a rapid onset, switching drive waveform used to modulate lamp output.

[10] Of course, the drive motor in the TCL should receive full voltage whenever the lamp is activated. It should not receive the modulated waveform depicted in Figure 67.

SPECIFICATIONS FOR THE RECOMMENDED SYSTEM

The presentation of results for Task 2 has necessarily been somewhat detailed. In addition, the selection process has evolved through two experiments and several analyses. It seems therefore that the system specifications in regard to lighting should be summarized, so that the reader can find them in one place.

Much of the lighting equipment was ordered from a single manufacturer (Federal Signal Corporation) and then adapted for use in the experiments. This particular vendor was selected because it had a product line in emergency signaling devices that most closely matched the needs of the project. By adapting these products, a good deal of design and development time was saved. Consequently, one simple expedient is to provide part numbers for the important components. It was decided to include the numbers, recognizing that other manufacturers may be able to supply equivalent components. However, by specifying part numbers it should be possible for others to quickly obtain components for use in further research, additional measurement, or possible deployment. In order to provide a concise set of specifications, only the final recommendations are included here.

Specifications

The final recommended system is composed of a three-cell lamp system, as shown in Figures 51.b, 65, and 66. The center section is the high-level signal. The outer sections represent the alternating pair. The system drive voltage is assumed to be 13.7 to 13.8 volts. Note that the metal enclosures specified may have to be modified when the three-lamp system is fabricated as a single unit.

Tables 13 and 14 present the specifications. They provide necessary information for duplicating the experimental setup. The light output values shown are for maximum output to be used during bright daylight. As explained earlier, these values would have to be reduced for other subdued ambient light conditions using a pulsed waveform. Also, the compartment measurements may have to be changed slightly in fabricating a three-cell enclosure.

Table 13. High-level signal (TCL – traffic clearing light).

Oscillating (M-sweep) parabolic mirror assembly with lamp socket:
F.S. #TCLF2
Dimensions overall: 11.9cm W x 8.8cm H x 9.6cm D
Frequency of oscillation (full sweeps per second): 2.0
Drive motor for above assembly:
F.S.#Z8572233
Bulb for above assembly:
Sylvania No. 795X-12V, Vertical Filament, Halogen, 50 watts nominal at 12 volts
Base: Bayonet
F.S.#Z8107141A
Bare bulb measured characteristics for applied voltage of 13.7V:
Current: 4.22a
Power: 57.8w
Light output: 152 equivalent cd (measured at a distance of 2 m.)
Lens: Nondispersive, red tint:
Effective dimensions: 10.7cm W x 7.0 cm H
Overall dimensions: 10.9 cm W x 7.9 cm H x 2.3 cm D
Transmissivity characteristics and color coordinates: (See Appendix E)
F.S.#Z8575030-A-02
Light-tight compartment housing the components, with lens at front aperture:
Custom-made metal enclosure (excluding lens):
12.7 cm W x 9.5 cm H x 10 cm D
System on-axis light output in equivalent candelas (measured at 8m with 13.7v at lamp):
Max: 2304
Min: 96
Average: 544

Table 14. Stopped/slowly-moving vehicle signal (alternating pair).

2 each of the following:
Stationary parabolic mirror assembly with lamp socket (note that a rotating mirror assembly was modified by fixing the rotation assembly with a screw and nut):
F.S.#Z8583142A
Dimensions overall[11]: 11.0 cm W x 8.0 cm H x 5.3 cm D
Bulb (same bulb as the High-Level signal, TCL):
Lens: Dispersive, amber tint
Effective dimensions: 10.5 cm W x 5.0 cm H
Overall dimensions: 11.8 cm W x 5.7 cm H x 4.5 cm D
Transmissivity characteristics and color coordinates: (See Appendix E)
F.S.#Z8573001B-01
Light-tight compartment housing the components, with lens at front aperture:
Custom-made metal enclosure (excluding lens): 12.5 cm W x 9.0 cm H x 6.5 cm D
System on-axis output in equivalent candelas (measured at 8m with 13.7V at lamp):
One lamp "on" steady: 2112
Average for alternating pair: 1664
Frequency of flashing in full-cycles per second: 2.0

[11] The base of the rotating assembly was cut to produce a more compact design. The dimensions given are after the modification.

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APPENDIX A: ALGORITHMS FOR ACTIVATION OF ENHANCED REAR SIGNALING SYSTEMS

CLOSED-LOOP REAR-LIGHTING ACTIVATION PROGRAM

Main Program

This program is intended to activate the high-level rear-lighting system when a rear-end collision is imminent. Criteria to be met include range, R, equal to or less than R_{min}, and return angle within specifications, to be described later.

To understand how this program can be developed, it is first necessary to understand how a typical radar unit mounted at the rear of the lead vehicle transfers data. Figure 1 shows a typical data format. As the radar scans and detects a target, it provides a target designation number, range, range-rate, and angle to the target in a serial datastream. If there is more than one target, the datastream continues until all of the target ranges, range-rates, and angles are specified, as shown in Figure A1.

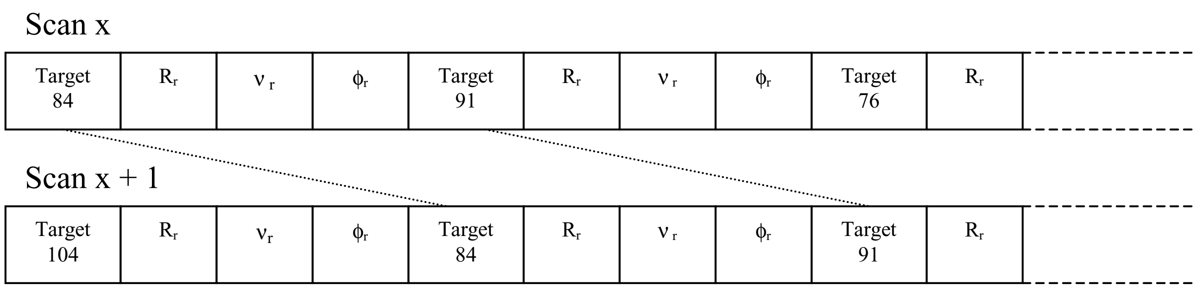


Figure A1. Depiction of the datastream from the radar antenna unit (note that the stream length varies with the number of targets detected).

Radar processing is usually consistent in terms of target number designation, but not always. In other words, when it designates the given target by a number, it is usually consistent in this designation in the following scans. However, occasional mis-designations do occur. Also, the datastream may place the targets in any order. These aspects are important for the program design.

Figure A2 shows the main blocks of the activation program. The program is intended to provide rapid response in activating the high-level rear lighting while minimizing false triggering. The program begins by examining two consecutive scans (datastreams) from the radar. Only when data in the two scans are consistent in all indications that a rear-end collision is imminent is the rear lighting activated. Once activated, the high-level rear lighting remains activated for t_1 seconds, which is estimated to be about 2 seconds. If later scans continue to indicate that a collision is imminent, the t_1 second timeout is renewed. Thus, under ordinary circumstances, the high-level rear lighting would be continuously renewed, without extinguishing, as long as the collision danger persists.

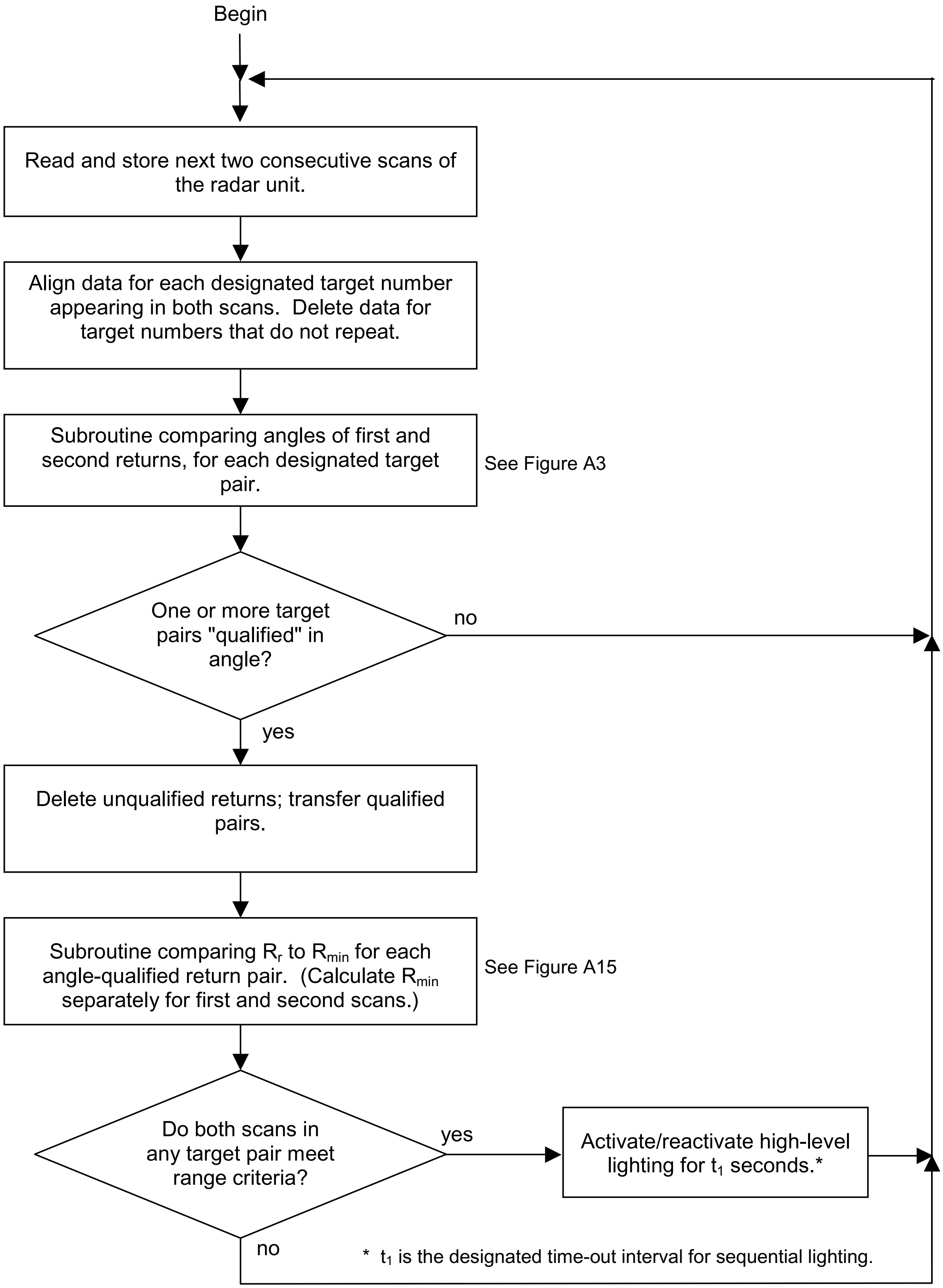


Figure A2. Overall flow diagram for activation of closed-loop high-level rear-lighting system.

As the program indicates, the two scans are read and stored. Any targets that do not appear in both scans are deleted. For those remaining, the first scan and the second scan are analyzed and compared. First the returns are analyzed with respect to angle. This is primarily a comparison subroutine, which will be described later. If any return pair is "qualified" in angle, it is transferred (along with other qualified pairs) to a second subroutine that is used to determine if both scans in each target pair are "qualified" in range. If any target pair is qualified in both angle and range, the high-level rear-lighting system is activated or re-activated for a specified time, t_1 seconds. If there are no pairs qualified in both angle and range, the lighting is not activated/re-activated, and the process is repeated.

Generally, the time required to complete one pass through the program is expected to be relatively short, that is, about 100ms. This would include the time for the radar to produce the two scans and for the processing system to arrive at a decision regarding whether or not to activate/reactivate the lighting. To account for this time in the computations, that is, to offset the computation lag, it is only necessary to increase the perception-reaction time value, t_{pr}, in the equation for R_{min} by the amount of the expected lag. [12]

This proposed program seems to offer the right blend of rapid response and immunity from false triggering. Some adjustments may be necessary once the initial program is developed. However, the general concept is expected to be retained.

The next sections describe the two subroutines in detail. The first is used to qualify a given target in regard to angle, and the second to qualify it in regard to range. Note that each target pair must be passed through the subroutines until it reaches a "no threat" condition, or until it passes completely through as "qualified."

Introduction to the Angle and Range Subroutines

Determining whether a rear-end collision is likely to occur must be based on whether the target to the rear is on an intersecting trajectory and is at or within the minimum stopping distance. A radar (or scanning laser) mounted at the rear bumper of the lead vehicle provides information about the "target" following vehicle. Specifically, it returns range, range rate, and target angle. Using these values as well as parameters taken from the lead vehicle, a decision must be made as to whether the following vehicle represents a "threat," that is, the following vehicle is very likely to "rear-end" the lead vehicle.

As previously indicated, two subroutines are required. One deals primarily with angle, and the other deals with range and range rate. If either subroutine returns an indication that the target is "not a threat," then there is no need to activate the rear-lighting countermeasures. On the other hand, if both of the subroutines return a "threat" indication, then the countermeasures should be activated. These concepts are taken into account in the overall block diagram of Figure A2.

[12] Mathematical quantities are defined later in this appendix.

Subroutine for Qualifying a Target Return in Terms of Angle

There are two possible conditions for qualifying whether the return angle is from a threat vehicle. They can be expressed simply as follows:

1. For a following vehicle to strike a lead vehicle in the rear, the probability is high that the following vehicle will approach the rear within a small angle to the longitudinal axis of the lead vehicle, and

2. For a following vehicle to strike a lead vehicle, the probability is high that the following vehicle will approach the rear at a constant angle to the longitudinal axis of the lead vehicle.

The first condition results from the fact that most rear-end collisions occur with vehicles traveling in the same direction. If a vehicle is traveling at an off-angle position, it is either on a trajectory that will not intersect, or it will pass quickly across the previous path of the lead vehicle. Crashes at large rear angles (say, 15°) are rare, and it is doubtful that enhanced rear lighting would prevent them.

The second condition is a result of the well-known "necessary" condition used in navigation, namely, that vehicles on a collision course (ships and aircraft, for example) are at a constant angle to one another prior to collision. (There are some assumptions associated with this condition, but they are not particularly constraining.)

The two conditions can be used to "qualify" a target in regard to angle. Usually this requires two returns, because the radars that are available do not compute angular rate.

The subroutine for qualifying a target in angle is shown in Figure A3. In this diagram, a "no-threat" indication is used to indicate that the next target should be examined, if there is one. If not, the subroutine should be exited and control returned to the "Begin" point of Figure A2.

In Figure A3, R_{r_1}, ϕ_{r_1} represent the range and angle to the first return, and R_{r_2}, ϕ_{r_2} represent the range and angle to the second return (of a designated target). The maximum absolute angle, ϕ_{max}, is measured from the longitudinal axis of the lead vehicle. This angle should initially be specified as 0.07 radian (4.0 degrees); it may have to be adjusted.

The first two decisions (diamonds) determine if the two returns are within the specified maximum allowable angle. Thereafter, the third decision is associated with determining if the angle remains relatively constant. This represents a complex tradeoff between allowance for radar scintillation and qualifying targets that are not actually at a constant angle to the lead vehicle. Examination of one radar system indicates that scintillation does not exceed approximately 1.0 ft in the target lateral position. Therefore, the maximum allowable scintillation (y_{max}) should be specified at about 0.5 ft in each direction. Converting this to an angle involves dividing by the average range. Thus, the absolute difference in the angle between returns (in radians) should be less than y_{max} divided by the average range.

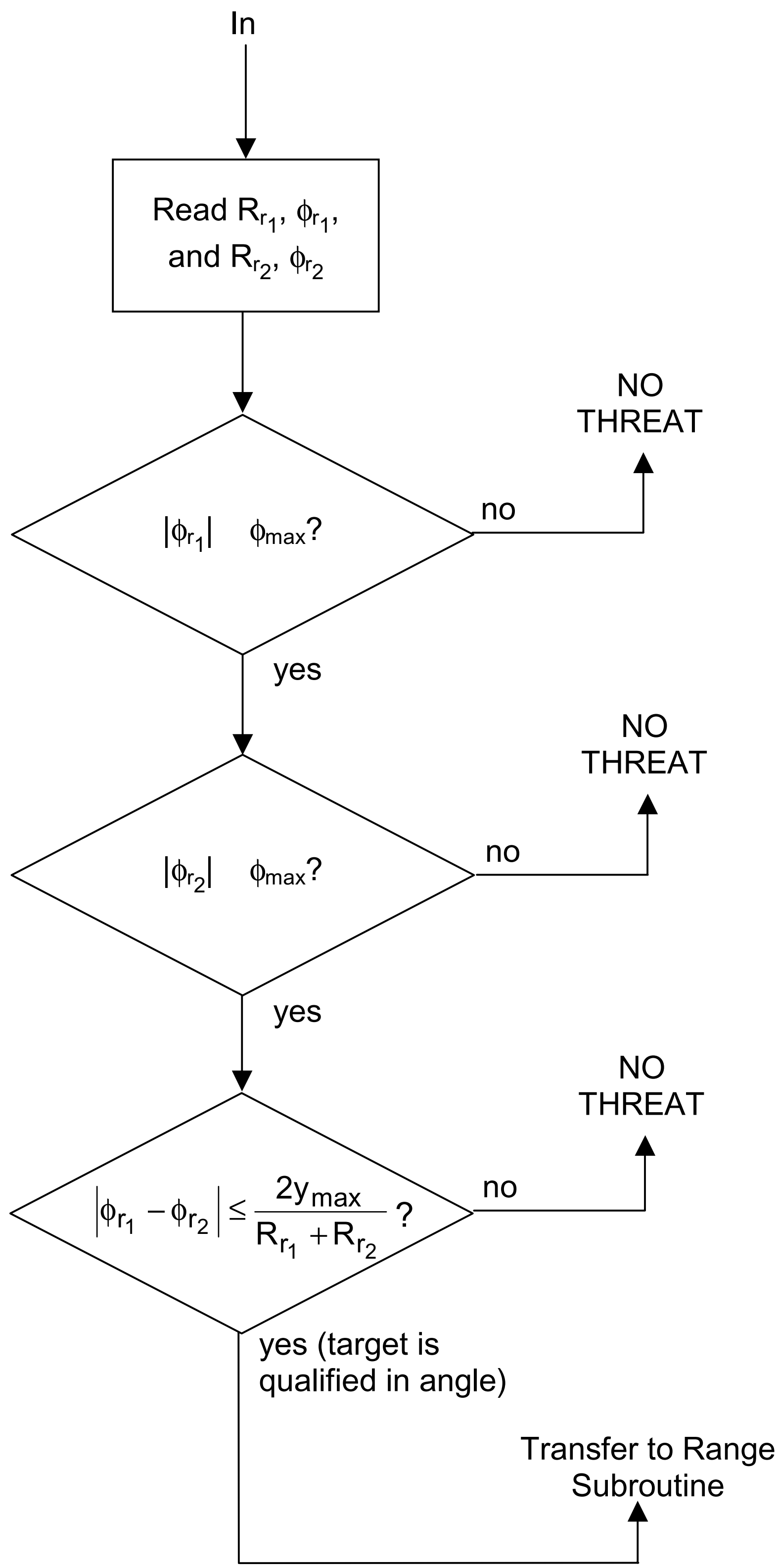


Figure A3. Subroutine diagram to determine if a given target is "qualified" in regard to angle.

In concluding this discussion on angle qualifications, it should be mentioned that an alternative technique could possibly be used. This involves the assumption that for a vehicle to rear-end the lead vehicle, it is most likely to follow the path of the lead vehicle. Considerable time and effort were devoted to conceptual development of a subroutine that would take advantage of this alternative. However, after the development, it was decided that the subroutine would be too complex and might not provide reliable indications. An initial conceptual description of the subroutine appears as the last major section of this appendix, for use in possible future work.

Subroutine for Qualifying a Target Return in Terms of Range

The subroutine qualifying a return in terms of range makes use of multiple computations and is the main discrimination method. The angle criteria just described are intended to delete targets that clearly do not qualify. Thereafter, range-related criteria are used as the method of precise determination. Because the presentation is quite involved, it is presented next in a separate main section.

DETERMINATION OF WHETHER A RADAR RETURN IS FROM A "QUALIFIED" THREAT RANGE

Background

Five scenarios have been developed for determining whether or not a radar (target) return from the following vehicle represents a "qualified" threat. A qualified threat is one that will lead to a rear-end crash unless appropriate action is taken. The derivation process is very involved and requires many pages. Therefore, results of all five scenarios will be presented, along with a graphical depiction of each.

To begin, it is first necessary to frame the problem. Consider Figure A4, which shows the relative movements of the following vehicle and the lead vehicle for the specific case in which the lead vehicle is at a constant-slower velocity equal to v_{L_i}.[13] The vehicles are initially separated by R_{min}, the minimum distance for which there will be <u>no</u> collision. During the perception-reaction time of the following driver, the following vehicle moves a distance d_{F_p}. The lead vehicle travels a corresponding distance d_{L_p}. Once braking begins, the following vehicle travels a distance d_{F_b}, while the lead vehicle continues to travel at a constant velocity for a corresponding distance d_{L_b}. For minimum separation, both vehicles have the same forward velocity at the instant they touch. Thereafter, the following vehicle once again falls behind due to continued deceleration, but there is no collision.

[13] This description corresponds to Condition 2, to be presented later.

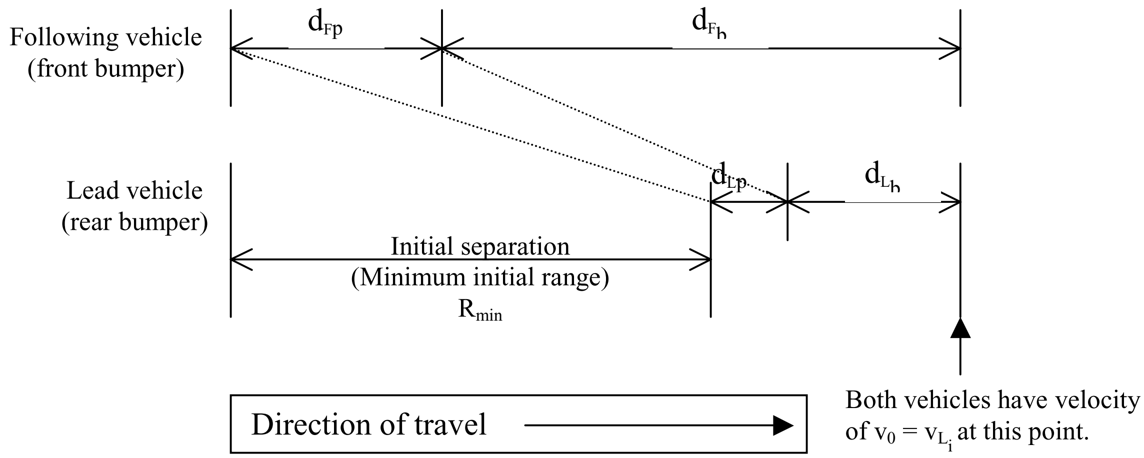


Figure A4. Depiction of the limit condition for a constant velocity lead vehicle.

If the radar return range, R_r, is equal to or less than R_{min}, and if it is from a "qualified" angle, then the following vehicle represents a "threat," and countermeasures should be activated. The elements of the problem, as depicted in Figure A4, must be kept in mind as the various conditions are presented. The five scenarios will be individually presented. Thereafter, a computer subroutine block diagram is presented for implementation of the results.

Nomenclature

a_L = acceleration of the lead vehicle in g's ($a_L = -c_L$)

c_F = deceleration of the following vehicle in g's during braking (positive for deceleration)

c_L = deceleration of the lead vehicle in g's during braking (positive for deceleration) ($c_L = -a_L$)

d_{F_b} = distance traveled by the following vehicle from the initiation of deceleration until the "touch point" is reached

d_{F_p} = distance traveled by the following vehicle during perception-reaction time, t_{pr}

d_L = distance traveled by the lead vehicle from t = 0 to the "touch point"

g = acceleration due to gravity; 32.2 ft/sec^2

R_{min} = the minimum initial separation without a collision, measured between the lead vehicle rear bumper and the following vehicle front bumper

R_r = range of the return from the radar, measured from the rear bumper of the lead vehicle

t = running time from the start of the problem, or the time axis

t_0 = time when the touch point is reached

t_L = time when the lead vehicle stops due to deceleration

t_{pr} = following driver's perception-reaction time

v = general velocity, or the velocity axis

v_0 = velocity when the two vehicles reach the touch point (in Conditions 1 and 4 to be presented, $v_0 = 0$)

v_{F_i} = initial velocity of the following vehicle; also the velocity (assumed constant) during the perception-reaction time period

$v_F(t)$ = following vehicle velocity (after the perception-reaction time period)

v_{L_0} = the minimum velocity of the lead vehicle for which a time-headway calculation should be carried out

v_{L_i} = the initial velocity of the lead vehicle (velocity at t = 0); $v_{L_i} = v_L(0)$

$v_L(t)$ = lead vehicle velocity

v_r = initial closing rate between vehicles; negative for following vehicle closing on lead vehicle ($v_r = v_{L_i} - v_{F_i}$)

x = general distance, or the distance axis

ϕ_r = angle of the return from the radar, measured from the longitudinal axis (and at the rear bumper) of the lead vehicle

τ_H = minimum allowable time-headway for the following vehicle without countermeasure activation

Units: All distances are in ft.
All velocities are in ft/sec
All accelerations and decelerations are in g's, except that g = 32.2 ft/sec^2
All times are in seconds

<u>Limit Conditions</u>

Limit Condition 1

In this condition, the lead vehicle is standing still on the pavement as the following vehicle approaches. The following vehicle brakes (to a stop) after the perception-reaction time of its driver. The two vehicles touch at $t = t_0$, with both vehicles having zero velocity. Figure A5 shows the plot of distance as a function of time for each vehicle, and Figure A6 shows vehicle velocities as a function of time. Since the lead vehicle is standing, its velocity is zero throughout the interval. Note that the following vehicle velocity is assumed constant during perception-reaction time, and linearly decreasing during deceleration.

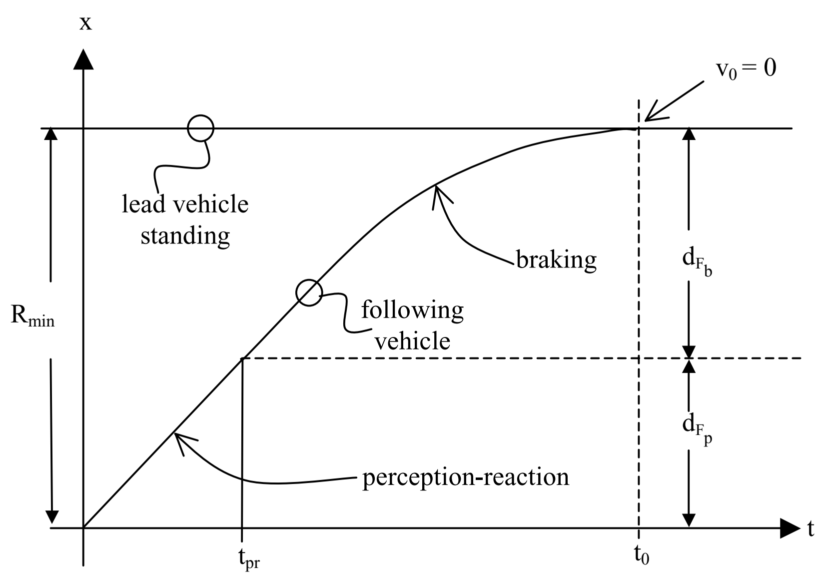


Figure A5. Position of each vehicle as a function of time; Condition 1.

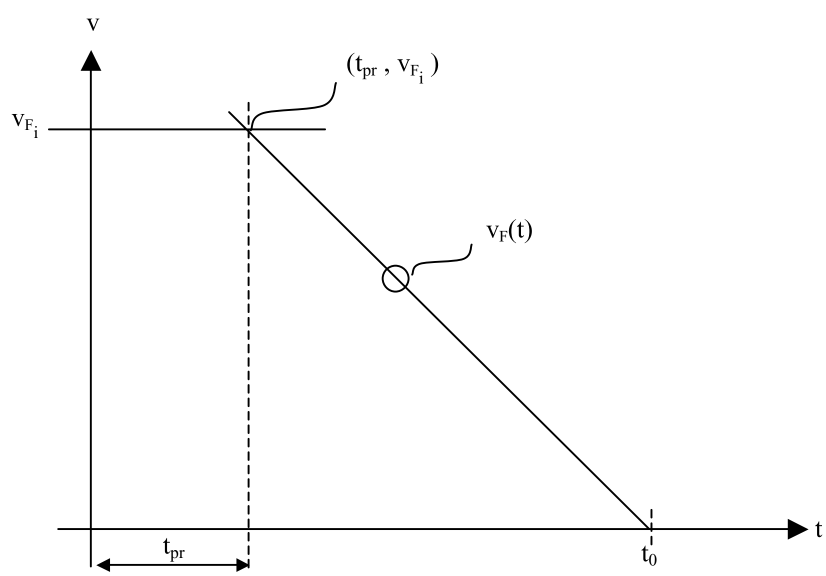


Figure A6. Velocity of the following vehicle as a function of time; Condition 1.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = -v_r t_{pr} + \frac{v_r^2}{2gc_F}$$

Time to touch:

$$t_0 = t_{pr} - \frac{v_r}{gc_F}$$

Necessary conditions for the equation to be valid:

$v_{L_i} = 0$

$c_L = 0$

$v_r < 0$

Limit Condition 2

In this condition, the lead vehicle is traveling at a slower (constant) velocity than the following vehicle. The following vehicle brakes after the perception-reaction time of its driver. The two vehicles eventually touch at t_0, with both instantaneously at velocity v_0. Note that this is the situation depicted earlier in the background section. Figure A7 shows the plot of distance as a function of time for each vehicle, and Figure A8 shows vehicle velocities as a function of time.

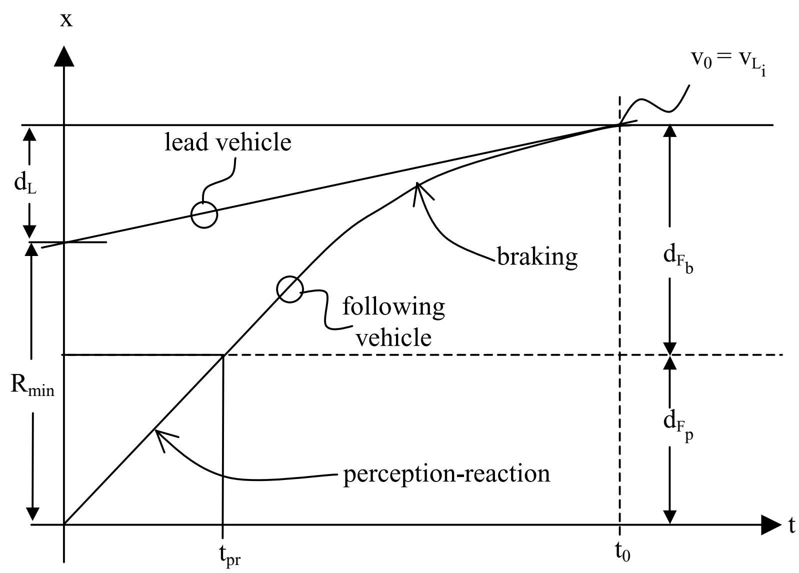


Figure A7. Position of each vehicle as a function of time; Condition 2.

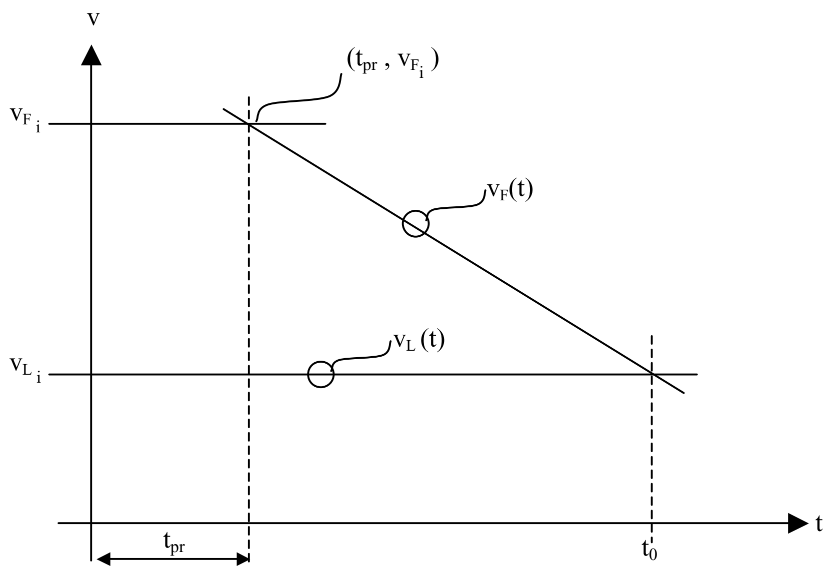


Figure A8. Velocity of each vehicle as a function of time; Condition 2.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = -v_r t_{pr} + \frac{v_r^2}{2gc_F}$$

Time to touch:

$$t_0 = t_{pr} - \frac{v_r}{gc_F}$$

Necessary conditions for the equation to be valid:

$v_{L_i} > 0$

$c_L = 0$

$v_r < 0$

Limit Condition 3

In this condition, the lead vehicle decelerates. The following vehicle brakes after the perception-reaction time of its driver. The two vehicles eventually touch at $t = t_0$, with both instantaneously at velocity v_0. Note that the deceleration of the lead vehicle is relatively small; otherwise the lead vehicle will stop before it is touched (corresponding to Condition 4). Figure A9 shows the plot of distance as a function of time for each vehicle, and Figure A10 shows the vehicle velocities as a function of time.

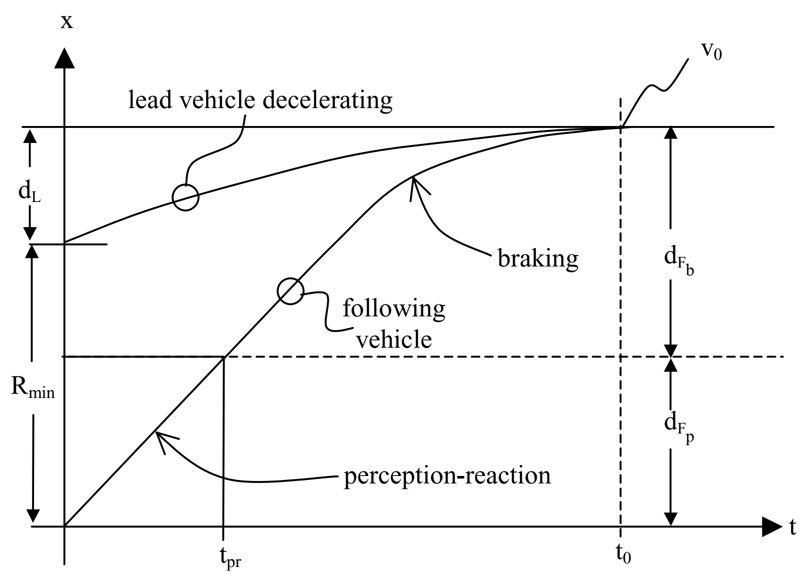


Figure A9. Position of each vehicle as a function of time; Condition 3.

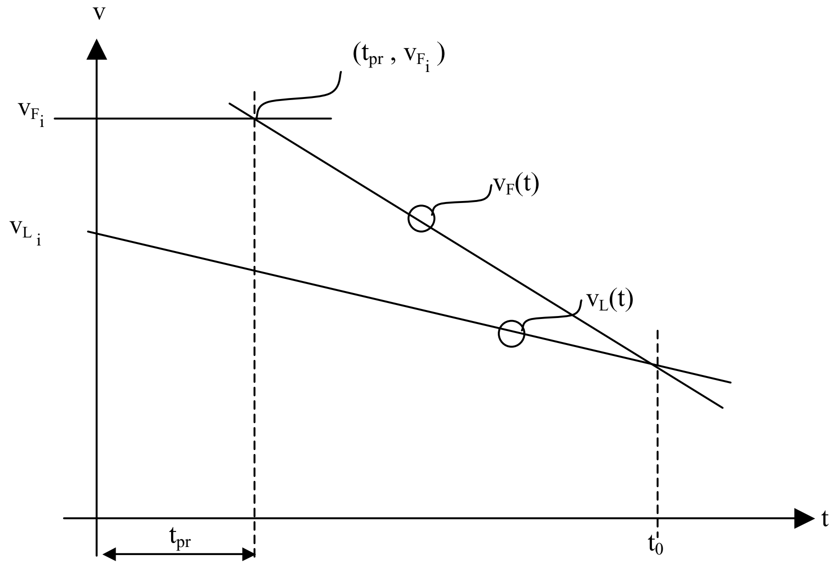


Figure A10. Velocity of each vehicle as a function of time; Condition 3.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{v_r^2 - 2v_r\, c_F\, g\, t_{pr} + c_F\, c_L\, g^2\, t_{pr}^2}{2(c_F - c_L)g}$$

Time to touch:

$$t_0 = \frac{-v_r + c_F\, g\, t_{pr}}{(c_F - c_L)g}$$

Necessary conditions for the equation to be valid:

$(c_F - c_L)\, v_{L_i} + c_L\, v_r - c_L\, c_F\, g\, t_{pr} \quad 0$

$v_{L_i} > 0$

$c_L > 0$

$v_r < 0$

Limit Condition 4

In this condition, the lead vehicle decelerates to a stop and then stands on the pavement. The following vehicle brakes (to a stop) after the perception-reaction time of its driver. The two vehicles eventually touch at $t = t_0$, with both vehicles having zero velocity. Figure A11 shows the plot of distance as a function of time for each vehicle, and Figure A12 shows the vehicle velocities as a function of time.

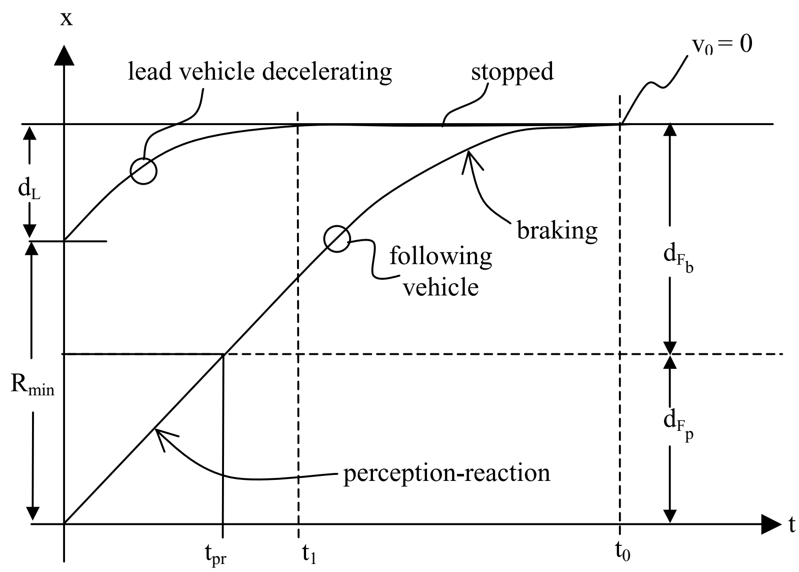


Figure A11. Position of each vehicle as a function of time; Condition 4.

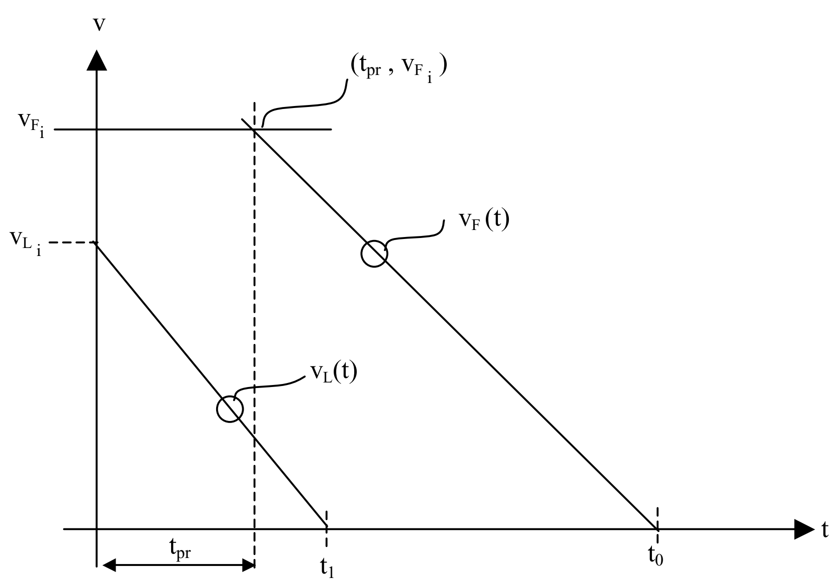


Figure A12. Velocity of each vehicle as a function of time; Condition 4.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{\left(v_{L_i} - v_r\right)^2}{2c_F g} + \left(v_{L_i} - v_r\right) t_{pr} - \frac{v_{L_i}^{\ 2}}{2c_L g}$$

Time to touch:

$$t_0 = \frac{v_{L_i} - v_r + c_F\ g\ t_{pr}}{c_F\ g}$$

Necessary conditions for the equation to be valid:

$0 \quad (c_L - c_F)\ v_{L_i} - c_L\ v_r + c_L c_F\ g\ t_{pr}$

$c_L > 0$

$v_{L_i} > 0$

Limit Condition 5

In this condition, the lead vehicle accelerates, but at a sufficiently low value so that braking (after perception-reaction time) is required of the following vehicle. The two vehicles touch at $t = t_0$, with both vehicles at velocity v_0. Thereafter, the lead vehicle continues to accelerate and the following vehicle continues to decelerate. Figure 13 shows the plot of distance as a function of time for each vehicle, and Figure 14 shows the plot of velocity for each vehicle as a function of time.

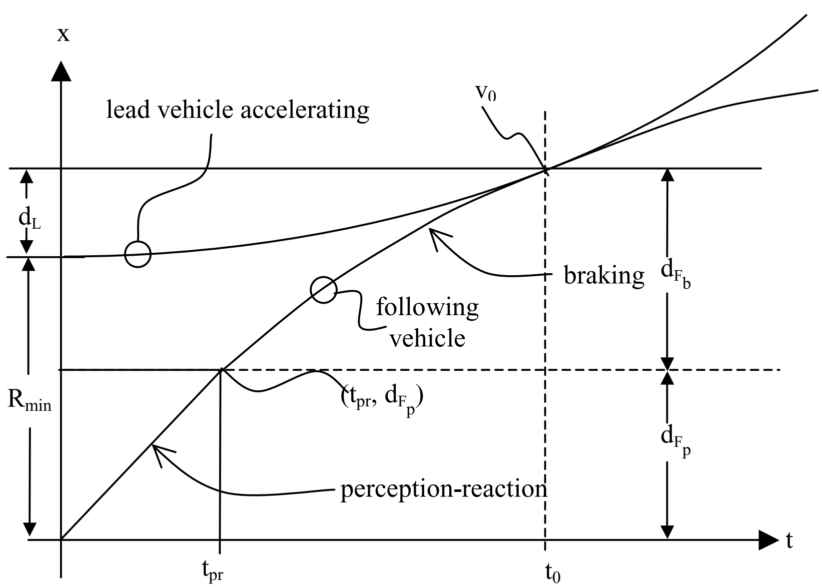


Figure A13. Position of each vehicle as a function of time; Condition 5.

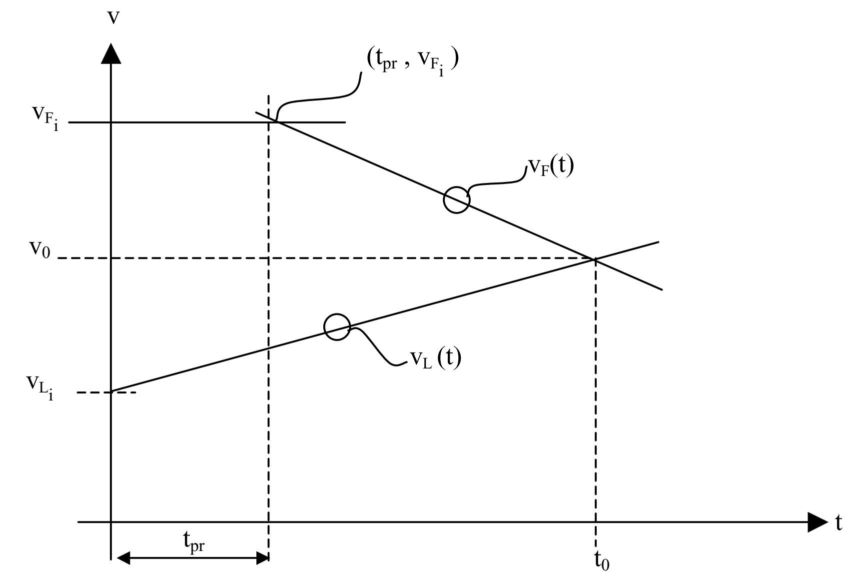


Figure A14. Velocity of each vehicle as a function of time; Condition 5.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{v_r^2 - 2v_r\, c_F\, g\, t_{pr} - c_F\, a_L\, g^2\, t_{pr}^2}{2(c_F + a_L)g}$$

Time to touch:

$$t_0 = \frac{-v_r + c_F\, g\, t_{pr}}{(c_F + a_L)\, g} \qquad \text{where } v_r = v_{L_i} - v_{F_i}$$

Necessary conditions for the equation to be valid:

$- v_r - a_L\, g\, t_{pr} \quad 0$

$a_L > 0$

$v_{L_i} > 0$

$v_r < 0$

Additional notes on the conditions

In all of the conditions presented, it is assumed that the following vehicle maintains constant velocity during perception-reaction time, and the braking thereafter creates constant deceleration. These assumptions appear reasonable and make it unnecessary to determine the acceleration of the following vehicle.

The equations have been derived so that closing (relative range) rate and range are the only required values. (Target angle is needed elsewhere, but not in these equations.) A radar placed at the rear bumper of the lead vehicle is capable of providing these parameters. An inexpensive longitudinal accelerometer on the lead vehicle (for lead vehicle acceleration/deceleration) and velocity are required. Thus, the measures needed for the computations are v_r, v_{L_i}, and c_L (or a_L). The range to the following vehicle, R_r, is also required to determine how it compares to R_{min}.

Other parameters must be specified for the solution. Essentially, these are assumed values for the following vehicle. Included are c_f, the deceleration of the following vehicle during braking, and t_{pr}, the following driver's perception-reaction time. A typical value for c_F is 0.70, and a typical value for t_{pr} is 1.5 seconds (Burgett, Carter, Miller, Najm, and Smith, 1998; Roess, McShane, and Prassas, 1998).

It should be noted that in computing R_{min}, there may be computational lags. If, for example, two consecutive radar returns are used (one for detection and one for verification), then there will be a short resulting delay. Other small delays may occur in computation. The easiest way to handle these is to artificially increase t_{pr} by the total computation lag, possibly resulting in a value such as t_{pr} = 1.75 seconds. Equivalently, t_{pr} may be replaced by the sum of two values: one being the perception-reaction time and the other being the computational lag. The equations would have exactly the same form.

Finally, in regard to Conditions 3 and 4, note that the first necessary conditions for each of them are the exact opposites of one another. In other words, if the parameters do not satisfy the first necessary condition for Condition 3, they will satisfy the first necessary condition for Condition 4, and vice versa. Thus, the decision as to whether Condition 3 or Condition 4 exists is a straightforward one. Also, the first necessary condition under Condition 5 determines whether a collision is possible. If the acceleration of the lead vehicle is too high, there is no threat of a collision; the first necessary condition tests for this.

PRELIMINARY SUBROUTINE FLOW DIAGRAM TO DETERMINE WHETHER THE TARGET IS WITHIN THE THREAT RANGE

The purpose of this subroutine is to apply the proper equation to a radar return to determine if R_r R_{min}. The value R_r is the range to the target at the rear, as provided by the rear-looking radar. The radar also supplies v_r, the closing rate, and ϕ_r, the angle of the return. To qualify the return in terms of angle, ϕ_r is also used elsewhere. If R_r R_{min}, and the angle is qualified, then the countermeasure should be initiated. These conditions indicate that a rear-end crash is imminent.

The subroutine "qualifying" range uses a logic procedure to determine which equation is the correct one. It then evaluates the value of R_{min} and compares it to R_r for a decision. Figure A15a is the portion of the flow diagram that separates the computation into one of three classes: Condition 1 or 2, Condition 3 or 4, or Condition 5. First, it is determined whether the following vehicle is closing. If not, it is assumed that the following vehicle is not in danger of colliding. A time-headway option can be included and is described in the next section.

Assuming that the following vehicle is closing, the "class" decision is based entirely on the state of acceleration of the lead vehicle, as shown in Figure A15a. Figure A15b corresponds to Conditions 1 and 2 in which the lead vehicle is either standing or moving forward at a constant velocity. Similarly, Figure A15c corresponds to the lead vehicle decelerating (Conditions 3 and 4), while Figure A15d corresponds to the lead vehicle accelerating. Note in Figures A15c and A15d that the qualifying conditions are computed first. In A15d, if the qualifying condition is not met, there is no threat. Assuming that R_{min} does get calculated by a logic path shown in Figures A15b, A15c, or A15d, the value is compared to R_r in A15e, and the corresponding threat indication is returned.

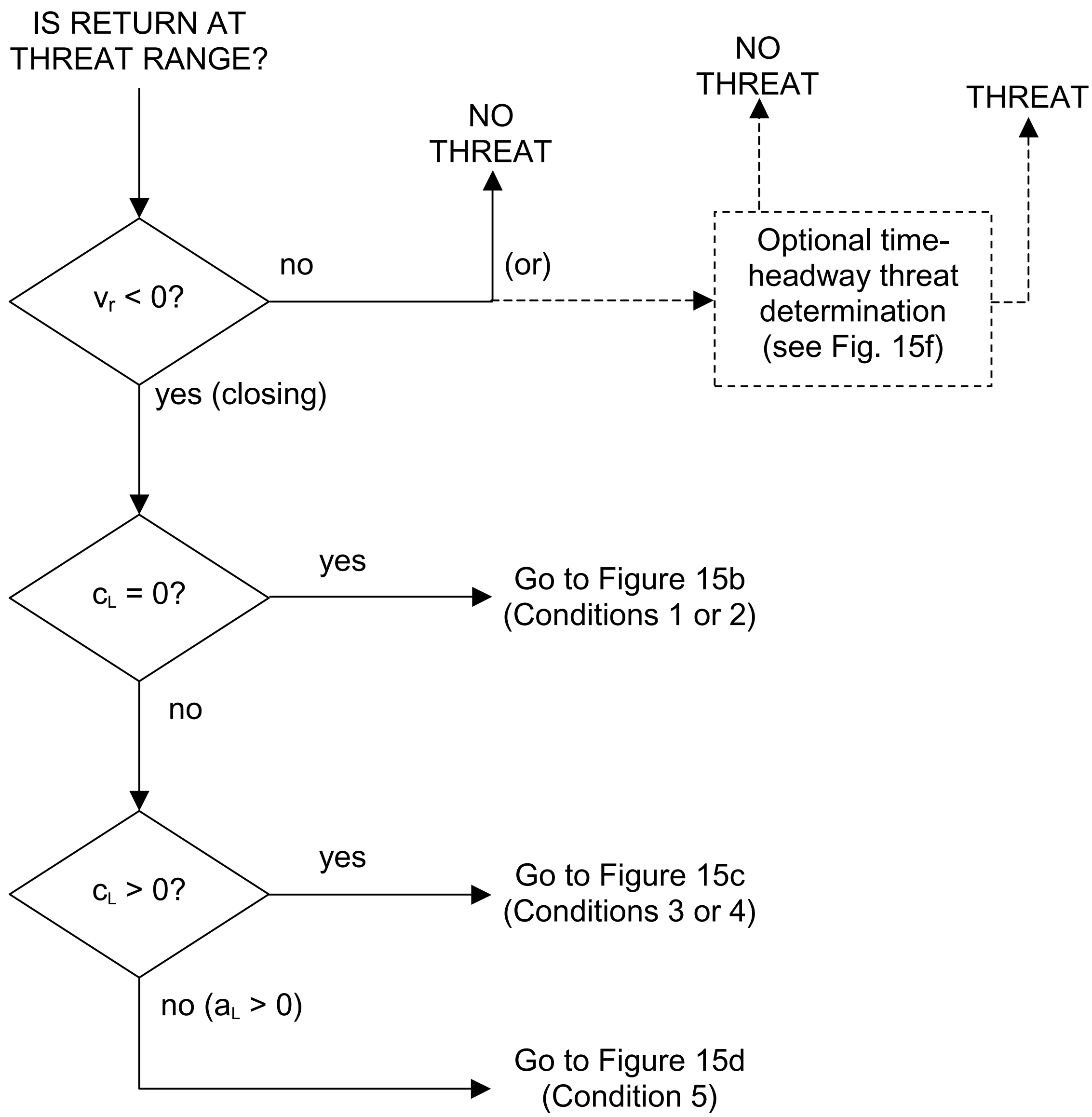


Figure A15a. Subroutine to determine if return is at threat range (classification).

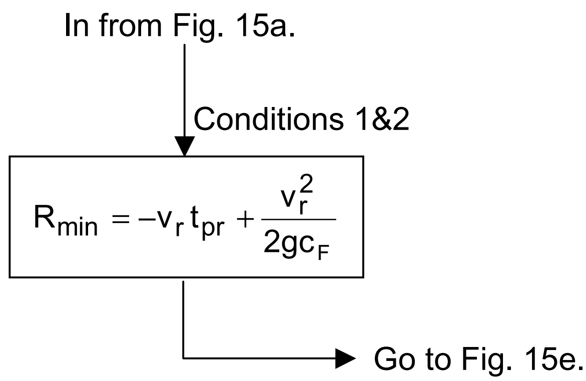


Figure A15b. Subroutine to determine if return is at threat range (for Conditions 1 and 2).

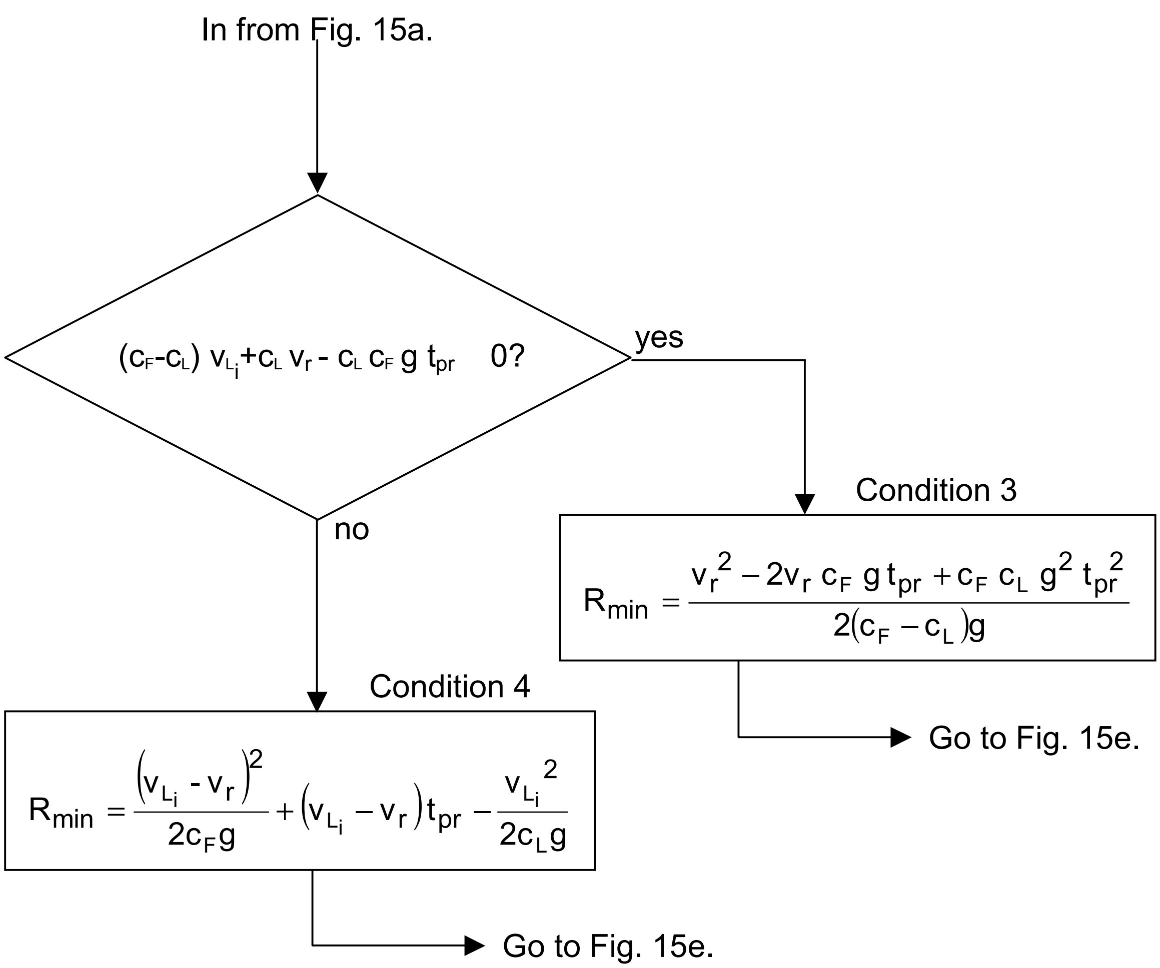


Figure A15c. Subroutine to determine if return is at threat range (for Conditions 3 and 4).

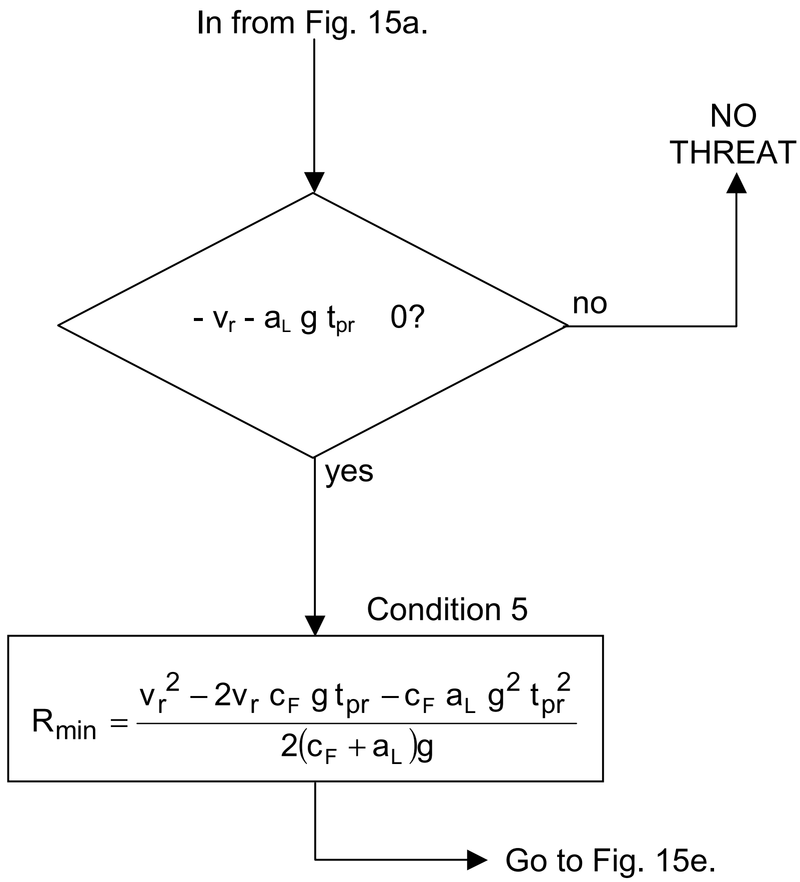


Figure A15d. Subroutine to determine if return is at threat range (for Condition 5).

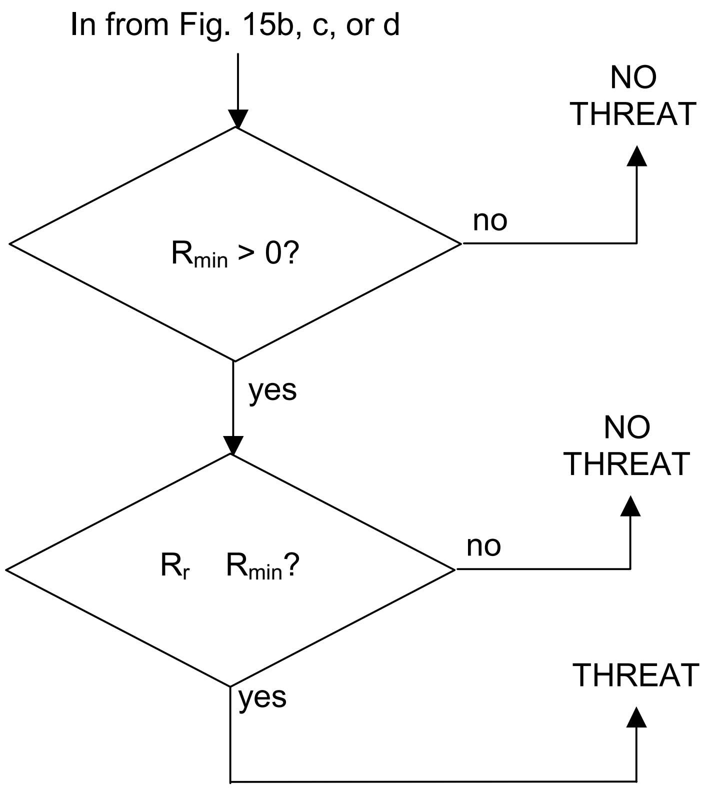


Figure A15e. Subroutine to determine if return is at threat range (comparison).

Short Time-Headway Option

As shown in Figure A15a, unless v_r is negative, the subroutine returns a "no threat" condition. In other words, if the following vehicle is not closing on the lead vehicle, it is assumed that a rear-end collision would not occur. In fact, for a collision to occur, the following vehicle must eventually close on the lead vehicle. Therefore, there should be a future radar return with v_r negative, in which case the possibility of a threat would be re-determined.

There is, however, an optional condition that might be included when v_r is zero or positive. It is the case of following too closely. Some drivers will tailgate to such an extent that they are creating a hazard, that is, they could not avoid a rear-end collision if the lead vehicle had to brake for an emergency. Under such circumstances, it might be desirable to initiate the countermeasure.

To include the "following too closely" case, time-headway can be computed and compared to a minimum acceptable time-headway, τ_H (in seconds). This value might be set at 0.5 to 0.75 second, well within the instructed time-headway of 2.0 seconds. It would probably be desirable to include a minimum permissible velocity under which this time-headway computation is performed. If, for example, the lead vehicle is traveling at less than approximately 20 mph (v_{L_0} = 30 ft/sec), a no-threat condition is returned. This would prevent actuation of countermeasures in slow-moving, heavy traffic (except as determined through the R_r vs. R_{min} comparison). Figure A15f shows the additional logic for inclusion of a time-headway option.

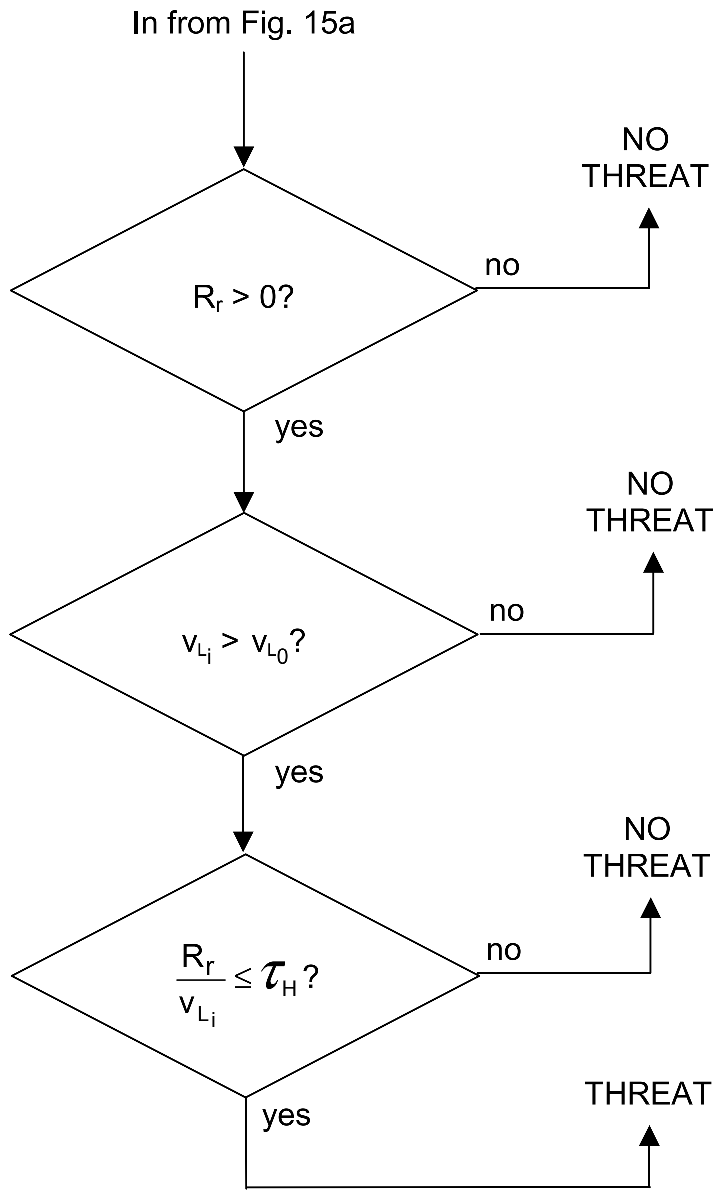


Figure A15f. Optional time-headway threat determination.

OPEN-LOOP REAR-LIGHTING ACTIVATION PROGRAM

Background

In the open loop case, as explained earlier, all parameters are taken from the lead vehicle. There are no parameters indicating range, range-rate, or angle to the following vehicle. Therefore, an attempt must be made to use the available lead vehicle parameters to activate the rear lighting. This process involves two levels of rear lighting: one that would remain activated as long as the vehicle is braking lightly or standing, and one that would be used more sparingly for additional (more salient) warning and would be based on heavier braking.

The two levels of rear lighting are expected to have different properties. For the "low" level, the intent is to provide a warning, but to do so in a way that is tolerable to a driver of a vehicle behind the lead vehicle. To the extent possible, the goal is to also gain the following driver's attention if that driver is looking away. For the "high" level, the goal is to provide a warning of substantial deceleration of the lead vehicle and to gain the following driver's attention more positively if that driver is looking away. For the high level, since it is not ordinarily used in a static situation, annoyance/glare is not as serious a problem. Saliency can therefore be increased. These aspects are summarized in Table A1.

Table A1. Activation levels and assumed characteristics for open-loop rear lighting.

Activation Level	Saliency	Annoyance/Glare	Conditions
"Low" level activation	Moderate	Low to Moderate	Standing or Moving Very Slowly
"High" level activation	High	Moderate or High	Moderate to Heavy Braking plus Time-Out Feature

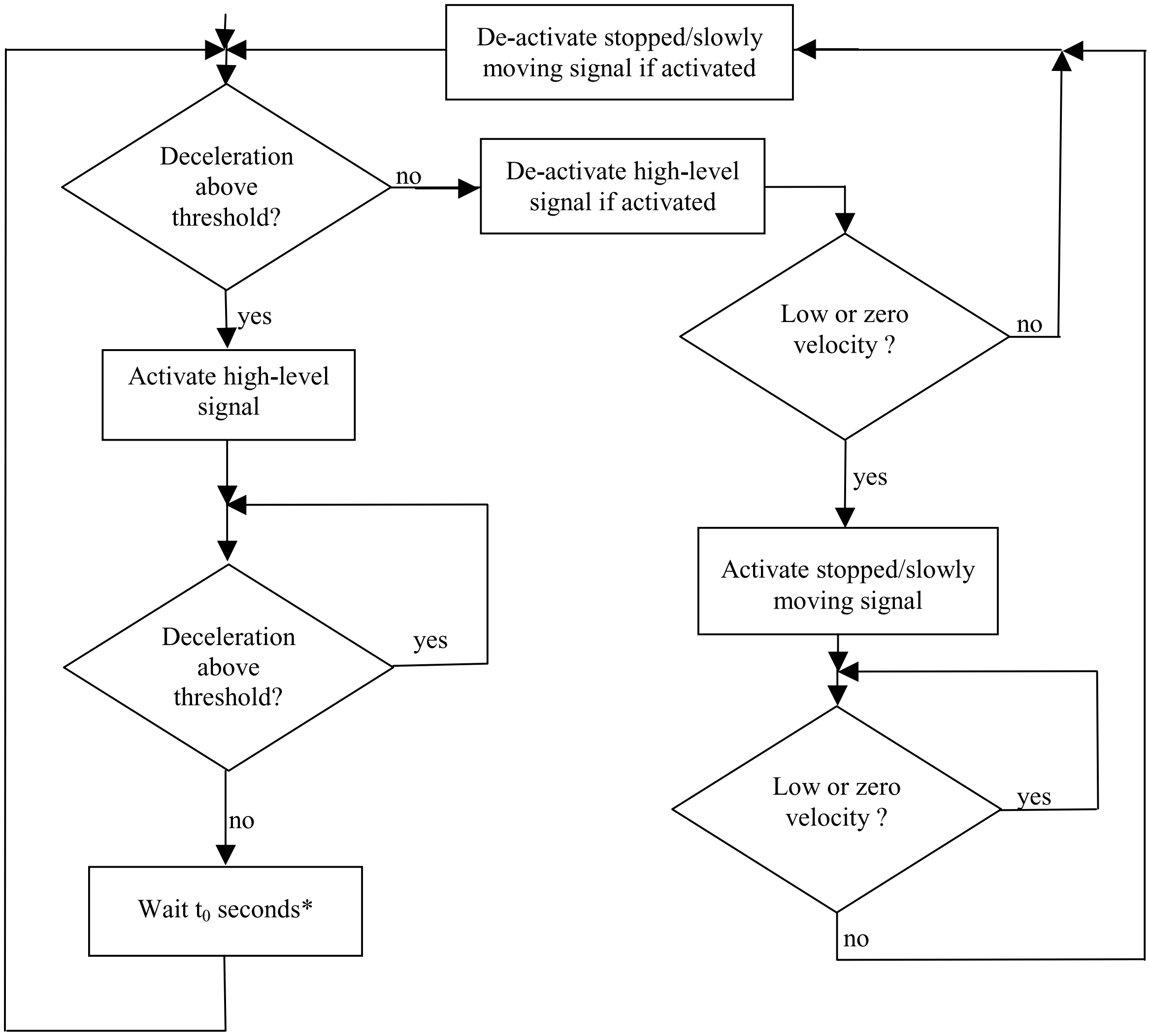
Sample Application

Figure A16 shows a block diagram of the activation logic for the open loop system. The high deceleration threshold would be determined through testing. An inexpensive longitudinal accelerometer would then detect when the threshold is exceeded. Whenever the threshold is exceeded, the high-level lighting (TCL) would be activated. It would remain activated until t_0 seconds after deceleration falls below threshold.[14]

If deceleration is not above threshold, the system checks for zero or low velocity. When this condition is detected the stopped/slowly-moving vehicle signal (alternating pair) is activated.

[14] The reason for delaying deactivation is the high probability that the resulting lower speed could cause a slightly delayed rear-end crash.

Note for the diagram shown that TCL activation takes precedence over the stopped/slowly-moving vehicle signal. Other possibilities exist, as described earlier in the text. However, the initial proposed logic is that shown in Figure A16.



* t_0 is the designated time-out interval for high-level lighting.

Figure A16. Logic flow diagram for open-loop auxiliary rear-lighting system. (Conventional rear-lighting system operates as usual and is not affected by the auxiliary lighting system.)

Setting the Threshold for High-Level Activation

The problem of setting the threshold for high-level activation represents a compromise or tradeoff. The threshold involves specifying the deceleration value above which the high-level lighting would be activated. If the deceleration value is set too low, there would be numerous false alarms and a good deal of annoyance for following drivers. In addition, the enhanced rear lighting may lose its effectiveness because it is always "crying wolf." On the other hand, if the level is set too high, there may be rear end crashes in which the driver is not warned. These situations represent missed detections, because the high-level activation does not occur.

Analyses

To determine the appropriate level for the threshold, two analyses were conducted. The first was analytical, and the second was experimental. In the analytical approach, minimum separation distances were computed for several typical conditions. The equations developed for the closed-loop algorithms were used. The main objective of the analytical approach was to determine how initial separation distances increase with deceleration magnitude of the lead vehicle, under typical conditions. Conditions 3, 4, and 5 of the closed-loop algorithms were used.

Figure A17 shows the results of the analysis for the case in which the following vehicle is initially traveling at 60 mph. Curves are shown for the lead vehicle initially traveling at 20, 30, and 40 mph, and for various deceleration values. As can be seen, the effects of lead vehicle deceleration are dramatic. For example, R_{min} (minimum range without a collision) goes from approximately 100 ft for a lead vehicle at 30 mph and constant velocity, to approximately 200 ft for the lead vehicle initially at 30 mph and then decelerating at 0.3 g. This suggests that lead vehicle deceleration greatly increases required vehicle separation, and that a high-level signal is indeed desirable.

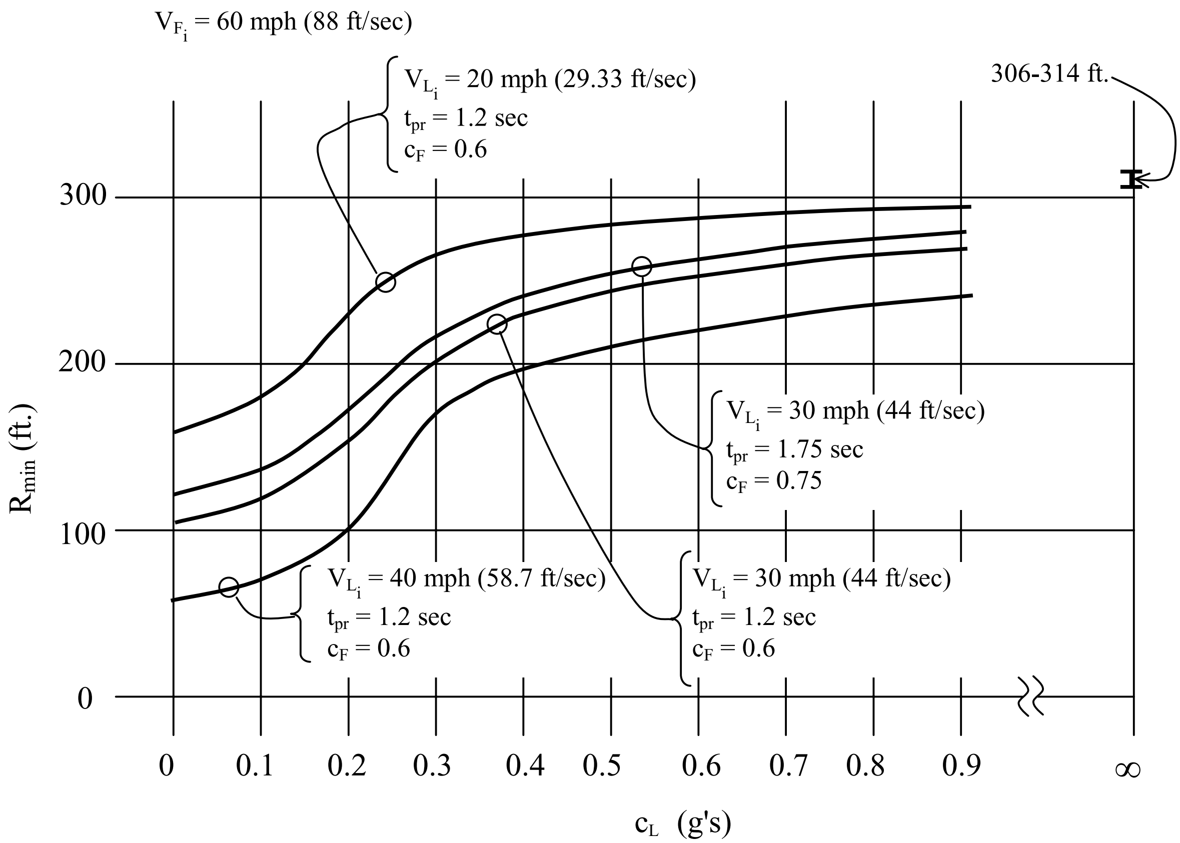


Figure A17. R_{min} values for following speed of 60 mph.

Figure A18 shows two curves for a following vehicle initial speed of 40 mph. Only two curves are shown, because the range of coverage is smaller. As can be seen, a deceleration of 0.3 g doubles the required separation when the lead vehicle is at 20 mph. For the lead vehicle at 10 mph, the lead vehicle is brought to a stop very quickly, in which case there is not as much change in stopping distance. These results show clearly that a high-level signal would be desirable for lead vehicle decelerations around 0.25 g. However, the results do not account for possible false alarms.

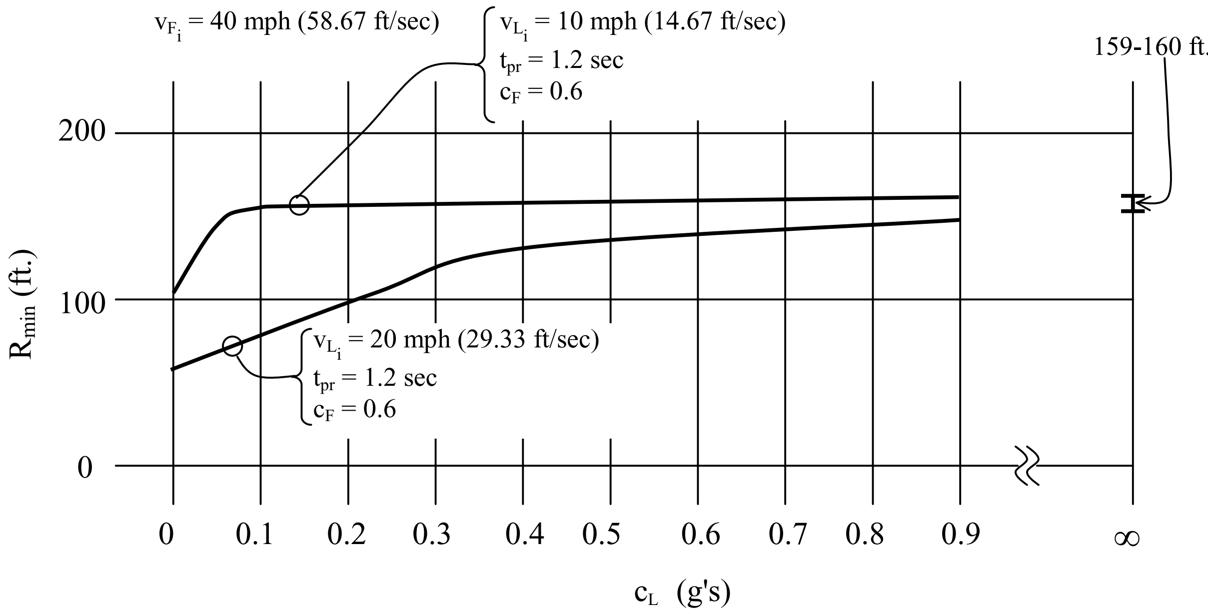


Figure A18. R_{min} values for a following speed of 40 mph.

The research team then installed a "g-meter" in an intermediate sedan. This vehicle was fitted with an accelerometer aligned with the longitudinal axis of the vehicle. It was interconnected through a serial interface to a microcomputer and plotting routine. The team then performed braking maneuvers in traffic starting at various initial speeds (while ensuring that there were no following vehicles).

Figure A19 shows typical braking maneuvers starting from speeds between 45 and 50 mph. The maneuvers were rated subjectively by the research team. Figure A19a shows braking at a typical light level. Figure A19b shows moderate-to-heavy braking, A19c shows heavy braking, and A19d shows severe braking. Note that A19d does not represent the maximum possible braking for the vehicle. Although not tested, it is estimated that maximum braking with good adhesion would have been at least 0.75 g. In these maneuvers, the initial or final values are sometimes not exactly at zero g. This is a result of slight uphill or downhill grades, or pavement irregularities. (The accelerometer was not compensated for vehicle pitch.)

The results of these experimental maneuvers suggest that decelerations up to near 0.25 g are routine in traffic. If this value of threshold were used, there would be numerous false alarms. To avoid excessive false alarms, the threshold should probably be set above 0.30 g, perhaps at 0.35 g. Doing so may mean that the high-level lighting may not by activated in a few cases where it could be useful. However, lowering the threshold would result in numerous false alarms. Thus, a good compromise appears to be 0.35 g. This value may have to be adjusted after some field experience with a complete open-loop system.

Summary

In summary, for the open-loop system it appears that two levels of lighting would be desirable. The low level would activate whenever the vehicle is at very low or zero velocity. A suggested value for the low velocity threshold is 5 mph. The high-level lighting would activate whenever the vehicle deceleration is above a specified threshold. The high level would be timed-out when deceleration falls below the specified threshold[15]. Initial indications are that the activation threshold should be set at 0.35g of deceleration. The activation hardware and logic for the open-loop configuration are relatively straightforward.

[15] It might be advantageous to use a lower threshold for deactivation of the high-level lighting. This would help ensure that the system does not "time-out" too quickly. A deactivation threshold might be in the range of 0.15g. Of course the t_0 time-out extension would follow this.

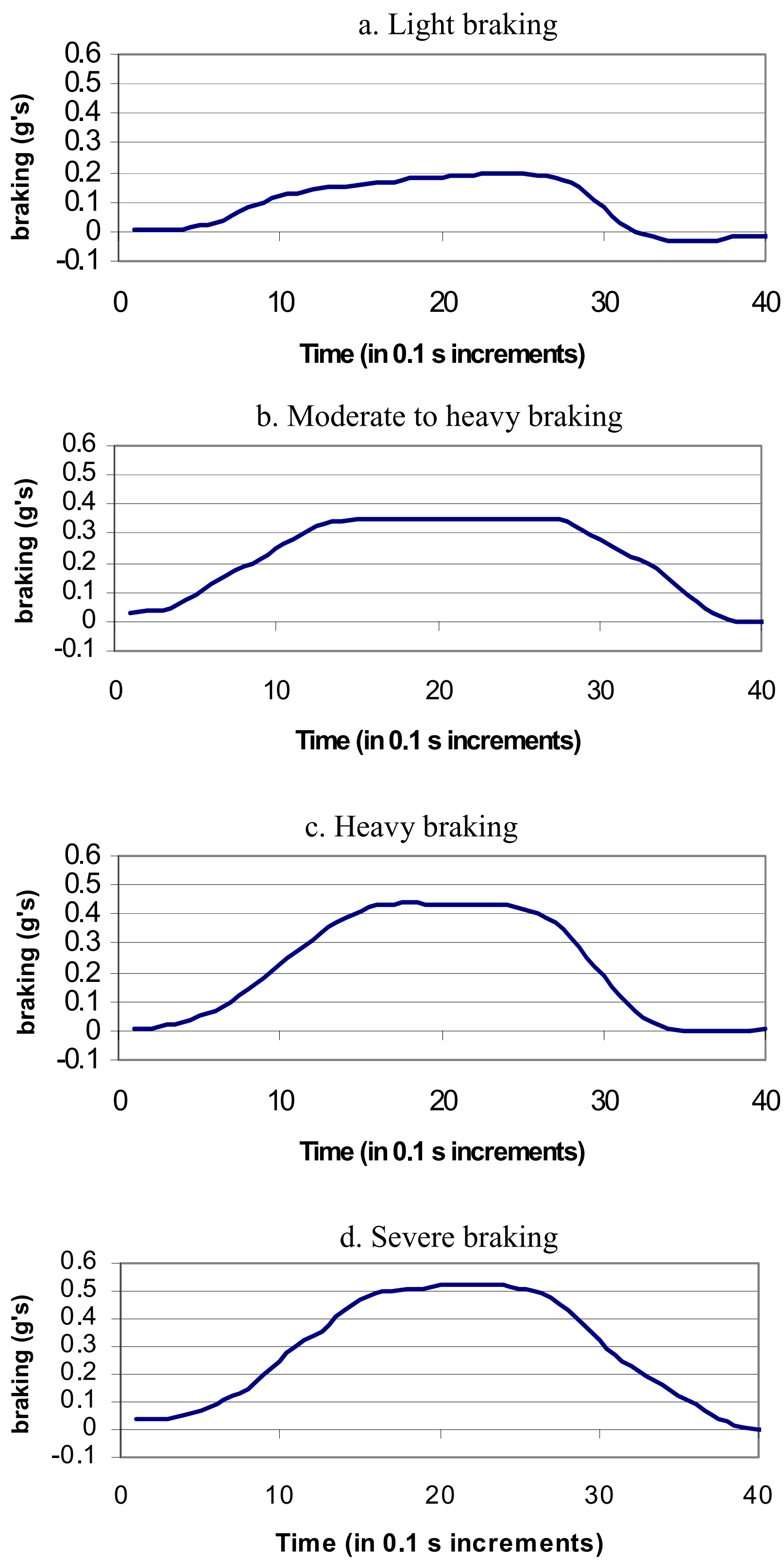


Figure A19 (a-d). Examples of braking levels with subjective descriptors.

SUBAPPENDIX A1: PRELIMINARY DESCRIPTION OF AN ALTERNATIVE SUBROUTINE QUALIFYING A RADAR RETURN IN TERMS OF ANGLE

Background

Consider that a rear-end crash is very likely to occur if the following vehicle follows a path similar to the lead vehicle (and range and range-rate conditions are met). There are other possibilities, but the likely scenario is a crash from a vehicle at the rear in the same lane. To determine if a return is from an appropriate angle, consider the situation in Figure A20.

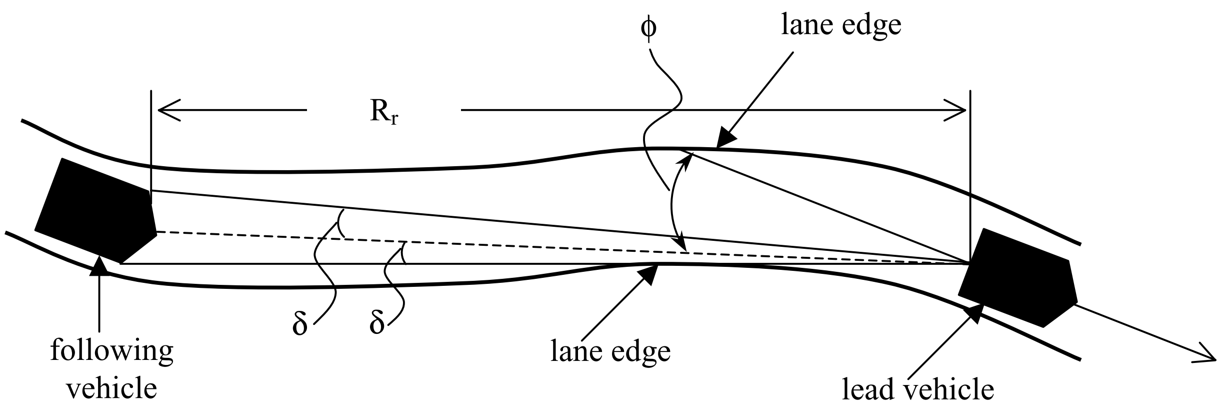


Figure A20. General geometry of the vehicle paths, shown exaggerated; Condition 1.

The radar detects a return at a relative azimuth angle from somewhere off the following vehicle. At the given range, R_r, the "qualified" return should come from an angle $\phi \pm \delta$, where ϕ is the nominal angle from the longitudinal axis of the lead vehicle and δ is one half the angle associated with the width of the following vehicle.

Note that Figure A20 shows a compound curve. In most cases, the curvature will be slight, except when turning at intersections. Note also that unless the return angle is "qualified," the radar will pick up target vehicles in adjacent lanes that are *not* on a collision course with the lead vehicle. To determine if the *following* vehicle is on the same path, the path of the *lead* vehicle is determined in the backward direction.

Calculation of the backward path can be determined using the time history of the lead vehicle speed and lead vehicle turn angle. Turn angle can be obtained from a stabilized compass or gyro with turn angle output.[16]

[16] In this development the understeer characteristics of the lead vehicle are neglected because turn angles and speeds are low.

Analytical Interpretation

To compute the reverse path, consider the diagram in Figure A21. A point on the past trajectory is represented by the polar coordinates R_n, ϕ_n. The point previous to this (one sample further into the past) is R_{n+1}, ϕ_{n+1}. The values of R_{n+1}, ϕ_{n+1} are computed from the values, R_n, ϕ_n, using the vehicle longitudinal velocity v_n and azimuth relative to the present longitudinal axis. Thus, the trajectory of the vehicle into the past is determined by incremental dead reckoning into the past.

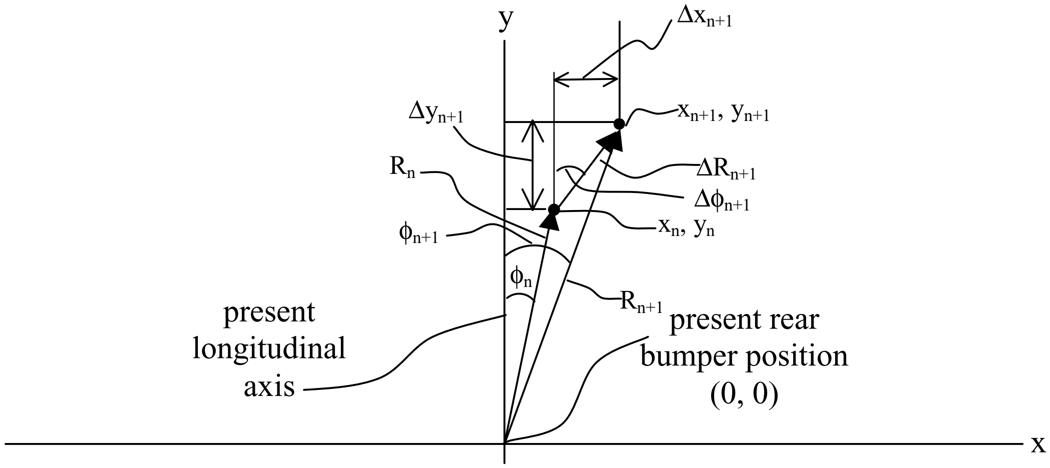


Figure A21. Specific geometry of the backward path of the lead vehicle.

Nomenclature

Δt is the sampling interval in seconds.

v_n is the longitudinal velocity at n intervals into the past.

$\Delta\phi_{n+1}$ is the azimuth angle between the n^{th} and $n+1^{st}$ samples, measured relative to the present longitudinal axis of the vehicle.

x_{n+1}, y_{n+1} are the coordinates of the $n+1^{st}$ sample, and

x_n, y_n are the coordinates of the n^{th} sample, all measured relative to the present position of the rear bumper of the lead vehicle.

R_{n+1}, ϕ_{n+1} are the polar coordinates of the $n+1^{st}$ sample, and

R_n, ϕ_n are the polar coordinates of the n^{th} sample, all measured relative to the present position of the rear bumper of the lead vehicle. (Note that ϕ is measured from the longitudinal axis of the vehicle, or equivalently, the y axis.)

ΔR_{n+1} is the resultant increment between the points x_{n+1}, y_{n+1} and x_n, y_n.

Δx_{n+1} and Δy_{n+1} are the components of ΔR_{n+1} resolved along the axes x and y.

Derivation of the coordinates R_{n+1}, ϕ_{n+1} in terms of known quantities is as follows:

$\Delta y_{n+1} = \Delta R_{n+1} \cos \Delta\phi_{n+1}$ $\qquad$ $y_{n+1} = y_n + \Delta y_{n+1}$

$\Delta x_{n+1} = \Delta R_{n+1} \sin \Delta\phi_{n+1}$ $\qquad$ $x_{n+1} = x_n + \Delta x_{n+1}$

$\Delta R_{n+1} = v_n \cdot \Delta t$

$$R_{n+1} = \left(x_{n+1}^2 + y_{n+1}^2\right)^{1/2}$$

$$\phi_{n+1} = \arctan \frac{x_{n+1}}{y_{n+1}}$$

where $x_{n+1} = x_n + v_n \, \Delta t \sin \Delta\phi_{n+1}$

and $y_{n+1} = y_n + v_n \, \Delta t \cos \Delta\phi_{n+1}$

Note that the sequence of coordinates (R_{n+1}, ϕ_{n+1}, where n = 0, 1, 2, . . ., N) represents the past path (or trajectory) of the lead vehicle in polar coordinates, relative to the present position.

Programming a Subroutine

To program and use the equations, the following general steps will be needed.

- Read the present values of azimuth and longitudinal velocity. Calculate the sequence of past azimuth values relative to the present azimuth values. Obtain the sequences:

  $v_0, v_1, \ldots, v_N$

  and

  $\Delta\phi_1, \Delta\phi_2, \ldots, \Delta\phi_N$

  where N is sufficient to project backward 300ft. Minimum N can be estimated by

  $N \geq \dfrac{300}{v_0 \cdot \Delta t} + k_0$, where k_0 is an integer equal to, perhaps,10. [17]

[17] If v_0 10 ft/sec, see note at the end of the subroutine sequence.

- Using the previous equations, calculate R_1, ϕ_1 by setting x_0, y_0 = 0,0.
- Using the previous equations calculate the entire sequence:
  $R_1, \phi_1; R_2, \phi_2; R_3, \phi_3; \ldots ; R_N, \phi_N$. These values represent the path of the vehicle into the past, in polar coordinates.
- Scan the values of ϕ_n for any value larger than ϕ_{max}, where ϕ_{max} is initially specified as 4°. If such values exist, exit the subroutine with the notation that the return is “not a threat.” (Large angular values indicate substantial turning, which would invalidate the likelihood that the radar can accurately detect a vehicle on a collision course.)
- Initialize routines for piecewise linear interpolation of values for ϕ given R.
- For a radar return coming from R_r, ϕ_r, where the subscript r designates that the data are from the radar, substitute R_r into the interpolation equations for R and obtain ϕ.
- If $|\phi - \phi_r| \le \frac{\delta}{R_r}$, exit the subroutine with the indication that the return is "qualified." An appropriate value for δ is 4 ft, since trucks may be up to 8 ft wide. If the return does not pass the test, exit the subroutine with the notation that the return is "not a threat."
- Note that if v_0 is below, say, 10 ft/sec, the lead vehicle is moving very slowly or is stopped. Under these conditions, it should be assumed that the path approach criterion is inappropriate; the constant-angle criterion described in the main text should be used instead.

APPENDIX B: BULB AND LAMP PARAMETER TESTS

Following human subject data gathering for Experiments 1 and 2, the test rig was taken into a darkened laboratory for lighting parameter determination. The purpose of these tests was to make important radiation and power consumption information available for the configurations that were tested. Three sets of tests were performed. In the first set "bare bulb" tests were performed for a single medium-output halogen lamp and for a single high-output halogen lamp. These tests were intended to provide information on the bulbs used.

The second set of tests was performed for the Experiment 2 configurations, which were considered to be the "final" candidates. These tests included both clear and tinted lenses. The third set of tests was performed on the Experiment 1 configurations using clear lenses only. A few of the configurations in Experiment 2 were the same as those in Experiment 1. If so, those results are repeated in the presentation of the third set. Details and results of the tests are provided in the following sections.

Bare-Bulb Tests

As indicated, these tests provided information on the bulbs used for the medium and high-output halogen lamps. Because it was not possible to measure the instantaneous light output waveforms of the strobe bulbs with the equipment available, no "bare strobe" tests were performed.

Each bulb type was supported by its base only, with the sensor facing the bulb, in an effort to test the bulb as an isotropic radiator. The measurement sensor was placed exactly 2.0 meters (6ft., 6¾ in.) away in the horizontal plane with the sensor facing the bulb. Tests were run with the room darkened, except for the illumination of the bulb. Voltage and current readings were taken, and power consumed was calculated as the product of the voltage and current. Each reading in lux was multiplied by 4.0, that is, $(2.0\text{m})^2$, to obtain the bulb output in candelas. The results appear in Table B1.

As can be seen, the high-output halogen bulb consumed approximately twice the power of the medium-output bulb, but produced approximately three times as much visible light output.

Table B1. Bare-bulb tests for the medium-output and high-output halogen bulbs.

Type	Applied Voltage	Current (amps)	Power (Watts)	Light Output (Candelas)
Medium-output	13.7	2.18	29.9	52
High-output	13.7	4.22	57.8	152

Tests for Experiment 2 Configurations

These tests were run using the lamps exactly as they were used in (human-subjects) Experiment 2. Thus, the tests included the drive electronics (if any), the parabolic reflectors, the lenses, and the lamp housings. In all cases the system applied voltage was 13.8 volts, slightly above that for the bare bulb tests previously described. However, there may have been a small voltage drop due to line losses and drive electronics, bringing the estimated bulb voltage to around 13.7 volts, similar to the value used in the bare bulb tests (this latter number is an estimate).

In this set of experiments the measurement sensor was placed at a distance of exactly 8.0 meters (26 ft., 3 in.). The sensor was placed in the same horizontal plane as the lamps, with the sensor facing the lamp(s) of interest. The lighting rig was exactly perpendicular to the sensor with the sensor on the centerline of the lamp configuration.

Some of the configurations used nondispersive lenses, while others used dispersive lenses. A nondispersive lens is one that does not change the direction of the light rays (similar to a flat pane of glass). Dispersive lenses on the other hand spread the light somewhat (similar to a typical automobile taillight lens). Nondispersive lenses using parabolic reflectors will produce a brighter and more directional beam, since the light energy is not dispersed over as wide an area.

Photometric output measurements were obtained in lux. These were multiplied by 64 (that is, $8m^2$) to obtain the equivalent on-axis source output in candelas. Average current readings were also obtained. Note that current readings are, of course, independent of lens type (dispersive/nondispersive) and tint (clear/amber/red). Table B2 shows the results of the tests for the Experiment 2 configurations. In all cases the *system* applied voltage was 13.8.

Table B2. Experiment 2 lighting system measurements.

Description	System avg. current (amps) & power (watts)	Lamp aperture dimensions (cm)	Lens type	Lens tint	Equivalent on-axis output (cd)
Medium-output halogen. Alternating pair (with one lamp distance separation)	2.45a 33.8W	5.0 H x 10.5 W	Dispersive	Clear	576
				Amber	416
				Red	256
			Nondispersive	Clear	960
				Amber	640
				Red	352
High-output halogen. Alternating pair (with one lamp distance separation)	4.80a 66.2W	5.0 H x 10.5 W	Dispersive	Clear	2304
				Amber	1664
				Red	992
Traffic clearing light (TCL)	4.20a 58.0W	7.0 H x 10.7 W	Nondispersive	Clear	1408 avg
					6912 max
					256 min
				Amber	1088 avg
					4992 max
					192 min
				Red	544 avg
					2304 max
					96 min

The results show that the lens type, lens tint, and bulb type have a profound effect on the equivalent output of the lamp system. Nondispersive lenses produced higher readings than dispersive lenses, and clear lenses produced higher readings than amber lenses. In turn, amber lenses produced higher readings than red lenses. The extremely high maximum output values for the TCL are noteworthy. These values as well as the minimum values were obtained by temporarily disconnecting power from the mirror motor and turning it by hand until the output of the photometer reached the extreme value. Such values help to explain the high attention-getting ratings of this lamp.

For purposes of possible further analysis, readings were also taken for single, steady burning medium-output and high-output lamps. These results are presented in Table B3.

Table B3. Steady single lamp measurements (for purposes of comparison).

Description	System Ave. current (amps) & power (watts)	Lamp aperture dimensions (cm)	Lens type	Lens tint	Equivalent on-axis output (cd)
Medium-output halogen. Single, steady lamp	2.10a 29.0W	5.0 H x 10.5 W	Dispersive	Clear	640
				Amber	448
				Red	256
			Nondispersive	Clear	1088
				Amber	768
				Red	384
High-output halogen. Single, steady lamp	4.25a 58.7W	5.0 H x 10.5 W	Dispersive	Clear	3008
				Amber	2112
				Red	1216

Only two of these configurations were tested on human subjects, and in those cases, the tests were performed in Experiment 1. The medium-output, steady, dispersive, clear lens condition corresponds to Configuration I of Experiment 1, and the high-output, steady, dispersive, clear lens condition corresponds to Configuration J of Experiment 1.

The results in Table B3 can be compared to those in Table B2. For example, the medium-output alternating pair, in which one or the other of two lamps is illuminated most of the time, produces slightly lower average light output than the corresponding single steady-burning lamp. This difference can be explained by bulb warm-up and slight off-time during lamp switching.

<u>Tests for Experiment 1 Configurations</u>

These human-subjects tests were run using clear lenses only (producing white light). Thus, photometric measurements for these configurations are limited to clear lenses. As in previous tests, the applied system voltage was 13.8, and average currents were determined. Power was then calculated as the product of voltage and average current. Photometric readings were again taken at a distance of 8.0 meters, in lux. Thus, multiplying the readings by 64 yielded the equivalent on-axis light output in candelas. Data for the TCL, appearing in Table B2, and data for configurations I and J, appearing in Table B3, are repeated here for convenience. Table B4 provides a summary of results.

Table B4. Experiment 1 lighting system measurements.

Description		System Ave. current (amps) & power (watts)	Lamp aperture dimensions (cm)	Lens type	Equivalent on-axis output (cd)
Sys	Pattern, lights exposed				
A	eight-lamp, pattern A, 1-8	4.85a 66.9W	5.0 H x 10.5 W	Dispersive	2112
B	eight-lamp, pattern B, 1-8	3.90a 53.8W	5.0 H x 10.5 W	Dispersive	576
C	eight-lamp, pattern C, 1-8	9.40a 129.7W	5.0 H x 10.5 W	Dispersive	1920
D	eight-lamp, steady, 1-8	16.6a 229.1W	5.0 H x 10.5 W	Dispersive	4544
E	4-lamp, inner-outer, 1,2,7,8	4.79a 66.1W	5.0 H x 10.5 W	Dispersive	960
F	2-lamp, outer alternating, 1,8	2.45a 33.8W	5.0 H x 10.5 W	Dispersive	448
G	2-lamp, inner alternating, 4,5	2.45a 33.8W	5.0 H x 10.5 W	Dispersive	576
H	1-lamp, center flashing, 4	1.15a 15.9W	5.0 H x 10.5 W	Dispersive	256
I	1-lamp, center steady, 4	2.10a 29.0W	5.0 H x 10.5 W	Dispersive	640
J	High-output unit, center, steady	4.25a 58.7W	5.0 H x 10.5 W	Dispersive	3008
K	High-output unit, center, flashing	2.40a 33.1W	5.0 H x 10.5 W	Dispersive	1280
Note that letters L, M, and N are reserved at present.					
O	Quad-strobe, inner, then outer, 1,2,6,7	4.30a 59.3W	5.0 H x 10.5 W	Dispersive	576
P	Dual-strobe, outer, alternating, 1,6	2.60a 35.9W	5.0 H x 10.5 W	Dispersive	288
Q	Dual center strobe, alternating, 6,7	2.60a 35.9W	5.0 H x 10.5 W	Dispersive	320
R	Single center strobe, 6	1.29a 17.8W	5.0 H x 10.5 W	Dispersive	160
S	Viper, 5	1.89a 26.1W	5.9 H x 11.5 W	Nondispersive	416
T	Traffic clearing light , 3	4.20a 58.0W	7.0 H x 10.7 W	Nondispersive	1408

An additional word of explanation is necessary for strobe configurations O, P, Q, and R. The same electronic drive system was used for all four of these configurations. When going from four to two strobes, two of the strobes were simply switched to strobes in a light-tight box. Similarly, when going from four strobes to one strobe, three of the strobes were switched to strobes in a light-tight box. This procedure ensured that the high voltage circuits operated into the proper load. Of course, such an approach requires the same current and power.

Thus, to estimate the system current required for dual strobes (configurations P and Q), the measured quad-strobe current was multiplied by 0.55. Similarly, to estimate the system current for a single strobe (configuration R), the quad strobe current was multiplied by 0.30.

The results of Table B4 demonstrate clearly that there were large differences in average on-axis light output and power consumed among the configurations. Of course, peak light outputs for the strobe configurations and the TCL were much higher than the average values that are shown in the table.

APPENDIX C: ANOVA SUMMARY TABLES AND INTERACTION PLOTS FOR EXPERIMENT 1

Table C1. ANOVA Summary Table for Final Attention-Getting Rating.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	13.0012	15.6791	2.72	0.1375
Gender	1	3.1875	3.1875	0.67	0.4375
Age*Gender	1	13.5110	13.5110	2.83	0.1310
Subjects/Age*Gender	8	38.1961	4.7745		
Within					
Configuration	**16**	**250.8652**	**15.6791**	**13.19**	**<0.0001**
Age*Configuration	16	10.8113	0.6757	0.57	0.9023
Gender*Configuration	16	14.7917	0.9245	0.78	0.7079
Age*Gender*Configuration	16	10.2181	0.6386	0.54	0.9227
Config*Subjects/Age*Gender	128	152.1373	1.1886		
Total	203	506.7194			

Table C2. ANOVA Summary Table for Discomfort-Glare Rating.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	47.0784	47.0784	2.27	0.1704
Gender	1	0.1765	0.1765	0.01	0.9288
Age*Gender	1	15.9265	15.9265	0.77	0.4065
Subjects/Age*Gender	8	165.9608	20.7451		
Within					
Configuration	**16**	**339.1569**	**21.1973**	**11.65**	**<0.0001**
Age*Configuration	16	25.5882	1.5993	0.88	0.5943
Gender*Configuration	16	23.0735	1.4421	0.79	0.6915
Age*Gender*Configuration	16	17.0735	1.0671	0.59	0.8894
Config*Subjects/Age*Gender	128	232.8725	1.8193		
Total	203	866.9068			

Table C3. ANOVA Summary Table for Horizontal Peripheral Detection.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	15531.3726	15531.3726	4.89	0.0580
Gender	1	10544.6623	10544.6623	3.32	0.1060
Age*Gender	1	1359.6950	1359.6950	0.43	0.5314
Subjects/Age*Gender	8	25422.2222	3177.7778		
Within					
Configuration	**16**	**33072.3312**	**2067.0207**	**14.09**	**<0.0001**
Age*Configuration	**16**	**5450.1089**	**340.6318**	**2.32**	**0.0049**
Gender*Configuration	**16**	**5040.5229**	**315.0327**	**2.15**	**0.0099**
Age*Gender*Configuration	16	2429.1939	151.8246	1.03	0.4250
Config*Subjects/Age*Gender	128	18777.7778	146.7013		
Total	203	117627.8867			

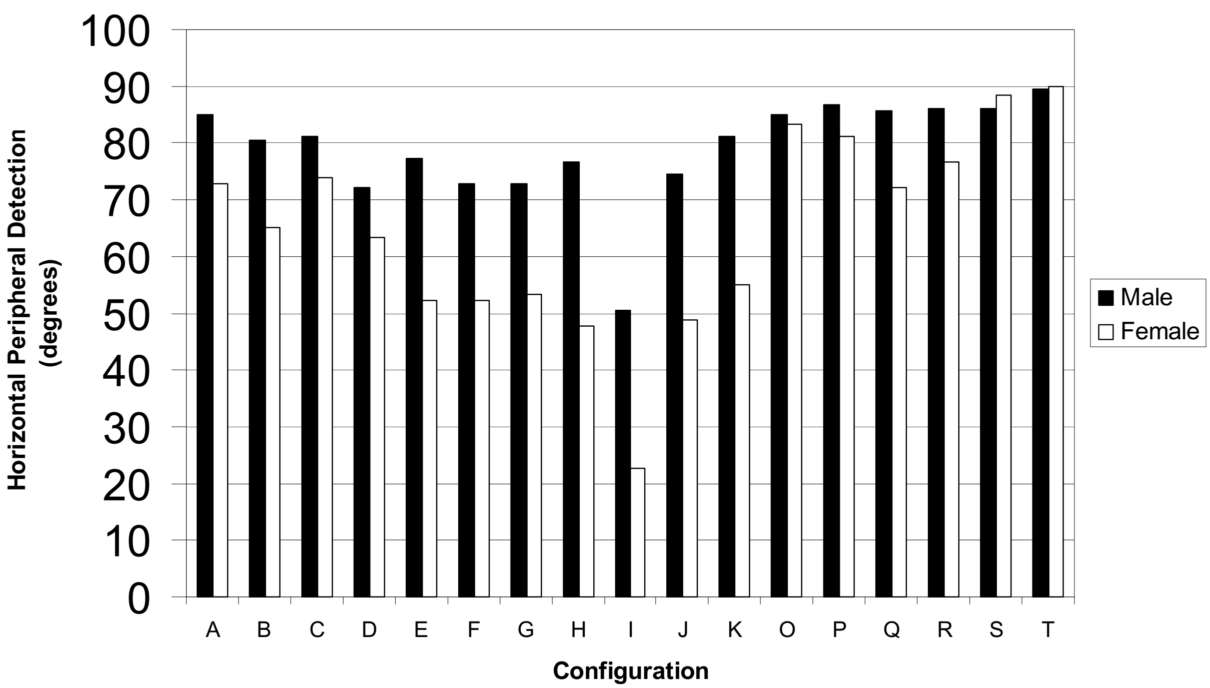


Figure C1. Significant two-way interaction of Configuration by Gender for Horizontal Angle.

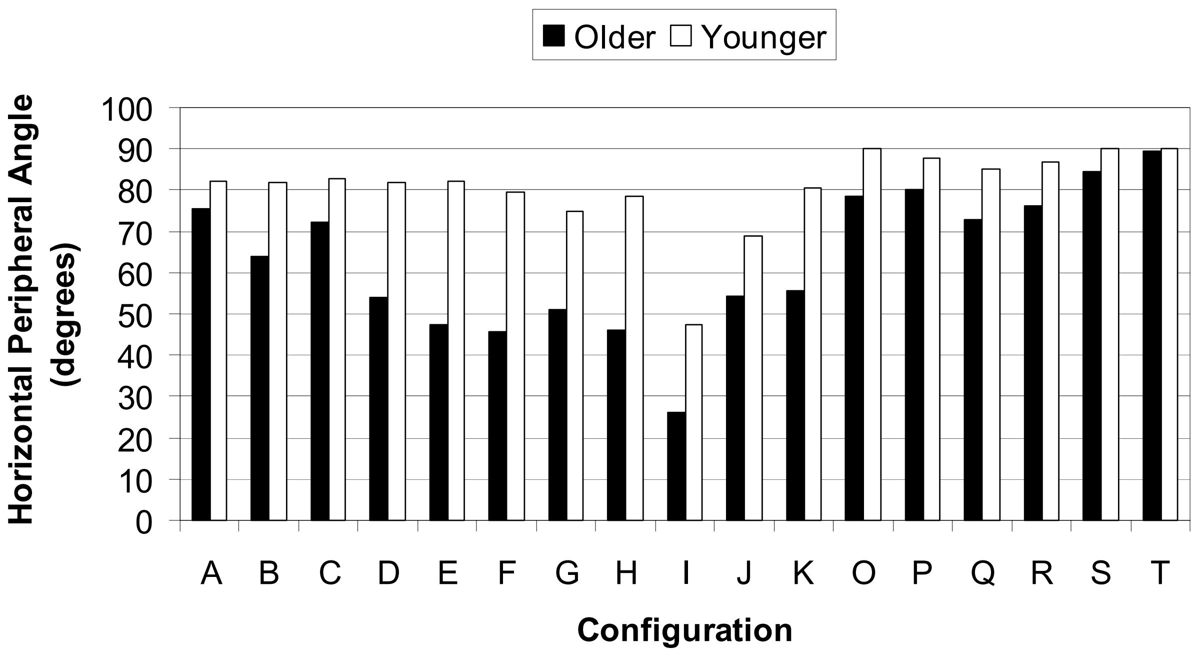


Figure C2. Significant two-way interaction of Configuration by Age Group for Horizontal Angle.

Table C4. ANOVA Summary Table for Diagonal Peripheral Detection.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	2621.8061	2621.8061	2.10	0.1850
Gender	1	4561.6754	4561.6754	3.66	0.0921
Age*Gender	1	584.5839	584.5839	0.47	0.5128
Subjects/Age*Gender	8	9970.1743	1246.2718		
Within					
Configuration	**16**	**11541.6852**	**721.3553**	**7.63**	**<0.0001**
Age*Configuration	16	1974.0643	123.3790	1.31	0.2034
Gender*Configuration	**16**	**3664.3431**	**229.0215**	**2.42**	**0.0032**
Age*Gender*Configuration	16	598.4346	37.4022	0.40	0.9815
Config*Subjects/Age*Gender	128	12094.7146	94.4900		
Total	203	47611.4815			

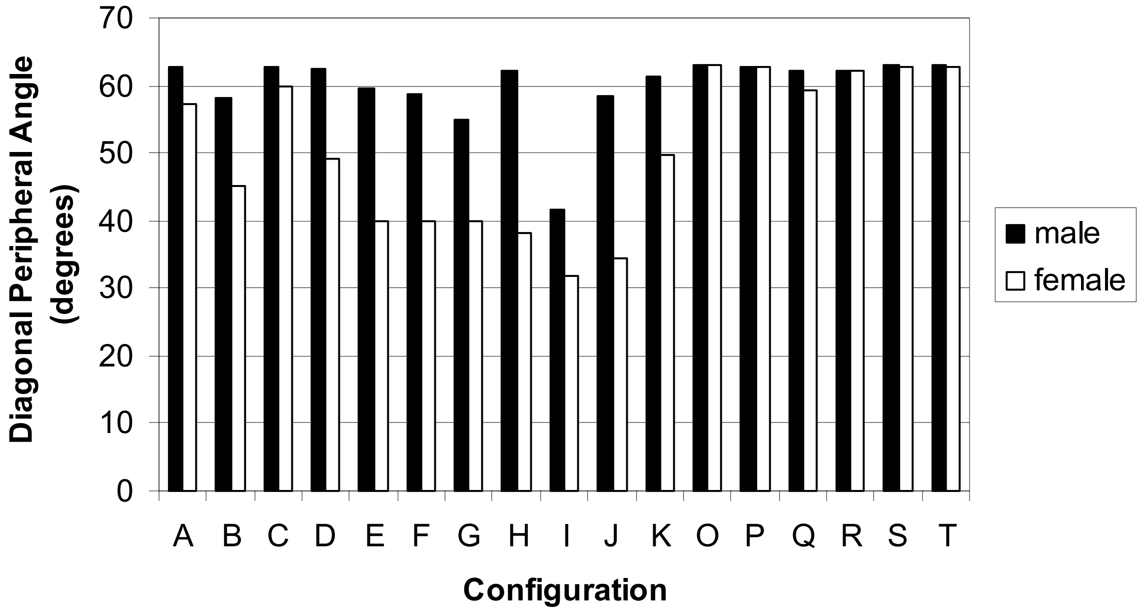


Figure C3. Significant two-way interaction of Configuration by Gender for Diagonal Angle.

APPENDIX D: ADDITIONAL PHOTOGRAPHS OF THE LIGHTING AS IT WAS USED IN EXPERIMENT 2.

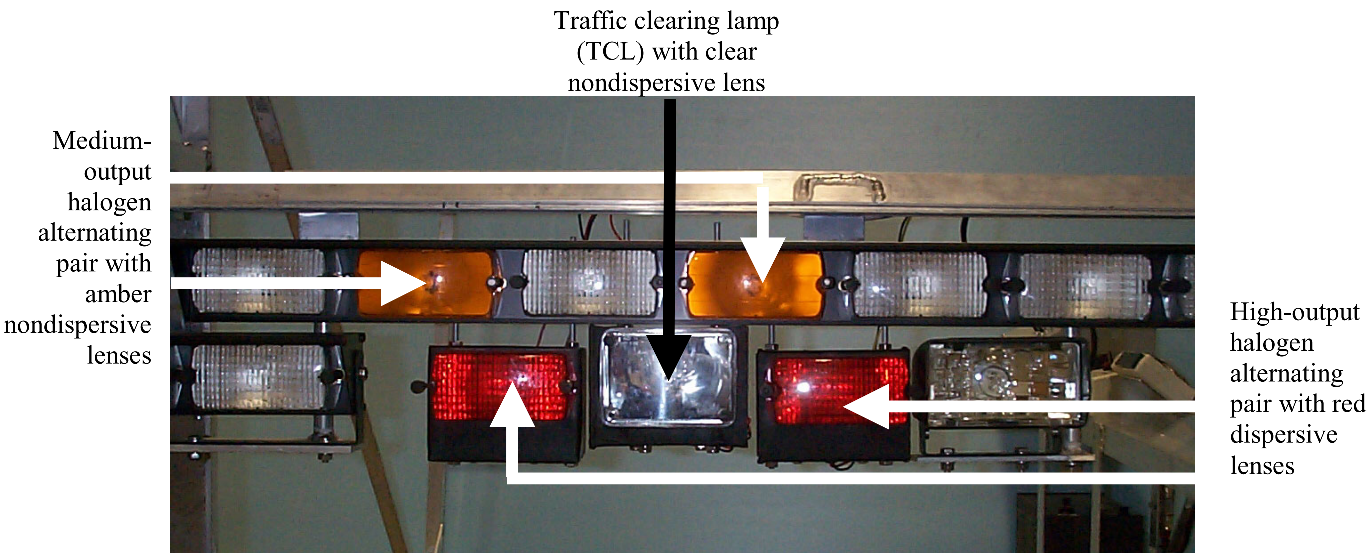


Figure D1. The lights used for Experiment 2.

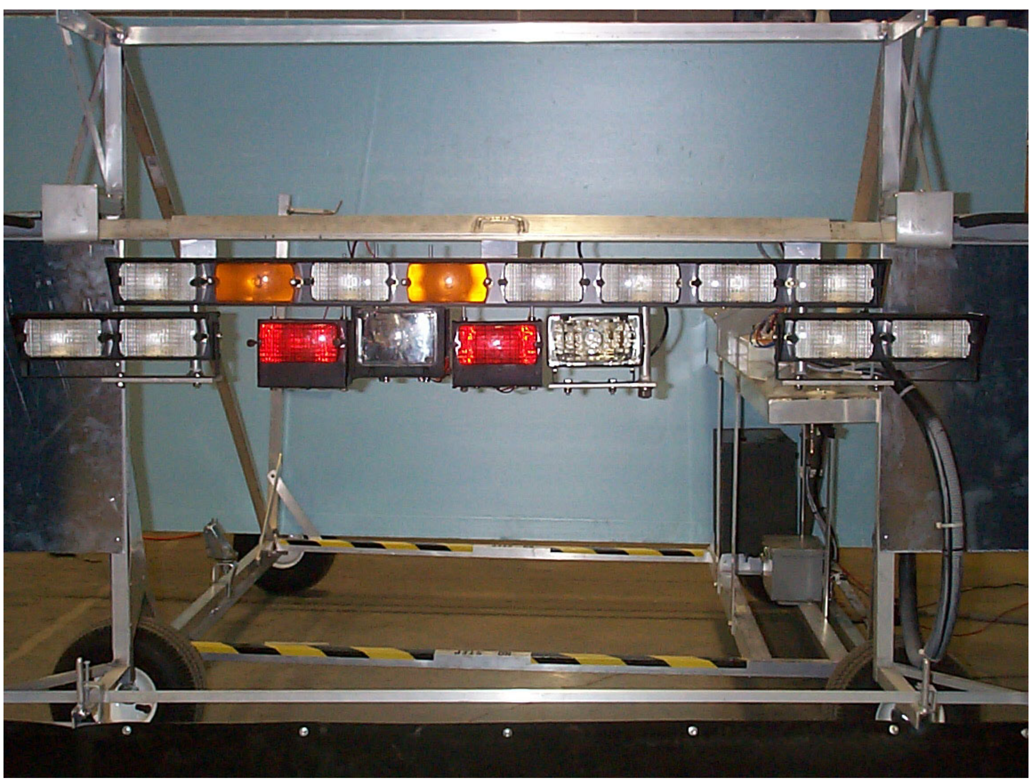


Figure D2. The lighting assembly showing all lights used for Experiments 1 and 2.

Figure D3. The control panel for the lighting assembly test rig. The power supply is shown in the bottom left corner, while the light-tight box used for the strobes is in the lower right. The upper left box is the main control panel. In the upper middle is the timer controls for the timed peripheral detection tasks, and in the upper right is the voltmeter which was monitored to assure a consistent power supply.

APPENDIX E: LENS PARAMETER MEASUREMENTS

Following completion of Experiments 1 and 2, and following photometric measurements of the lighting configurations, samples of each type of lens were measured to obtain color coordinates. The purpose of the measurements was to provide information on specifications of the lenses for possible future use in any field studies.

To accomplish these measurements, a white surface was illuminated by a white light at a 45 degree angle (from the perpendicular). Then a Minolta CS 100 Chromometer was aimed at the surface from the opposite 45 degree angle. The light source was shaded in such a way that its light output could not directly enter the lens of the meter. The Chromometer and the light source were each approximately 30 cm from the white surface.

Readings were then made for the white surface and for each type of lens inserted in the optical path of the meter. The focus was not changed when the lens was inserted. The lens was placed approximately 6 cm from the meter, and again, care was taken to ensure that the light source did not directly illuminate the lens. In other words, all light measured was a result of reflection from the white surface.

Table E1 shows the results of the tests. In the table, the first column of data is the measured luminance. The second and third columns represent the x and y color coordinates using the 1931 CIE standard. All measurements were made and then repeated. No differences were detected.

Table E1. Lens Parameter Measurements.

Description	Tint	Luminance cd/m^2	x	y
White surface (no lens)	NA	2660	0.385	0.399
TCL nondispersive	Clear	2220	0.387	0.400
	Amber	1880	0.506	0.493
	Red	394	0.639	0.354
Medium-output halogen nondispersive	Clear	2210	0.386	0.399
	Amber	1610	0.523	0.476
	Red	387	0.649	0.350
Medium-output halogen/high-output halogen dispersive*	Clear	1660	0.391	0.403
	Amber	1280	0.517	0.481
	Red	382	0.638	0.359

* The same dispersive lenses were used for the medium-output halogen dispersive configurations and the high-output halogen dispersive configurations.

APPENDIX F: ANOVA SUMMARY TABLES AND INTERACTION PLOTS FOR EXPERIMENT 2

Table F1. ANOVA summary table for Attention-Getting Rating.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	0.0017	0.0017	0	0.9892
Gender	1	0.0851	0.0851	0.01	0.9248
Age*Gender	1	0.1406	0.1406	0.02	0.9034
Subjects/Age*Gender	8	71.7361	8.9670		
Within					
Configuration	**3**	**159.1719**	**53.0573**	**70.36**	**<.0001**
Age*Configuration	3	4.4358	1.4786	1.96	0.1468
Gender*Configuration	3	2.1024	0.7008	0.93	0.4417
Age*Gender*Configuration	**3**	**11.1302**	**3.7101**	**4.92**	**0.0084**
Config*Subjects/Age*Gender	24	18.0972	0.7541		
Color	2	1.9688	0.9844	0.65	0.5374
Age*Color	2	10.1493	5.0747	3.33	0.0618
Gender*Color	2	2.8160	1.4080	0.92	0.4172
Age*Gender*Color	2	1.6354	0.8177	0.54	0.5950
Color*Subjects/Age*Gender	16	24.3889	1.5243		
Configuration*Color	6	5.8646	0.9774	1.91	0.0990
Configuration*Age*Color	6	4.1840	0.6973	1.36	0.2499
Configuration*Gender*Color	6	1.1840	0.1973	0.38	0.8851
Config*Age*Gender*Color	6	0.5313	0.0885	0.17	0.9829
Config*Color*Subj/Age*Gender	48	24.6111	0.5127		
Total	143	344.2344			

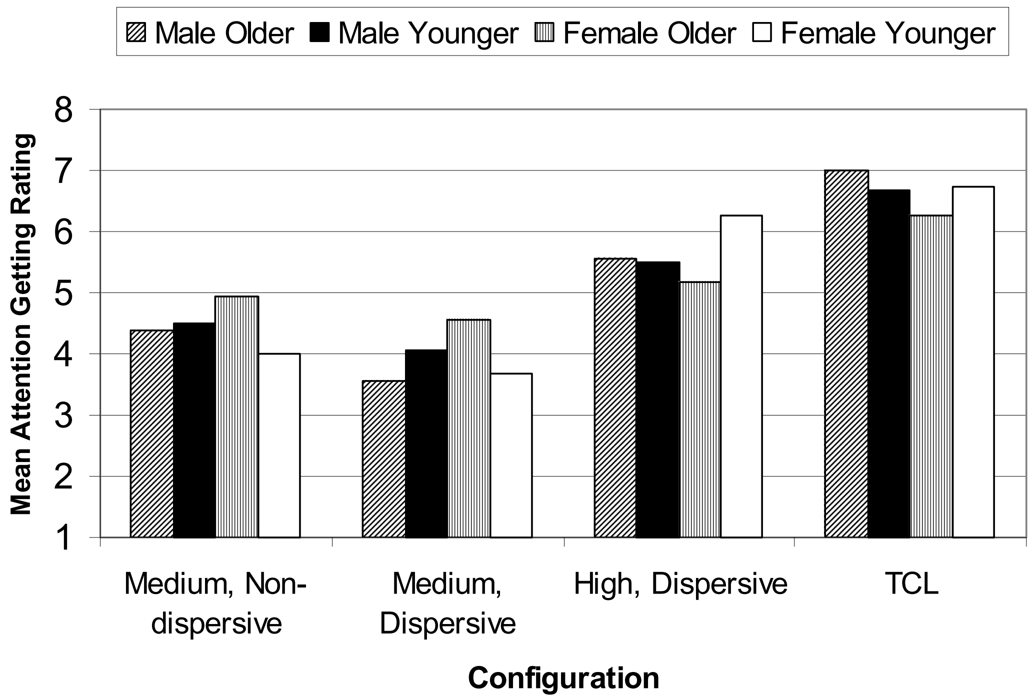


Figure F1. Significant three way interaction of Age by Gender by Configuration for Attention-Getting. Note that the first two configurations show the same age by gender pattern, and that the last two configurations share a different pattern.

Table F2. ANOVA summary table for Discomfort-Glare Rating.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	22.1684	22.1684	4.31	0.0716
Gender	1	0.5017	0.5017	0.10	0.7628
Age*Gender	1	0.2934	0.2934	0.06	0.8173
Subjects/Age*Gender	8	41.1667	5.1458		
Within					
Configuration	**3**	**375.4497**	**125.1499**	**55.57**	**<.0001**
Age*Configuration	3	9.4635	3.1545	1.40	0.2669
Gender*Configuration	3	1.4080	0.4693	0.21	0.8896
Age*Gender*Configuration	3	9.7274	3.2425	1.44	0.2559
Config*Subjects/Age*Gender	24	54.0556	2.2523		
Color	**2**	**43.3438**	**21.6719**	**8.32**	**0.0033**
Age*Color	2	13.9201	6.9601	2.67	0.0997
Gender*Color	2	3.0243	1.5122	0.58	0.5709
Age*Gender*Color	2	0.2118	0.1059	0.04	0.9602
Color*Subjects/Age*Gender	16	41.6667	2.6042		
Configuration*Color	6	0.8368	0.1395	0.24	0.9594
Configuration*Age*Color	6	5.4271	0.9045	1.58	0.1729
Configuration*Gender*Color	6	2.2951	0.3825	0.67	0.6750
Config*Age*Gender*Color	6	2.8299	0.4716	0.82	0.5564
Config*Color*Subj/Age*Gender	48	27.4444	0.5718		
Total	143	655.2344			

Table F3. ANOVA summary table for Horizontal Peripheral Detection Angle.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	3633.4105	3633.4105	5.22	0.0518
Gender	1	3370.4475	3370.4475	4.84	0.0590
Age*Gender	**1**	**7950.6944**	**7950.6944**	**11.41**	**0.0097**
Subjects/Age*Gender	8	5573.4568	696.6821		
Within					
Configuration	**3**	**16658.2562**	**5552.7521**	**54.92**	**<.0001**
Age*Configuration	**3**	**1326.1574**	**442.0525**	**4.37**	**0.0136**
Gender*Configuration	**3**	**1354.5525**	**451.5175**	**4.47**	**0.0125**
Age*Gender*Configuration	**3**	**3089.1204**	**1029.7068**	**10.18**	**0.0002**
Config*Subjects/Age*Gender	24	2426.5432	101.1060		
Color	**2**	**1558.7963**	**779.3981**	**4.96**	**0.0211**
Age*Color	2	173.3025	86.6512	0.55	0.5866
Gender*Color	2	114.0432	57.0216	0.36	0.7012
Age*Gender*Color	2	358.7963	179.3981	1.14	0.3439
Color*Subjects/Age*Gender	16	2513.5803	157.0988		
Configuration*Color	6	747.9938	124.6656	2.15	0.0645
Configuration*Age*Color	6	505.0926	84.1821	1.45	0.2149
Configuration*Gender*Color	6	113.7346	18.9558	0.33	0.9196
Config*Age*Gender*Color	6	331.9444	55.3241	0.95	0.4659
Config*Color*Subj/Age*Gender	48	2782.7161	57.9733		
Total	143	54582.6389			

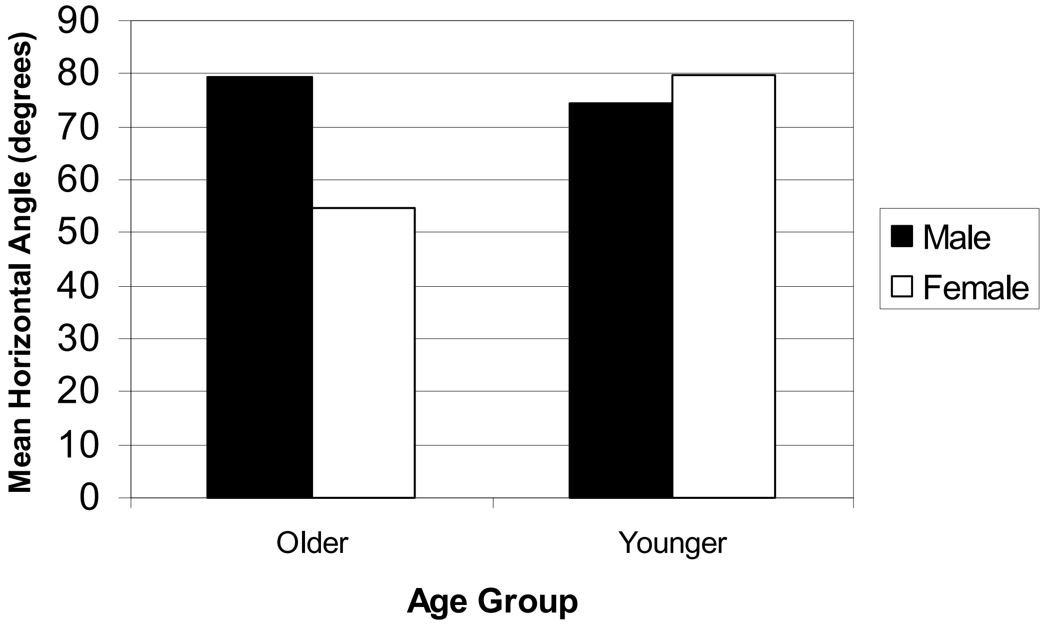


Figure F2. Significant two-way interaction of Age by Gender for Horizontal Angle. Note the large discrepancy between the older females and the other three age/gender groups.

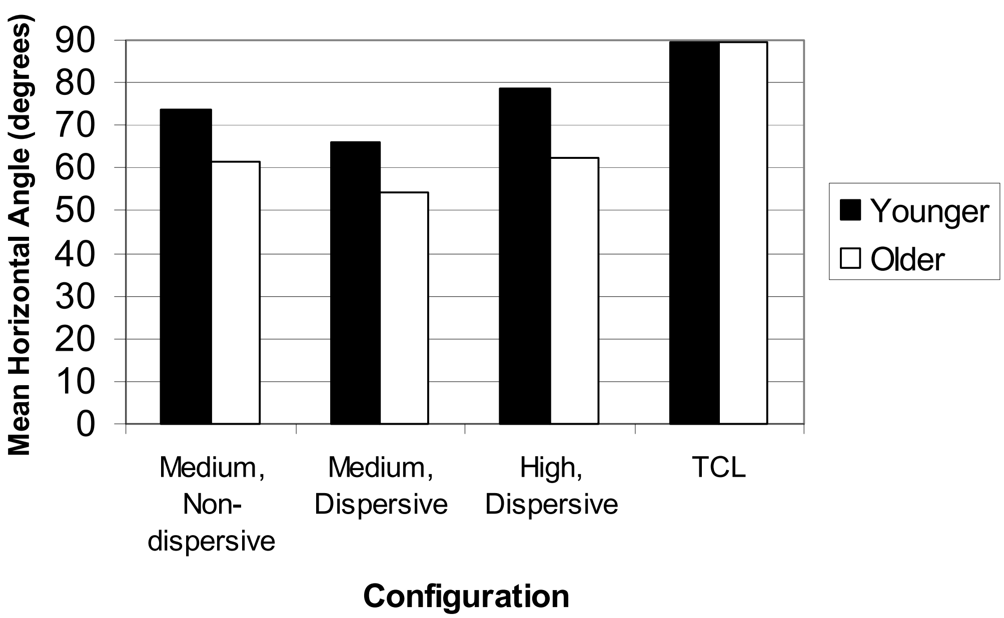


Figure F3. Significant two-way interaction of Age by Configuration for Horizontal Angle. Note that the TCL appears to be immune from age effects for horizontal angle.

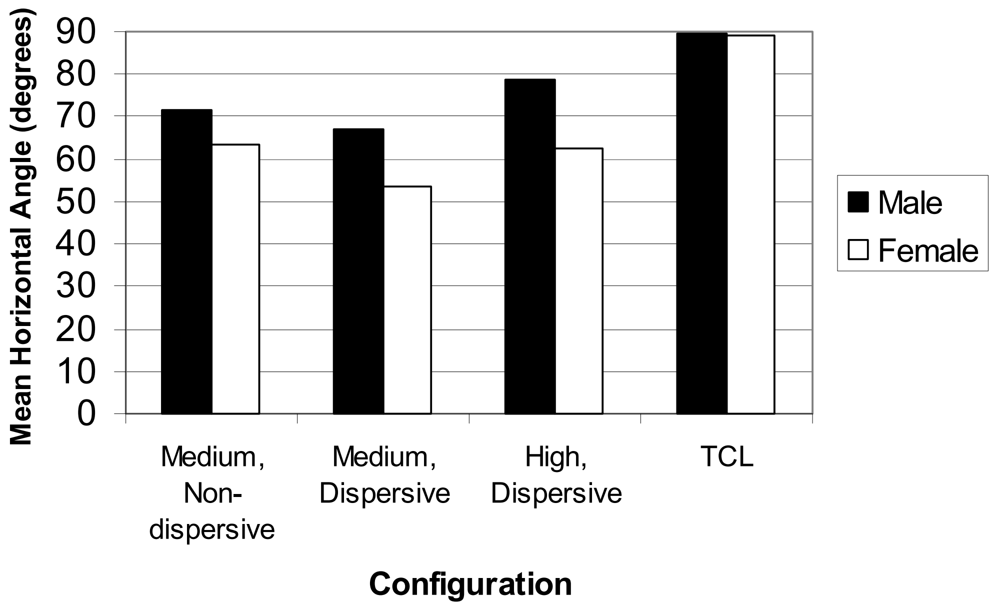


Figure F4. Significant two-way interaction of Gender by Configuration for Horizontal Angle. Note that the TCL appears to be immune from gender effects for horizontal angle.

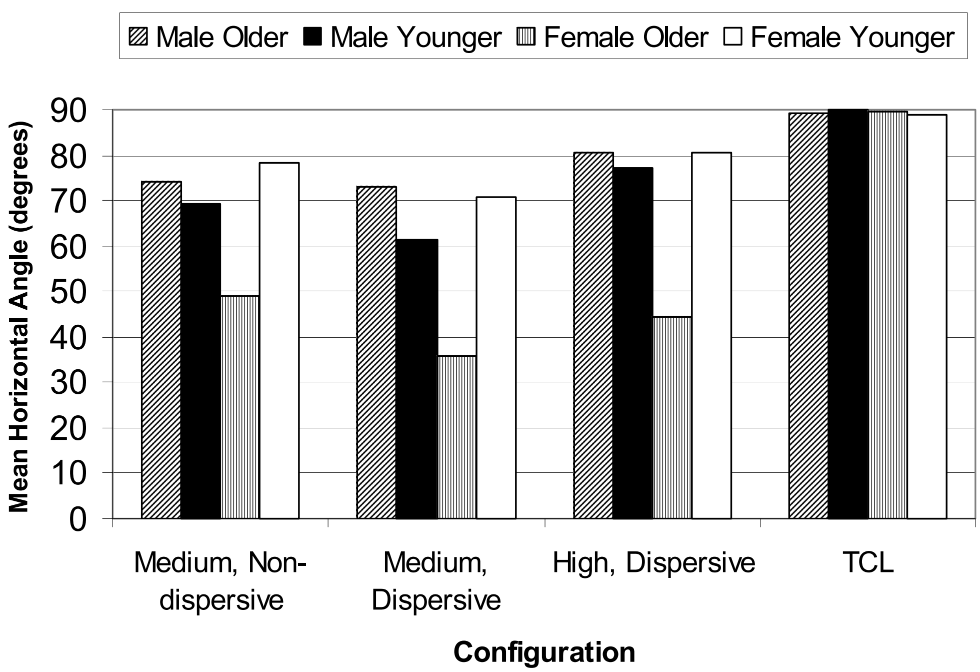


Figure F5. Significant three way interaction of Age by Gender by Configuration for Horizontal Angle. Note the large discrepancy between the older females and the other three age/gender groups for all configurations except the TCL.

Table F4. ANOVA summary table for Diagonal Peripheral Detection Angle.

Source	df	Sum of Squares	Mean Square	F value	*p* value
Between					
Age	1	1448.2253	1448.2253	1.42	0.2669
Gender	1	841.0000	841.0000	0.83	0.3897
Age*Gender	**1**	**5467.7809**	**5467.7809**	**5.38**	**0.0490**
Subjects/Age*Gender	8	8134.4259	1016.8032		
Within					
Configuration	**3**	**8355.6605**	**2785.2202**	**24.79**	**<.0001**
Age*Configuration	3	270.4599	90.1533	0.80	0.5048
Gender*Configuration	3	230.1790	76.7263	0.68	0.5712
Age*Gender*Configuration	3	510.9414	170.3138	1.52	0.2359
Config*Subjects/Age*Gender	24	2696.6852	112.3619		
Color	**2**	**2093.7238**	**1046.8619**	**8.45**	**0.0031**
Age*Color	2	71.4090	35.7045	0.29	0.7534
Gender*Color	2	107.5602	53.7801	0.43	0.6552
Age*Gender*Color	2	77.5478	38.7739	0.31	0.7356
Color*Subjects/Age*Gender	16	1981.8333	123.8646		
Configuration*Color	6	188.7701	31.4617	0.68	0.6687
Configuration*Age*Color	6	217.0725	36.1788	0.78	0.5908
Configuration*Gender*Color	6	343.2052	57.2009	1.23	0.3073
Config*Age*Gender*Color	6	121.8966	20.3161	0.44	0.8503
Config*Color*Subj/Age*Gender	48	2230.4630	46.4680		
Total	143	35388.8395			

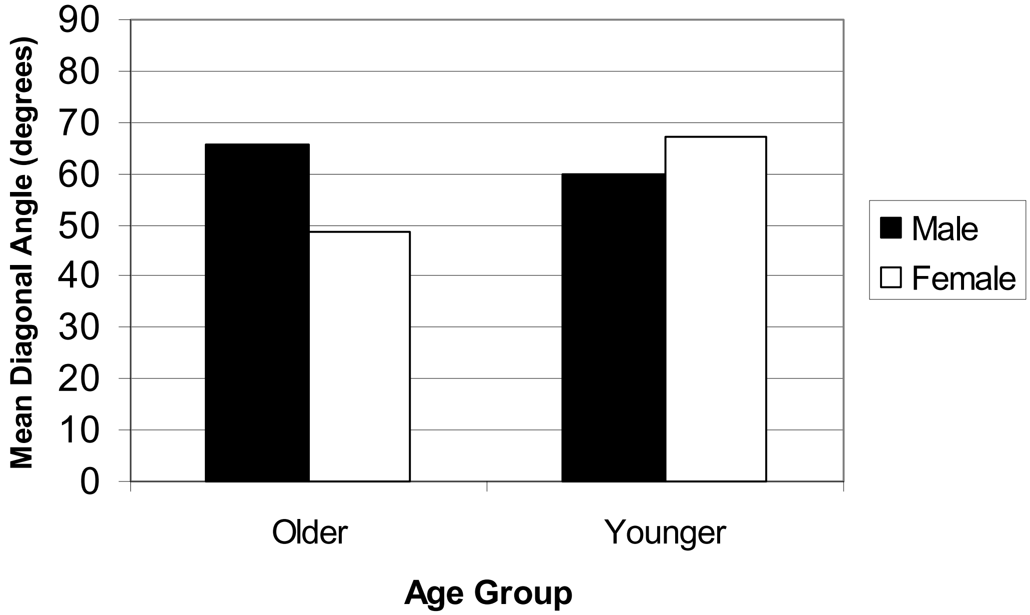


Figure F6. Significant two-way interaction of Age by Gender for Diagonal Angle.

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