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MOTOR VEHICLE REAR LIGHTING AND SIGNALING: EFFECTS OF SPACING, POSITION, INTENSITY, AND COLOR An Applied-Literature Review	January 1978
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16. Abstract

This review is designed to determine the current status of research dealing with spacing, position, intensity, and color of rear lighting and signaling lamps on motor vehicles. The relevant domestic as well as international applied research is included.

The review contains tabular summaries of the design, results, and recommendations of 36 experimental investigations as well as reprints of the original abstracts. Finally, a synthesis of the experimental findings is presented.

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INTRODUCTION

This literature review is designed to determine the current status of applied research dealing with spacing, position, intensity, and color of rear lighting and signaling lamps on motor vehicles. The review includes experimental investigations of <u>how</u> information about the intentions or actions of a driver should be displayed utilizing spacing, position, color, and intensity of rear lamps. Studies concerned with <u>what</u> information should be conveyed (e.g., Bolt, Beranek and Newman, 1968; Rockwell and Treitener, 1966; Voevodsky, 1974) address a different set of problems and thus were beyond the scope of this review. The present review covers applied research only--whether on the road or in a driving simulator. Purely basic research is not included.

The literature search revealed some limitations of existing research. First, in some studies several variables were manipulated in such a way that their effects were confounded. In order to systematically investigate effects of one parameter (e.g., color) on human performance, this parameter must be varied while other variables (e.g., intensity, spacing, position, size, mode of operation) are kept constant. In studies where effects of several variables are confounded no conclusions about the effect of any one variable could be safely made. Such studies evaluated not parameters but complete rear lighting systems (thus are valuable in their own right), and they were so identified in this review. Second, the tested range of a variable was frequently rather narrow or was defined by so few points (often two values only), as to make the identification of relationships difficult. Third, in several studies the dependent variable was not sufficiently clearly defined. As an example, "subjective effectiveness" is a rather vague expression by itself. Since subjective effectiveness has several possible meanings (e.g., brightness, visibility, conspicuity), different subjects are likely to respond to different aspects of "effectiveness," with a consequent undesirable increase in variance.

Within the limitations stated earlier, an effort was made to include all relevant work which is generally accessible. It should be noted that a given investigation might be included in this review without reviewing all of its experiments, since only those experiments dealing with spacing, position, intensity, and color are covered. Also, if the same set of data were encountered in several different reports, only one report is reviewed here.

TABULAR SUMMARIES

Each summary contains the following information:

Independent variable: The name of the variable (dimension, parameter) which was varied independently. (In the case of confounded independent variables the phrase "rear lighting systems" is entered and the confounded variables are listed in parenthesis. If, however, two or more systems differed on one variable only, an indented entry is made under "rear lighting systems.")

Range: Tested range of the independent variable.

Dependent variable(s): The way the effects of the independent variable were quantified.

Method: Main features of the experimental set-up.

Results: Numerical values are presented if 1) the original work does provide them and if 2) the results are not too complex for a summary statement.

Recommendations: Recommendations, if any, of the original author(s) which are relevant to the questions of optimal spacing, position, intensity, or color.

Abstract, summary, or conclusions: Reprint of either the abstract, summary, or conclusions, if the original work contained any.

Allen, M.J., Strickland, J., and Adams, A.J. Visibility of red, green, amber and white signal lights in a highway scene. <u>American Journal of Optometry</u>, 1967, <u>44</u>, 105-109.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color	Amber, green, red, white	Reaction time	Test light superimposed on a movie of highway traffic, time-sharing task	Given equal subjective brightness, no difference between colors	

Attwood, D.A. Automobile rear signal research I: Effects of signal colour and intensity, ambient illumination and driver age on laboratory performance. Technical Memo No. RSU 77/3, Transport Canada, 1977.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of a turn signal)	125, 200 cd	Reaction time to turn, stop, and turn & stop signals, errors	Simulated stationary vehicle, stationary subject, brake lights: 200 cd, run-night lights: 3-6 cd, two conditions of ambient information	No difference	
Color (of a turn signal)	Amber, red	Reaction time to turn, stop, and turn & stop signals, errors	Simulated stationary vehicle, stationary subject, brake lights: 200 cd, running lights: 3-6 cd, two conditions of ambient illumination	No difference	

ABSTRACT

The experiment investigated the ability of subjects to perceive automobile rear-signal information.

Thirty subjects, in two age groups, were instructed to respond as quickly and accurately as possible to different combinations of lights presented on the rear of a model automobile. The combinations simulated normal as well as malfunction signal conditions. Turn signals, which were either red or amber, were presented at one of two light intensities, each corresponding to intensities currently required on the road. Selected stimuli were viewed separately against two extreme conditions of ambient illumination. In addition, brake lights were alternately combined with low-intensity presence lights under one lens.

Results indicated that neither the colour nor the intensity of turn signals affected the performance of either group of subjects. The performance of the older subjects, though routinely worse than the younger group was never significantly so, owing to large inter-subject variability. Performance in the ambient illumination condition in which the light-to-background contrast was markedly reduced was significantly worse than performance in the high contrast condition.

Results are discussed in terms of the potential benefits of colour and intensity as redundant methods of coding information.

Automobile Manufacturers Association, Status report on the Vehicle Lighting Committee program to evaluate various rear lighting systems and signaling color, 1967.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, position)	8 systems	Subjective rating of signals	Stationary observer, stationary target vehicle, nighttime and daytime	The first choice among the systems consisted of horizontal array, two lights on each side where both are used as brake lights and one as a running light; both are used to indicate turns by flashing.	COLOR stop: red turn: amber tail: red INTENSITY (min/max) stop: 250/750 (day) 50/150 (night) turn: 300/900 (day) 60/180 (night) tail: 3/12
Color, intensity	Amber, red (intensity range unspecified)	Subjective judgments of acceptable minimum daytime and maximum nighttime intensity of stop lamp	Nighttime and daytime, range of viewing distances, presence or absence of a glare source	Complex	
Color	Amber, red, white	Necessary intensity for a given visibility distance	Bright sunlight	At 500 feet the candlepower requirements are 300 for white, 250 for amber and 175 for red; at 100 feet they are 350 for white and 300 for both amber and red.	
Intensity	Unspecified	Subjective judgments of acceptable minimum and maximum intensity for tail lights	Unspecified	The greatest number of observers preferred 7.5 cd and lower values as a maximum and 4 cd as a minimum.	

Automobile Manufacturers Association, 1967 (continued)

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color	Amber, green, red	Reaction time to turn, stop, and stop & turn signals	Moving observer, moving target vehicle, stationary observer, stationary target vehicle	Reaction time (sec.) Dyna-mic / Static 2GR: .90 .88 2RR: .98 .95 2AR: .89 .94 Also 2GR*: 1.01 .98 1RR: 1.10 1.04 (First number indicates single or separate housing; first letter indicates color of the taillight and the second letter color of the brake light.) *Green for taillight and intensified green for turn signal.	

Campbell, J.D., and Mortimer, R.G. The HSRI part-task driving simulator for research in vehicle rear lighting and related studies. HSRI, University of Michigan, Report No. UM-HSRI-HS-72-12, 1972.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, color)	5 systems	Reaction time to stop, turn, stop & turn, turn & stop signals, accelerator release and brake application frequencies	Driving simulator presentations	System with green taillights, amber turn signals, and red stop signals yielded shortest reaction time (mean difference between the best and the worst system: .28 sec.) and most frequent accelerator releases. Brake application frequencies were the same for all systems.	Color coding and functional separation
Color (of the turn/presence lamp)	Green, red	Reaction time to stop, turn, stop & turn, turn & stop signals	2 lamp system, brake lamp always red, driving simulator presentations	Shorter reaction time with green turn/presence lamps	
Color (of the turn/presence lamp)	Green, red	Accelerator release and brake application frequencies	2 lamp system, brake lamp always red, driving simulator presentations	No difference	

ABSTRACT

This report describes the design, performance, and operation of a driving simulator for use in vehicle rear lighting and related studies. The results of two simulator validation studies are also described.

The purpose of the simulation was to represent a straight, two-lane road with a lead vehicle in the lane being driven. The test subject has accelerator and brake controls only, steering not being provided. Car-following tasks or overtaking without passing can be simulated, in day or night driving conditions. Approximations to rear vehicle acceleration and braking dynamics are used. Scaling and control of lamp intensity and color is achieved, with flexibility in varying rear lighting system display and operational characteristics. Lead car speed and signaling can be controlled manually or by magnetic tape records. The latter reproduces the speed-time history and signal actuations from a real vehicle under the highway and traffic conditions existing when the recordings were made. A digital computer interface provides system control, storage of rear lighting systems, and real time data acquisition and analysis.

Case, H.W., Hulbert, S.F., Patterson, O.E., Emori, R.I., English, J.M., Lyman, J.M., O'Brien, P., and Wojcik, C. Development and evaluation of vehicle rear lighting systems. ITTE, University of California, Los Angeles, Report No. 68-24, 1968.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (color, location, number of lamps, functional separation, shape)	3 systems	Reaction time of vehicle control movements	Driving simulator, nighttime with fog	Fastest reaction time to a complex system having (besides other features) green running light	Color coding, brake light of a different color from the directional and running lights (red recommended for brake light)

SUMMARY

Determination of Approach

When the Institute of Transportation and Traffic Engineering first addressed itself to the problem of vehicle rear lighting, certain preliminary observations were made. Rear lighting was recognized as encompassing a great many interacting variables and far from being a separate component of the vehicle. It was, in fact, an integral part of the overall problem of vehicle lighting and driver communication. It was a subsystem of a master system, and should be approached as such.

On the basis of these observations, it was concluded that vehicle rear lighting criteria could best be developed by utilizing systems engineering techniques. It was determined that the development and evaluation of rear lighting systems was not a quick task that could make use of "off-the-shelf" know-how and experience. Rather, it would call for innovative simulation and data-collection techniques along with painstaking development of system requirements.

It was also determined that full consideration must be given to human factors (since it was a man-machine communication system under study), and a research methodology oriented to human response and specifically geared to vehicle rear lighting must be developed if valid evidence was to be obtained. The special-purpose methodology should include, (a) a technique for developing system requirements, (b) a means of displaying alternative taillight configurations in the Driving Simulation Laboratory, (c) an instrumented vehicle system for field experimentation, (d) the backup of existing research facilities within ITTE.

Objectives Defined

The primary end product (goal) of Phase I, therefore, was considered to be a developed and validated special-purpose research methodology geared specifically to vehicle rear lighting investigations, which could be used to generate valid evidence in Phase II of the project.

The objectives of Phase I (as described in the proposal and the contract) were considered to be the means of achieving this higher-level goal. And, while it would be hoped that certain recommendations for rear lighting configurations would result from the Phase I effort, it was agreed that the most important use of the data collected would be to validate the effectiveness of the methodology.

Professional-Technical Relationship

The study was structured to proceed along two parallel avenues: professional (academic), and technical. These two aspects were closely related, having common objectives. All technical decisions reflected the involvement and planning of professional (academic) staff members.

Case et al., 1968 (continued)

Nature of Results

An analytical technique for developing vehicle rear lighting system requirements was formulated. The technique was utilized to generate preliminary performance requirements and to translate them into alternative design approaches. Two candidate rear lighting configurations were then designed and fabricated as scale models.

A method of superimposing programmed images of candidate rear lighting configurations onto motion picture highway scenes in the Driving Simulation Laboratory was developed and evaluated.

Preliminary evaluation of the two candidate configurations was conducted, utilizing the newly developed superimposition technique to present moving vehicle situations to drivers and compare their responses to a "normal" taillight configuration.

An instrumented vehicle system for field experimentation was designed, components acquired and/or fabricated, and assembly of the system conducted.

A literature search was conducted, and a bibliography containing over five hundred entries was compiled. To facilitate utilization, the entries were also divided according to subject matter and according to author.

A photometric investigation was also conducted.

Case, H.W., Hulbert, S.F., Lyman, J.H., O'Brien, P., and Patterson, O.E. Selection of vehicle rear lighting systems. ITTE, University of California, Los Angeles, Report No. 70-9, 1969.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, redundancy of mode, position)	4 systems	Identification of intended message	Pictures of rear lighting systems were flashed on screen to simulate unexpected sudden appearance of another vehicle, stationary observer	A gain of 30% of correct responses by the proposed configurations over a conventional system with the intensity ratio of 1.5:1 between brake signal and running signal; no improvement over a conventional system with the ratio of 2.9:1.	
Rear lighting systems (number of lamps, color, position, functional separation)	8 systems	Identification of intended message	Colored cardboard squares were placed on a white background to represent each configuration, stationary observer	As the separation of function is increased, the percent of messages transmitted correctly is also increased. The Lazy T configuration, for example, made greatest use of separation of functions and scored a 75% gain in message accuracy over the conventional configuration.	
Color (of running lights)	Green, red	Reaction time of vehicle control movements	Film of traffic scenes, stationary observer	No difference	

Committee on Motor Vehicle (Exterior) Lighting of the Illuminating Engineering Society. Lighting study project report on motor vehicle (exterior) lighting. Illuminating Engineering, 1964, 59, 660-662.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color	Red, white, yellow	Candlepower for equal effectiveness	Unspecified	Red: yellow: white = 1:3:5	Turn signals should be yellow

Cook, K.G. Day and night intensities of rear signal system lights. Contract No.: FH-11-6602, Century Research Corp., 1969.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of a glare source)	0, 60, 300, 900 cd	Contrast threshold of a target	Stationary observer, stationary glare source vehicle, static target, nighttime	Increase of target contrast threshold with increase in glare source intensity	Recommended candlepower: Brake and turn = 100 min, 300 max; tail = 10 min, 30 max. Restriction of the use of specularly reflecting surfaces in the immediate surround of the light.
Intensity	2-1,000 cd	Detection of flashing signal light	Stationary observer, stationary target, daytime	Mean intensity threshold = 13-20 cd depending on the background	
Intensity	Unspecified	Detection of flashing signal light	Stationary observer, stationary target, daytime, with and without simulated sun reflection	Range of intensity thresholds: 7.5-17.1 cd (without sun reflection), 200-415 cd (with sun reflection)	

ABSTRACT

Field experiments were conducted to determine the disability glare produced by rear signal system lights at night, the daytime visibility of lights, and the degradation of daytime visibility caused by specularly reflecting surfaces near the lights.

A maximum intensity of 300 candelas of red light is indicated by results of the night tests. Daytime tests strongly indicate that specularly reflecting surfaces should be prohibited in the immeditae surround of signal lights.

Integration of the test results, literature, data on atmospheric effects, and current standards suggests that taillight intensities should be no less than 10 candelas and no more than 30 candelas; brake and turn signals should be 100 to 300 candelas. These suggestions assume that no specularly reflecting surfaces are permitted in the immediate surround of light.

Crosley, J.K. Automobile rear signal lights: An evaluation of high placement, accelerator switching and driver responses. Indiana University, 1966.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Position (vertical) of brake lights	Normal, roof-line height	Reaction time	Moving observer, moving target vehicle, daytime and nighttime	Shorter reaction time for the high location (.5-1. sec. difference)	The present rear system should be augmented with a high-placed system indicating accelerator release and brake application and a separate running lamp indicating the vehicle is in motion. Green for running light, amber for acceleration release, and red for brake application.

SUMMARY AND CONCLUSIONS

Rear-end collisions are the most frequent highway accident. Information available to a following driver is limited with present vehicular rear signal systems. Taillights and reflectors should enable the following driver to detect the presence and location of a vehicle day or night. Rear lighting should also be a means of communicating what the driver of the lead vehicle is doing or plans to do.

Present systems are incapable of transmitting sufficient information, especially from other than the immediately preceding vehicle. Experienced drivers attempt to overcome this deficiency in several ways. At night, a diffuse glow of red more than one car ahead can be a cue for judgment. In the daytime, reduced contrast eliminates this cue and the following driver only sees it by dangerously swinging to one side of the lane to peer ahead.

Noting the rear of a preceding vehicle suddenly rise upward can be a cue that the brakes have been applied.

Other cues that a vehicle several cars ahead is slowing might be an increase in visual angle, narrowing of apparent distance separation between two preceding vehicles, the presence of slow, puffy exhaust fumes indicating the release of the accelerator, or the dip of headlights at night. These cues, are not felt to provide sufficient information for high-speed, expressway-type driving.

A study involving 4 automobiles with normal plus high-placed signal lights has shown that in a grouped situation, following driver reaction time to an activated rear signal can be significantly reduced. This reduction at high speeds may be sufficient to avoid or attenuate a rear-end collision.

Following drivers have been found to react less frequently to a brake light than previously supposed. Further research is necessary to fully understand this observation.

The present rear signal system is insufficient for modern high speed, high volume traffic. It is suggested that it be augmented with a high-placed system indicating accelerator release, and brake application. It is further suggested that there be a separate running lamp indicating the vehicle is in motion. The colors which appear most acceptable are green for running light, amber for accelerator release, and red for brake application. The signal colors and placement should be standardized for the entire automobile industry.

Crosley, J.K., and Allen, M.J. Auxiliary lighting to improve rear visibility of trucks and buses. American Journal of Optometry, 1967, 44, 311-315.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Spacing (horizontal separation of tail-lights)	3-8'	Distance at which the target appeared to be stopped	Moving observer, stationary target: plywood panel simulating a truck rear-end, with and without flood lights	With separation of 3' the distance was 279' (638' with flood lights); with separation of 8' the distance was 447' (638' with flood lights)	Entire rear of trucks and buses be lighted

SUMMARY

A literature review shows that present vehicular lighting practices are hazardous. Space perception criteria indicate that present designs dictate a high accident and fatality rate.

Flood-type auxiliary lighting of the rear of a truck was judged to be easier to localize than ordinary taillighting.

Observations were made on a simulated truck rear-end with and without floodlighting at closing speeds of 20 m.p.h. The floodlighted "truck" was judged correctly to be stopped when the observer was an average of 638 feet away, compared to an average of 279 feet when normally spaced taillights alone were used.

It is recommended that the entire rear of trucks and buses be lighted, thus improving the distance and differential speed judgments by a following driver.

Domas, P.A. A subjective evaluation of turn signal effectiveness. In P.L. Olson, C.M. Jorgenson, J.K. Thomas, P.A. Domas, Factors influencing the effectiveness of automotive rear lighting systems. HSRI, University of Michigan, Report No. UM-HSRI-HF-75-4, 1975.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of a turn signal in a single two-filament lamp)	80, 120, 200 cd	Subjective evaluation of effectiveness defined as "attention getting	Stationary observer, stationary target lights	Increase in effectiveness with increase in intensity	

ABSTRACT

This paper is a subjective assessment of the effectiveness of flashing signals which go from signal intensity to off rather than from signal intensity to presence intensity. The results indicate that the former configuration would be undesirable first, because there appears to be little benefit in increased signal effectiveness by such an arrangement, second, in the event that the signal filament is burned out, one side of the car would be unmarked when the turn signals are used.

Fiat (Centro Ricerche). Evaluation of some visual signaling systems for vehicle state of motion. Turin, Italy, Report No. C.E. 1555, 1976.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (color, intensity, steady/flashing mode, size, number of lamps, position)	5 systems	Subjective evaluation of "luminous effective-ness," "conveyance effective-ness," and "transmitted information effective-ness"	Moving target vehicles, moving obser-vers	Best system: normal vehicle lighting with two additional lamps, one for indi-cating hard braking (red flashing lamp) and one for indi-cating traveling above a given speed (steady green lamp)	Color: not too reliable. Loca-tion: a valid means of differ-entiation. Intensity: not appreciable if there is not a reference inten-sity.

SUMMARY

A description is given of some rear luminous car signal systems set up and tested by FIAT. The various systems differed with regard to:

- the type of information to be transmitted to the driver of a following vehicle (speed, acceleration, deceleration, etc.);
- the information code used (i.e., the meaning to be attributed to the luminous patterns provided);
- the luminous signalling elements used to transmit the information (different coloured lights, different candle power, flashing lights, lamp size and geometric arrangement, etc.).

The tests consisted in operating a large number of cars for each system so as to simulate actual traffic conditions and in collecting information on luminous device conspicuousness, appreciablility of the information transmitted and its usefulness for safety.

The experimental data collected were then analyzed and the requirements to be met for an efficient signalling system defined. For application purposes the present "STOP" system was then considered critically and the possibility was investigated of a more definite and sound approach to the problem of a more efficient safety-related luminous signal system.

Forbes, L.M. The brightness of signal lights. Ford Motor Company, Report No. S-66-24, 1966.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Size (area)	3-80 sq. in.	Luminance level for discomfort glare	Nighttime, otherwise unspecified	With increasing size, discomfort glare occurs at progressively lower levels of luminance. In general, the relation is expressed by equation $S = \frac{1}{2\pi} \cdot \theta^{-0.6}$ where S is the maximum comfortable density in cd/ft^2 and θ is the angular size of the lamp in steradians (measured from the observation point).	
Luminance	0.72-513 cd/ft^2	Probability of identifying correctly the luminance level presented (out of a set of 5 luminance levels)	Nighttime, otherwise unspecified	Probability of confusion of two red signals is 0.33 if the ratio of their luminance is 1:5; .06 if the ratio is 1:22.	

CONCLUSIONS

Basic visual facts and the results of some small-scale laboratory experiments were gathered to provide a "state-of-the art" summary of principles that underlie the design of signal lights. Use of these results should reduce the amount of field testing.

Curves are presented which show how much the apparent candlepower of a signal light must be changed for different lens sizes, to maintain a given level of being objectionably "too bright" for viewing distances of 25 to 800 feet. For example, although a 6-inch diameter lens has an area 4 times greater than one of 3 inches, it may have an apparent candlepower no more than 50% greater than the 3-inch lens, for the same amount of glare.

Any light which is bright enough to be definitely visible in strong sunlight will be too bright in dark at viewing distances less than about 100 feet. The margin between adequate daytime visibility and night-time glare is worse for larger lens areas, best for the smallest lenses.

Human sensitivity to light is not directly proportional to candlepower, but increases only as the cube root of intensity (for a given size); light power must be increased about 10 times to seem twice as brilliant subjectively. It takes as much as 20 times more brightness for the driver to know for sure that he is looking at a stop light rather than a taillight when he did not witness the transition.

The SAE recommendations in J575 are based on apparent candlepower rather than brightness. Apparent candlepower is a suitable measure for illuminants, such as headlights; photometric brightness is the proper measure for signal lights. And even that is inadequate because it does not sufficiently relate to human sensitivity. Suggestions are contained for revision of the SAE recommendations.

Hitzemeyer, E.G., Wilde, H., Ellenberger, D. What color should rear turn signals be? Volkswagenwerk AG, Wolfsburg (Germany)/Volkswagen of America Inc., Englewood Cliffs, N.J. Society of Automotive Engineers, Passenger car meeting, Detroit, MI, 1977, Report No: SAE 770812.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Color (of turn signal)	Red, yellow	Subjective effectiveness ratings based on past experience	Not a controlled experiment but a survey of American soldiers and their families stationed in Europe; a questionnaire dealing with turn signal effectiveness in daytime as well as night-time driving	Yellow judged more effective than red	Yellow is the superior color for rear turn signal lamps if of correct brightness

ABSTRACT

Once optional, flashing turn signals have become standard equipment on motor vehicles around the world. However, distinctness of rear turn signals is often lost when combined in the same compartments with stop lamps of the same size, intensity, color and location. In the U.S., a proposed solution is physically separating the function, while other countries effect separation by color. The SAE is investigating more realistic red/yellow lamp outputs that would permit use of universal lamps, while in Germany, manufacturers have surveyed many experienced American and Canadian drivers to determine preference for the color of these lamps.

Kilgour, T.R. Some results of cooperative vehicle lighting research. Highway Research Board Bulletin 255: Night visibility 1960, Highway Research Board, Washington, D.C., 1960, pp. 92-100.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color	Amber, red, white	Specified only as "equal effectiveness"	Stationary observer, stationary target display, daytime	Intensity ratio of 1:3:5 for "equal effectiveness" of red, amber, and white signals	

Lindae, G. Uber die Sichtbarkeit von Fahrzeugleuchten im Nebel und die Dimensionierung einer geeigneten Nebelwarnleuchte. [The visibility of vehicle lights in fog and optimal dimensions of fog warning light.] Bosch Technische Berichte 1, Heft 2, 1965.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of a tail lamp)	2.5, 25, 250 cd	Visibility distance	Two levels of fog density, background luminance = 700 cd/m^2, size = 78 cm	Higher intensity yielded longer visibility distance.	Intensity = 250 cd (higher intensity would result in discomfort glare)

ABSTRACT

[Experiments with lights have shown that visibility distance of lights can be approximately doubled if the light intensity is increased 100 fold. Another increase in visibility distance could be achieved through higher luminance, although only up to a level where no disturbance due to glare is present in a fog-free atmosphere and not too high temperatures develop. The optimal light would have a surface of 15 cm^2 and intensity of 250 cd.]

Moore, R.L. Rear lights of motor vehicles and pedal cycles. Road Research Laboratory, Technical Paper No. 25, London: HMSO, 1952.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Intensity	Up to 1 cd	Visibility distances for judgments of a. just visible b. just unmistakable as a red light c. just obvious d. just brilliant	Nighttime, with or without a glare source, moving observer, stationary target vehicle	Increase of visibility distances with increase in intensity	The rear light must have an intensity of over .25 cd to be seen plainly at 400 feet.
Position (vertical)	± 1 ft. from a comparison light which was placed at a height of 3 ft.	Distance estimation	Stationary observer, stationary target lights	High mounted lights appear further away	Mounting height and intensity should be standardized.
Intensity	5x, 1x, $\frac{x}{10}$, where x is the intensity of a comparison light	Distance estimation	Stationary observer, stationary target lights	Brighter lights appear nearer	

SUMMARY

The Road Research Laboratory has recently investigated the adequacy of rear lights on motor vehicles and pedal cycles. The research was of two kinds, a statistical examination of reported front/rear collisions at night and a study of the visibility of rear lights of various intensities. Both investigations led to the same conclusion, that the majority of vehicle rear lights on the road today are inadequate.

Part of the accident analysis consisted of a comparison between the records of accidents at night to pre-war cars and post-war cars; the latter are fitted with greatly improved rear lighting. The results showed that a pre-war car, when stationary on the road at night, is about six times as likely as a post-war car to be hit in the rear by a following vehicle. Rear lights of commercial vehicles have not been improved to anything like the same extent as those of private cars and the records showed little difference between risks of front/rear accidents for pre-war and for post-war commercial vehicles.

The analysis showed that inadequate rear lights caused about 3400 casualties per year (about 9 per cent of all night casulties); the resulting monetary cost to the community is estimated to be about £2 000 000 per annum.

The effects of condensation on the windscreen and glare from opposing headlamps on the visibility distance of a rear light were studied and it was concluded that glare from opposing headlamps is probably the most important single factor reducing rear-light visibility. Taking a bad (but not the worst) case, viz., a rear light a few feet from the dipped headlamp of a car, it was found that the rear light must have an intensity of over 0.25 candela to be seen plainly at 400 ft. A survey of the intensity of the rear lights of vehicles on the road showed that three-quarters of private cars, commercial vehicles, public service vehicles and motor cycles, and 98 per cent of cycles, had rear lights less bright than this; 80 per cent of cycles and 60 per cent of commercial vehicles had rear lights of less than one-tenth of this brightness.

The judgment of the distance of a rear light was found to be greatly affected by the intensity and mounting height of the light. Bright lights appear near: high-mounted lights appear further away. It is concluded that the distances of rear lights could be more easily judged if they had a standard intensity and were mounted at a standard height. Further improvement would result if the two rear lights were placed a standard distance apart of 2 or more feet.

Reliability tests were also made on popular makes of cycle rear lamps. The lamps tested had a high failure rate, for battery lamps 35 per 1 000 night journeys; 75 per cent of the failures were due to bulb failure or running down of the battery, the remaining defects being chiefly faulty contacts and mechanical failure due to corrosion. The unreliability of rear lights may be the chief reason why cyclists so often fail to observer rear-light regulations.

Even a poor rear light was found to be more readily visible than either a reflector or a white mudguard; a white mudguard together with a reflector was better than either separately.

Moore, R.L., Crawford, A., and Odescalchi, P. Turn signals for motor vehicles. Highway Research Board Bulletin, No. 172, 1958, pp. 104-120.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Spacing (vertical separation of turn signals lamps from stop lamps)	3½, 9, 18"	Reaction time to turn signals	Stationary observer, stationary target vehicle, time sharing task, daytime and nighttime	Shortest reaction time for the highest-mounted turn signals (3½' = 1.31 seconds, 18' = 1.17 seconds)	Turn signals should be mounted on the sides of a vehicle roughly at the level of the driver's eyes.

ABSTRACT

An analysis of accidents in Great Britain has shown that it is important that direction signals on motor vehicles should be readily seen from the front and side as well as from the rear, particularly by cyclists and motorcyclists. In the light of this information the relative merits of present-day examples of semaphore-arm and flashing turn signals for use on cars have been compared.

It is concluded, over the wide variety of conditions tested, that a side-mounted amber flashing indicator (the "amber ear") is the most effective indicator. A rear indicator was found to become less effective the nearer it was to the stop light. There seem to be advantages in mounting signals at drivers' eye-level, and amber colored signals appear better than red or white ones.

The side-mounted indicator is likely to be of help to cyclists and motorcyclists, who are the chief victims of serious and fatal turning-car accidents at road intersections in Great Britain.

The importance of standardization in the choice of direction signals is stressed and recommendations are made regarding the choice.

Moore, R.L., and Smith, H.P.R. Visibility from the driver's seat: The conspicuity of vehicles, lights and signals. In Ergonomics and Safety in Motor Car Design, Institution of Mechanical Engineers, London, 1966.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity	2-1,000 cd	Visibility distance	Daytime, fog, otherwise unspecified	Visibility distance increases with increase in intensity (2 cd:110 ft.; 1,000 cd:290 ft.)	The conspicuity of vehicles in fog would be greatly improved with running lights of intensity in the 1,000 cd range. However, the lights would have to be switched off when the vehicle comes out of the fog to prevent dazzling following drivers.

ABSTRACT

The importance of good visibility of the road scene is discussed in relation to (a) visibility from the driver's seat, and (b) how clearly vehicles, rear lights, and signalling lights can be seen. Suggestions are made for additional arrangements of lights to assist in fog and in following in queue conditions. Methods by which direction indicator lamps could be made more efficient are noted.

It is concluded that, in the design of a vehicle, there is a need to study the conflicts that arise between good visibility and other safety factors.

Mortimer, R.G. Dynamic evaluation of automobile rear lighting configurations. HSRI, University of Michigan, Report No. HuF-1, 1968.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, color)	8 systems	Reaction time to stop, turn, turn & stop, stop & turn signals	Moving observers, moving target vehicle, nighttime, time sharing task	System with green taillights, amber turn signals yielded shortest reaction time (mean differences between the "best" and the "worst" system .25-.45 sec.).	Best rear lighting system employs both full functional separation and color coding.
Separation of lamps by function	1, 2, 3 set of lamps	Reaction time to stop, turn, turn & stop, stop & turn signals	Moving observers, moving target vehicle, nighttime, time sharing task	Systems where taillights, turn signals, and stop signals were represented by separate lamps yielded shortest reaction times.	
Separation of lamps by color	Amber, green, red	Reaction time to stop, turn, turn & stop, stop & turn signals	Moving observers, moving target vehicle, nighttime, time sharing task	Systems where taillights, turn signals and stop signals were represented by different colors yielded shortest reaction time.	

ABSTRACT

The purpose of this study was the evaluation of present and proposed means of coding automobile rear lighting systems. Variables considered in the study were: number of lamps, separation of lamps by function, and color. Also investigated were intensity and flash rate codes currently in use.

Testing was done at night with two specially equipped test vehicles. They were driven both on city streets and on a divided highway to provide "city" and "country" conditions. The lead car, equipped with eight rear lighting systems, displayed the test systems, one at a time, to two subjects in a following car. The test subjects (the driver and passenger) in the second vehicle performed a time-sharing task which required that they respond to turn and stop signals given by the lead car. Their reaction times, the number of missed signals, and subjective ratings were used to evaluate system performance. A total of 66 male and female subjects were used.

Results of the study indicate that the rear lighting system concept presently in use provided the poorest performance of all systems tested. Experimental systems show that the arousal property of signals is directly proportional to the number of lamps used. Separation of lamps by function and color coding of signals were also shown to be factors significantly affecting system performance.

The most effective systems were those in which taillights, turn signals, and stop signals were represented by separate lamps. The findings indicate that the light coding techniques represented by the experimental systems (and not currently employed in rear lighting systems) can lead to significant gains in driver performance.

Mortimer, R.G. Research in automotive rear lighting and signaling systems. G.M. Engineering Publication 3303, 1969.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (color, same or separate housings for turn/stop)	Amber, green-blue, red	Reaction time to stop, turn, and turn & stop signals	Stationary observer, stationary target vehicle, nighttime, time sharing task	Shortest reaction time for a system having green-blue for presence and red for stop & turn in two separate housings.	Signaling configuration using green-blue taillights with red stop-turn separated from the taillights is the most effective system. In a single color system the lamps should be separated a minimum distance of 6 inches edge-to-edge to be identified as separate lights at 400 feet.
Color	Amber, green-blue, red	Reaction time to flashing turn signals	Stationary observer, stationary target vehicle, daytime, time sharing task, luminance = 800 ft-L.	Reaction time in seconds: (normals/dichromats): Red: 1.1/1.48 Green-blue: 1.35/2.23 Amber: 1.36/1.78	
Color	Amber, green-blue, red	Recognition distance	Moving observer, stationary target vehicle, glare, luminance = 26 ft-L.	Recognition distance in feet (normals/dichromats): Red: 3000/1570 Green-blue: 2720/1420 Amber: 2500/1270	
Color	Green-blue, red	Candlepower for equal brightness with white	Fog, nighttime, stationary observer, stationary targets	Red of equal candlepower appeared brighter than green-blue.	
Spacing (horizontal separation between tail and signal lamps)	4, 6, 8" (edge to edge)	Perception of one or two lights	Nighttime, otherwise unspecified	Best performance with widest separation; at 400' a separation of 6 inches required to assure 90% probability that the lamps were seen as non-overlapping	

ABSTRACT

As part of a program of research in vehicle lighting and signaling systems, experiments were conducted to determine the detectability of various stop and turn signals. The applicability of the following coding dimensions was explored: (1) intensity, (2) flash, (3) number, (4) color. The conditions investigated were clear nighttime, simulated nighttime country and city driving, bright sunlight and simulated water fog. Color-blind subjects were included in some of the tests.

Mortimer, 1969 (continued)

In the evaluation of eight rear signaling systems, using a time-shared task to measure reaction time to stop and turn signals, the detectability of the signals of several experimental systems was found to be better (shorter recognition time) than that of the current system. Improvements resulted from the separation of the stop-turn lights from the taillights. The recognition distance for red taillights was greater than for either green-blue or amber with and without glare. A slightly higher intensity is required for green-blue for equal recognition with red in fog, but intensity had a much greater effect than color. Red was found to be more effective as a signal than either amber or green-blue in bright sunlight.

The rear lighting and signaling configuration using green-blue taillights with red stop-turn lights separated from the taillights was found to have the shortest detection time and might therefore be considered the most effective system. However, some improvement in detection time was also observed with the all-red system in which the taillights are separated from the stop-turn lights as compared to the present system.

No real driving circumstances were included in the research work nor were any considerations made regarding compatibility with existing systems.

Mortimer, R.G. Automotive rear lighting and signaling research. HSRI, University of Michigan, Report No. HuF-5, 1970.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, color, intensity)	5 systems	Reaction time to turn, stop, turn & stop, and stop & turn signals	Moving observer, moving target vehicle, nighttime	System with green-blue taillights, amber turn signals and red stop signals yielded shortest reaction time	Separation of lamps by function and color. Presence lamps should be green-blue, turn lamps amber, and stop lamps red.
Color (of the turn/presence lamp)	Green-blue, red	Reaction time to turn, stop, turn & stop, and stop & turn signals	Moving observer, moving target vehicle, nighttime	Shorter reaction time with green turn/presence lamp	
Intensity (of the turn signal)	35, 91 cd	Reaction time to turn, stop, turn & stop, and stop & turn signals	2 lamp system, turn/presence ratio: 13:1, moving observer, moving target vehicle, nighttime	The high signal intensity resulted in shorter reaction time than the low signal intensity.	
Color	Amber, green-blue, red, white	Intensity resulting in "adequate brightness for a stop signal	Stationary observer, stationary targets, bright daytime	Intensity ratios: Green:Red:Amber: White = 0.96:1:2.68:5.61 (color normals) 0.73:1:2.48:4.94 (color blinds)	Two intensity system, specific recommendation regarding daytime and nighttime minimum and maximum intensity values as a function of the lamp area.
Color	Amber, green-blue, red, white	Intensity resulting in uncomfortable brightness	Stationary observer, stationary targets, nighttime	Intensity Ratios: Green:Red:Amber: White = 0.64:1:1.78:2.55 (color normals) 0.42:1:.65:1.17 (color blind)	

Mortimer, 1970 (continued)

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Spacing (vertical or horizontal separation)	3.25, 6"	Displacement threshold; subjective evaluation of effectiveness in giving headway change information	Nighttime simulation, stationary observer, moving target	Wider separations resulted in lower displacement thresholds and higher subjective effectiveness. Vertical separations resulted in lower displacement thresholds and higher subjective effectiveness.	Minimum separation, measured edge-to-edge, should be 5 inches between stop and presence lamps and 3.5 inches between turn signal and presence lamps or turn signal and stop lamps.
Rear lighting systems (presence light arrays with varying size, color, spacing, location, number of lamps)	6 studies, several systems each	Displacement threshold; subjective evaluation of effectiveness in giving headway change information	Nighttime simulation, stationary observer, moving target	Complex	
Rear lighting systems (presence light arrays with varying number of lamps, location)	4 systems	Displacement threshold; subjective evaluation of effectiveness in giving headway change information	Moving observer, moving target vehicle	Four-lamp array resulted in the lowest displacement threshold and the highest subjective effectiveness.	

ABSTRACT

A review of previous NHSB vehicle rear lighting studies was carried out, and a research program was planned. Experiments were conducted in the laboratory, by simulation, by outdoor static tests, and in dynamic studies on public highways. Experiments concerned with the coding of signal lights showed that separation of lamps by function and color were effective techniques. It was recommended that presence lamps should be green-blue, turn lamps amber, and stop lamps red. An analytical car-following simulation showed that use of such a system should reduce rear-end collisions. There was a negligible effect upon response to rear signals of low doses of alcohol. It was found that rear turn signals should be augmented by forward mounted, amber repeater signals. Improvements in driver sensitivity to closure with another vehicle at night were obtained in simulation and field studies by an array of four presence lamps, two mounted high and two conventionally. Signals should not be given on each release of the accelerator nor can such signals reliably predict subsequent application of the brakes. Intensities needed for side turn signals, rear turn and stop signals were experimentally derived. Night intensity should be lower than day intensity. An intensity override switch should be provided to allow day signal intensities to be obtained to poor atmospheric conditions, and to raise presence light intensity to night signal levels.

Mortimer, R.G., Hoffman, E.R., Poskocil, A., Jorgeson, C.M., Olson, P.L., and Moore, C.D. Studies of automobile and truck rear lighting and signaling systems. HSRI, The University of Michigan, Report No. UM-HSRI-HF-74-25, 1974.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, color, functional separation, spacing, position)	24 systems	Identification of the meaning of the signal	Film segments of simulated car and truck rear lighting systems, nighttime simulation	For most of the lighting systems tested, subjects could reliably interpret unique signals after brief training.	Novel signaling displays can be expected to be readily identified by drivers with little introductory training needed.

ABSTRACT

This report consists of 4 studies related to vehicle rear lighting problems:

Accident Data Analysis
Interpretation of Signals [abstract below]
Responses of Naive Drivers to Presence and Stop Signals of Experimental Rear Lighting Configurations
Perception of Relative Velocity

INTERPRETATION OF SIGNALS

This was a laboratory investigation, the purpose of which was to determine whether naïve drivers could reliably interpret the meaning of unique signals as presented by various truck and automotive rear lighting systems.

The results indicate that, for most of the lighting systems tested, subjects could reliably interpret unique signals after brief trianing. Such errors as were made were not likely to increase risk.

Mortimer, R.G., Moore, C.D., Jr., Jorgeson, C.M., and Thomas, J.K. Passenger car and truck signaling and marking research: I. Regulations, intensity requirements and color filter characteristics. HSRI, University of Michigan, Report No. UM-HSRI-HF-73-18, 1973.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, color, intensity, spacing)	28 systems	Percent of signals identified correctly (turn, stop, turn & stop), subjective brightness, subjective effectiveness, daytime, nighttime	Stationary observer, stationary targets, daytime	Complex	Detailed intensity recommendations for various systems, e.g., for a 3 lamp system (presence-green, stop-red, turn-amber) the recommended candela values are as follows: Night (min/max) / Day (min) Presence 4/15 Stop 80/190 300 Turn 80/320 425
Color (of the turn signals; stop signal always red), spacing (vertical separation of turn and brake lights), intensity	Amber, red 2, 8" (edge to edge) 80, 185, 425, 1000 cd	Percent of signals identified correctly (turn, stop, turn & stop)	Stationary observer, stationary targets, daytime	Worse identification with amber turn signals; worse identification with 2" separation; amber signals needed higher intensity to reach a given level of performance	

Mortimer et al., 1973 (continued)

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color (of the turn signal; stop signal always red), spacing (vertical separation of turn and brake lights)	Amber, red 2, 8" (edge to edge)	Subjective ratings of effectiveness	Stationary observer, stationary targets, daytime	The system with red turn signal was judged more effective than the system with yellow turn signal; systems with wider separation were judged more effective (but not significantly so).	
Color (of the turn signal; stop signal always red), spacing (vertical separation of turn and brake lights), intensity	Amber, red 2, 8" (edge to edge) 80, 185, 425, 1000 cd	Subjective brightness rating (inadequate, excessive)	Stationary observer, stationary targets, daytime	Red turn signals required lower intensities for equivalent ratings than did amber turn signals; separation generally had no effect on ratings.	

Mortimer et al., 1973 (continued)

ABSTRACT

This report describes some of the studies conducted in a program of research in automobile and truck marking and signaling. A detailed summary of current U.S. vehicle marking and signaling lighting standards was prepared, and compared with the main features of foreign vehicle marking and signaling standards. These reviews suggested a number of topics that warrant further consideration such as area-intensity relationships of stop and turn lamps, the hazard warning (four-way flashing) signal being rendered inoperative if the brake pedal is depressed, reduced photometric and location requirements of rear turn signals on tractors, tractor clearance lamps indicating cab width rather than the width of the vehicle, the adoption of side turn signal lamps, white for front parking lamps, use of yellow for rear turn signal lamps, etc.

A review of the effectiveness of separation of rear marking and signal lamps by their functions, supports this general concept.

As a preliminary to studies to determine the intensity requirements of signal lamps, an analysis showed that signals should become identifiable at distances up to 2000 feet. The findings of the study of signal intensity requirements showed that these are affected by the system's configuration. Conflicts between the intensities needed for adequate identification of a signal and those causing discomfort glare can be resolved with dual-intensity lamps for systems using separation of function. Flashing lamps caused less discomfort glare than steady-buring lamps of the same intensity. Recommendations for the intensities of lamps of rear signal systems were made.

The final study in this report was a laboratory evalution of color discrimination and identification by normal and dichromatic observers, on the basis of which preliminary recommendations for chromaticity coordinates of red, yellow and green-blue lamp filters were derived.

Mortimer, R.G., and Sturgis, S.P. Evaluations of automobile rear lighting and signaling systems in driving simulator and road tests. HSRI, University of Michigan, Report No. UM-HSRI-HF-74-24, 1974.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, color)	7 systems	Reaction time to stop, turn, stop & turn, and turn & stop signals, vehicle following measures, car control activity, subjective effectiveness	Driving simulator presentation, daytime and nighttime	Simulated car-performance unaffected by the rear lighting systems, shortest reaction time and favorable subjective ratings for a system with added accelerator position signal	
Rear lighting systems (number of lamps, color, functional separation)	2 systems (a single pair of lamps vs. color coded/ functionally separated system having three pairs of lamps)	Reaction time to stop, turn, stop & turn, and turn & stop signals, error frequency, missed signals frequency	Moving observer, moving target vehicle, nighttime	No differences in reaction times exept for longer reaction time to stop & turn signal for the system with a single pair of lamps; no differences between the two systems on error and missed signal frequencies	

ABSTRACT

Simulator studies were made to evaluate a number of conventional and experimental vehicle rear lighting systems. In normal car-following conditions a number of experimental rear lighting systems, using functionally separated signal lamps or color coding provided better performance in signal identification. Some of the results were confirmed in a road test. There were no stable differences in car-following performance measures between systems in the simulator.

Analyses of rear-end collision reports were used to structure groups of scenes which were implemented in the simulator. In this test, which included these unusual (pre-crash) car-following maneuvers, there were no stable differences in performance of drivers attributable to various rear lighting systems, including a High Deceleration Signal (HDS) and an Accelerator Position Signal (APS). There were significant differences in performance due to the test conditions of relative velocity and acceleration, and inoperative stop signal lamps. Unobtrusive measurements of drivers on the road showed that they released the accelerator when the car with the APS coasted on their first exposure, but not in a second exposure. A subjective evaluation test of APS found favorable ratings of it, but an increase of accelerator pedal release frequency by the driver of the following car.

It was concluded that simulated car-following performance was unaffected by the rear lighting systems. The APS provided no benefits in car-following in normal or unusual conditions, while following driver behavior showed a potentially undesirable characteristic in increased accelerator releases. No benefits were found for the HDS in these tests, but no undesirable aspects of the signal were evident.

The findings are discussed in the context of previous studies.

Olson, P.L. The effect of rear lighting configuration on vehicle traffic flow characteristics. In P.L. Olson, C.M. Jorgeson, S.P. Sturgis, J.K. Thomas, and P.A. Domas. Factors influencing the effectiveness of automobile rear lighting systems. HSRI, University of Michigan. Report No. UM-HSRI-HF-75-4, 1975.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, position)	3 systems	Reaction time to signals, vehicle control measures (headway, relative speed)	Moving observer, moving target vehicle, nighttime, 2 car platoon	System with functional separation/color coding yielded generally the shortest reaction time. No significant differences were associated with any of the car following measures as a function of rear lighting systems.	Redundancy, separation of function, high-mounted signal lamps
Rear lighting systems (number of lamps, functional separation, position)	3 systems	Reaction time to signals, vehicle control measures (headway, relative speed)	Moving observer, moving target vehicle, nighttime, 3 car platoon	System with functional separation/color coding yielded generally the shortest reaction time. No significant differences were associated with any of the car following measures as a function of rear lighting systems.	
Rear lighting systems (number of lamps, functional separation, position)	2 systems	Reaction time to signals, vehicle control measures (headway, relative speed)	Moving observer, moving target vehicle, daytime, 3 car platoon	System having two additional high mounted brake/turn signals (in addition to a single pair of stop/turn/presence lamps) yielded shortest reaction time. No significant differences were associated with any of the car following measures as a function of rear lighting systems.	

Olson, 1975 (continued)

ABSTRACT

This is a report of an investigation of the effects of different rear lighting and signaling configurations on measures felt to be important in determining traffic flow characteristics. Three studies are reported: two were conducted during the night and one during the day. The two nighttime studies employed three different rear lighting configurations. The first study was carried out with a two-car platoon and the second with a three-car platoon. The only significant differences were in reaction time measures. A configuration having separation of function and color coding produced shorter reaction times than the other systems tested.

The daytime study was conducted primarily to investigate the value of high-mounted signal lamps. It was found that the high-mounted signal lamps significantly shortened reaction times in multiple car-following situations.

Parker, J.F., Jr., Gilbert, R.R., and Dillon, R.F. Effectiveness of three visual cues in the detection of rate of closure at night. Bio-Technology, Inc., Report No. 64-1, 1964.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of tail lamps)	880-5440 ft-L.	Distance at which detection of closure was made	Moving observer, moving or stationary target vehicle, nighttime	Earliest detection with most intense light	
Spacing (horizontal separation of tail lamps)	30-60" (center to center)	Distance at which detection of closure was made	Moving observer, moving or stationary target vehicle, nighttime	Earliest detection with widest separation	

SUMMARY AND CONCLUSIONS

This study was concerned with an evaluation of the visual cues used by a driver at night as he decides he is overtaking the vehicle in front of him. Based on a rational examination of this driving situation, three cues were selected for study. These were:

1. Change in apparent area (size) of taillight surfaces.
2. Change in apparent brightness of taillight surfaces.
3. Change in visual angle subtended by taillights.

The basic paradigm of this study was one in which, for any given experimental trial, two of these variables were manipulated so as to maintain an apparent constancy during an approach run. The third variable, or visual cue, was the one on which an "overtaking" decision had to be based. Results obtained under these isolated cue conditions were compared with a control condition in which the taillights were not manipulated and appeared as normal taillights.

The effectiveness of each cue was tested as three levels of cue intensity. For each cue condition, approach runs were made at 20, 30, 40 miles per hour.

The following conclusions are drawn from the data of this study:

1. The control condition, in which normal taillights were used, is significantly superior to the operation of any single cue. A rate of closure could be detected much sooner under these conditions.

2. The visual angle cue and the brightness cue each are superior to the area cue. There is some indication that visual angle is superior to brightness but this cannot be demonstrated statistically.

3. Level of visual angle and level of brightness were found to be significant. Level of area was not. Within the limits of the levels tested in this study, the ability of a driver to detect a rate of closure is influenced by how far apart the taillights are and how bright they are but not by how large they are.

4. Approach speed does not influence the effectiveness of any of the cue conditions or of the control conditions.

5. Sensitivity to change in the visual angle cue appears to conform to the Weber psychophysical function. However, the size of the constant of proportionality is found to be larger under the dynamic conditions of this study, in which a comparison must be made through a period of time, than typically is found for reactions to stimulus changes when the comparison is immediate.

Post, D.V. Performance requirements for turn and hazard warning signals. HSRI, University of Michigan, Report No. UM-HSRI-HF-75-5, 1975.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, functional separation, color)	3 systems	Reaction time to a turn signal, hazard signal, turn signal preceded by a brake signal, frequency of missed signals	Stationary observer, stationary target vehicle, time sharing task, nighttime and daytime	Shortest reaction time (mean = 1.28 sec.) and fewest missed signals for a system with 3 pairs of color coded and functionally separated lamps	Functional separation, since it allows more latitude in the selection of flash rates and flasher starter modes
Color (of turn signal)	Red, yellow (of equal brightness but unequal intensity: yellow = 275 cd, red = 110 cd)	Reaction time to a turn signal, hazard signal, turn signal preceded by a brake signal, frequency of missed signals	Stationary observer, stationary target vehicle, time sharing task, nighttime and daytime	System with yellow turn signal yielded shorter reaction time (1.28 vs. 1.42 sec.) and fewer missed signals (37 vs. 43).	

ABSTRACT

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

Generalized results are contained in the summary of this report.

Reilley, R.E., Gilbert, R.R., Dillon, R.F., and Parker, J.F., Jr. The translation of visual information into vehicular control actions. Bio-Technology, Inc., Report No. 65-2, 1965.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity (of tail lamps)	1,000, 4,000 ft-L	a. Distance at which detection of closure was made b. Peak magnitude of deceleration force developed during a stop after detection of closure	Moving observer, moving or stationary taillight display, nighttime	The brighter taillight resulted in: a. longer detection distances b. smaller peak deceleration force	Standardization of taillights with large, bright lights at a separation in the order of 60 inches
Spacing (horizontal separation of tail lamps)	15-60"	a. Distance at which detection of closure was made b. Peak magnitude of deceleration force developed during a stop after detection of closure	Moving observer, moving or stationary taillight display, nighttime	The widest separation of taillight resulted in: a. longest detection distances b. smallest peak deceleration force	

CONCLUSIONS

The objective of this study was to examine certain items of visual information available from the vehicle taillight system and the manner in which this information might be used by a driver as a basis for specific vehicular control actions. In this investigation particular attention was given to the angular velocity cue provided by the increase in the visual angle subtended by the two taillights as a driver approaches these lights.

Based on the data of this study, the following conclusions are drawn:

1. There is evidence of a functional relationship between the angular velocity cue and the distance at which deceleration begins. However, the angular velocity information used by a driver is weighted in terms of the speed at which he is traveling. Thus, if a driver knows he is traveling at 40 mph, he seems to initiate braking on the basis of a smaller angular velocity cue than if he is traveling at 20 mph. In short, a driver appears to use both angular velocity information and vehicle velocity information in making the decision to stop.

2. Although there is definite evidence that the angular velocity cue is important, there also are indications that other cues provide important perceptual information. In fact, individuals apparently operate in accordance with the entirety of the visual environment around them rather than on the basis of specific and isolated cues. A set of "expectancies" is learned concerning the manner in which this visual world behaves. Thus, when approaching a vehicle at night, if the angular velocity cue provided by the taillight is distorted or manipulated in any way, a driver seems to change his system of "weights" and to rely more heavily on the remaining cue complex, i.e., the apparent increase in brightness and size of the taillights. However, if the distortion is severe, as in changing from a 60-inch to a

15-inch taillight separation, the remaining cues are not adequate to overcome this distortion and a driver will be "lured in" so that deceleration starts at a point even closer to the lead vehicle than would be the case if a single taillight were used.

3. In this study, subjects were instructed to "maintain a constant speed until you can determine that the vehicle in front is stopped; then bring your car to a stop at a safe distance." Under these instructions, which did not allow coasting during the period of indeterminancy, peak deceleration force averages varied from 0.19 g to 0.42 g, depending on the configuration of the taillight display and approach speed used. There was no indication that the magnitude of the deceleration force was guided by the angular acceleration cue exisiting at the moment of brake application.

4. All data indicate that the visual information available to a driver is used in a highly systematic manner in effecting control actions. It is difficult, however, to derive simple functional relationships describing this use because of the adaptability of the driver. He appears to adjust the weighting given to any specific item in accordance with the overall situation in which he is operating.

5. These data show that specific characteristics of taillight systems have a significant effect on braking behavior. A system with large, bright lights set at a maximum separation (60 inches) produces a consistently better braking response than any other system having one or more of these characteristics degraded.

Rockwell, T.H., and Banasik, R.C. Experimental highway testing of alternative vehicle rear lighting systems. Final report, Project RF 2475, Prepared by Systems Research Group Department of Engineering, Ohio State University, Contract FH-11-6552, National Highway Safety Bureau, 1968.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Color	Amber, green, red	Closing rate, the following distance (the distance at which the subject discontinued his overtaking course)	Moving observer, moving target vehicle	No differences	

SUMMARY

The Systems Research Group compared four taillight systems with the conventional taillight system. These systems were designed to present information to the following driver. The systems were also evolutionary in that the more advanced a system was, the more information it presented (i.e., from a pedal information system to a more sophisticated system incorporating headway and relative velocity information). The systems tested were:

1. Tri-light, which presents pedal information; red for brake, amber for no pedal, and green for gas with the brake overriding the other conditions. This system has been tested by the Systems Research Group and possesses several advantages among which is reduced response time in lead-car coasting maneuvers.
2. Acceleration system, which presents green for acceleration, amber for mild deceleration, and red for rapid deceleration. Two levels of this system were tested: a sensitive system and a moderately sensitive system).
3. Advanced (H-RV), which incorporated headway, relative velocity and velocity of the following car. This system presented headway and relative velocity information as a function of the taillighting.
4. Fusion system, based on the fusion of lights at various distances. The system is based on the fact that at a distance two distinct lights appear to be one. By designing the system properly, a driver can determine his position when following a lead vehicle at a point where his lights appear to blend together. Of course, this need not be identical for every driver but each driver will be able to learn his own fusion points and be able to determine where his location with respect to another vehicle in a better manner than he can with the present system.

Each of the above systems was compared against the conventional system using various measures of performance. Examination of Figures 6 - (1, 2, 3, & 4) show that the H-RV system is superior to all others tested in terms of headway variance and mean relative velocity. This results from the presentation of information to the driver not available to the driver in the other systems (e.g., H & RV). In addition, since driving is often viewed as a skilled motor performance task and it is well known that more stable performance is obtained from small amplitude, high frequencey control movements than low frequency, large amplitude control movements; the H-RV system by design calls for frequent correction in car-following performance. The results were obtained even though the drivers were given no training for a novel system of this kind.

Upon consideration of other systems (e.g., Tri-light, sensitive acceleration and acceleration) all in general proved to be superior to the conventional system particularly in terms of providing advanced information for lead-car maneuver changes. This is reflected in the Gas Pedal Response Times during a coasting maneuver.

Rockwell, T.M., and Safford, R.R. Comparative evaluation of an amber-red taillight system and the conventional system under night driving conditions, Ohio State University, Systems Research Group, Columbus, Ohio. Report No. EES 272-1, 1966.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity ratio (of running light to brake light)	1:1-1:21.6	a. Reaction time of gas pedal release to the onset of brake lights b. Reaction time of brake pedal depression to the onset of brake lights c. Reaction time of gas pedal depression to the onset of running lights	Moving target vehicle, moving subject, nighttime	Rapid decrease of all reaction times measured as the ratio increased to 1:5.3. No further significant decrease in reaction time if the ratio is increased to 1:21.6.	Because of the sharp drop in performance below 1:5 intensity ratios for the conventional system, there is a need to conduct a study of actual intensity ratios found in use today and the effect brought about by dirty taillight lenses.
Intensity ratio (of running light to brake light)	1:1-1:21.6	Percent confusion of brake light for a running light	Moving target vehicle, moving subject, nighttime	Rapid decrease as the ratio increased to 1:5.3. No further significant decrease with increase in the intensity ratio.	
Rear lighting systems (color, number of lamps)	Red brake light and amber running light, conventional one taillight system	Reaction time as above, confusion errors as above	Moving target vehicle, moving subject, nighttime	No reaction time improvement of red-amber system over the conventional system with 1:5.3 intensity ratio; improved identification with the red-amber system.	
Color (of running lights)	Amber, blue-green, red	Distance estimation	Moving observer, moving target vehicle	Both amber and blue-green running lights make the car appear closer than it appears with red running lights.	

Rockwell, T.M., and Safford, R.R. An evaluation of automotive rear signal system characteristics in night driving. Ohio State University, Systems Research Group, Columbus, Ohio, 1968.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (number of lamps, color, functional separation)	3 systems	Various vehicle control variables	Moving observer, moving target vehicle, nighttime	Double lamp system with color change yielded fastest gas pedal depression (≈ 1.3 vs. .9 sec. for a conventional system having one pair of lamps); the conventional system resulted in the largest number of identification errors of brake vs. running light; other car control variables did not differentiate between the systems.	
Color	Amber, blue, blue-green, green, red, (of equal intensity)	Distance estimation	Stationary observer, moving target vehicle (opening or closing headway) and stationary comparison vehicle	Red appeared furthest away, blue and blue-green appeared closest.	
Intensity	"High" (brake light intensity), "low" running light intensity	Distance estimation	Stationary observer, moving tartet vehicle (opening or closing headway) and stationary comparison vehicle	No difference	
Position (vertical)	High (57½"), low (29")	Distance estimation	Stationary observer, moving target vehicle (opening or closing headway) and stationary comparison vehicle	Lights in the high location appeared closer than in the low location.	

Rockwell et al., 1968 (continued)

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Color	Amber, blue, blue-green, green, red	Headway changes in an overtaking situation	Moving observer, moving target vehicle, nighttime	No differences	
Position (vertical)	High (57½"), low (29")				

CONCLUSIONS

Phase I and Phase II of this research have shown that driving performance of a following car driver in terms of improved response times and decreased errors in judgment of taillight mode can be realized by substituting a "Double Red" or a "Color Change" system for the conventional system. Differences between colors, positions, and placements were found to be non-significant with respect to the criteria of Phases I and II.

Phase III results indicated that the color and placement do have a significant effect on distance estimation. These results indicate that blue-green or blue lights and lights at the outer edges of the vehicle are best with respect to the criteria of distance estimation since these make the vehicle appear closer.

The data obtained from the field study of vehicle taillights indicate that some method should be established that would insure that inadequate taillight systems could be detected and corrected.

As can be seen from these results almost any change from the current Conventional System results in an improvement. The results do not, however, point to an optimum system. It cannot be stated that the optimizing of a single aspect of a system holding all else constant will result in a better system. For example, the detectability of the current Conventional System could be improved by increasing the intensity of the signal one hundred fold. If this was done, further increases in intensity for purposes of signaling, braking, or turning would very likely suffer. This points out the fact that if an alternate to the current system is to be found, all aspects of system functions will have to be considered.

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

In summary, the research that has been presented in this report has shown that changes in the "informational content" and changes in the methods of presentation of the information contained in the current taillight system results in improvements. Research efforts should be made to explore the aspects of automotive rear-signal systems not covered by this and other research.

Transport and Road Research Laboratory, Crawthorne (England). Transport and Road Research, Annual Report, 1974. London: HMSO, 1975.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (color, intensity and mode of operation)	High intensity (continually on) red rear fog lamps vs. flashing amber lamps	Subjective conspicuity	Daytime and nighttime artificial fogs, dynamic and static tests	High intensity red rear fog lamps were significantly more effective than flashing amber lamps in increasing conspicuity.	High intensity red rear fog lamps having intensities between 150 and 300 cd

Transport and Road Research Laboratory, Crawthorne (England). Transport and Road Research, Annual Report, 1975. London: HMSO, 1976.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Spacing (separation of brake lights and high intensity rear fog lights)	0, 5, 15, cm	Percent missed brake signals	Unspecified	55% of brake light onsets were missed with 0 separation, 11% with 5 cm separation, and 4% with 15 cm separation.	

University of California at Berkely. Motor vehicle rear lighting and signaling, Final Report. Prepared by the Vehicle Technology Facility, Institute of Transportation and Traffic Engineering, Richmond Field Station, Contract FH-11-6553, National Highway Safety Bureau, 1968.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLE	METHOD	RESULTS	RECOMMENDATIONS
Intensity, size	0.5-890 cd, 2, 5, 7" (diameter)	Subjective visibility rating	Single red flashing lamp (turn signal), moving observer, moving target vehicle, nighttime and daytime	As the area of a flashing lamp is increased, the intensity must also be increased for the lamp to receive the same subjective visibility rating. The 7 inch lamp requires approximately 200 cp to receive the mean preference level, the 2 inch lamp approximately 100 cp.	Detailed description of a recommended rear signal system. (One of the recommendations: intensity ratio for night, day and fog conditions = 1:4:16)
Intensity	4-77 cd	Subjective visibility rating	Two red steady burning 2" lamps (taillights) moving observer, moving target vehicle, nighttime and daytime	Mean preferred intensity: nighttime: 7 cd daytime: 52 cd	
Intensity spacing	4, 8 cd (night), 40, 80 cd (day) 3.5, 7" (center to center)	Subjective visibility rating	Two steady burning arrays of 3 red lamps each, moving observer, moving target vehicle, nighttime and daytime	3.5" spacing was preferred during the day; no preference during the night. As observation distance is increased, the spacing has less effect and the intensity becomes an important factor.	

ABSTRACT

A general investigation into the subject of motor-vehicle rear lighting was undertaken to determine what avenues would most likely lead to the establishment of specifications for an improved rear lighting system. The work of the investigation includes both analytic and experimental approaches, and also draws heavily on expert judgment as derived from the published literature on the subject and from direct consultation with individuals experienced in the subject field.

The problems associated with vehicle rear lighting are analyzed and discussed in terms of the functional and physical factors involved, and the requirements of a rear lighting system are listed.

University of California at Berkely, 1968 (continued)

The results of a survey of existing rear lamps are presented to show the distribution and trend in beam intensities and luminous areas over the years 1965 through 1967. A computer simulation model based on an adaptive matrix is described and shown as being feasible and offering a number of important advantages for the evaluation of rear lighting and other parameters of interest in a driver-vehicle system. Initial results from a number of subjective tests with specially instrumented vehicles are reported and a number of test variables found to be statistically significant in the subjective evaluations of rear lamps are listed. Salient findings from previously performed subjective tests on summation of luminous areas, adaptation luminance and visibility of light sources in fog are also given. A procedure is described for the semi-automatic determination of "effective projected luminous area" of rear lamps. On the basis of present knowledge, some tentative proposals are made for an improved rear lighting system together with suggestions for further work needed to establish the detailed specifications for such a system. A selected bibliography listing published works on the subject is also included.

Wallner, F. Zum Einfluss konstruktiver Massnahmen am Fahrzeug auf das Folgeverhalten einzelner Fahrzeuge und auf das dynamische Verhalten von Fahrzeugkolonnen. [The effect of structural modification of the vehicle on the following behavior of individual vehicles and on the dynamic behavior of vehicle platoons.] Strassenverkehrstechnik, 1969, 13, 177-184.

INDEPENDENT VARIABLE	RANGE	DEPENDENT VARIABLES	METHOD	RESULTS	RECOMMENDATIONS
Rear lighting systems (intensity, mode of operation)	Two level braking (deceleration) signal vs. conventional system	Number of "crashes," following distance	Driving simulator	Fewer "crashes" with the new system; no difference in following distance	

A SYNTHESIS OF EXPERIMENTAL FINDINGS

I. SPACING

A. Separation of left-side lamps from right-side lamps.

The reviewed studies indicate that the widest tested separation (5-8') resulted in: longest distance at which detection of closure was made (Parker et al., 1964; Reilley et al., 1965), longest distance at which the target appeared to be stopped (Crosley and Allen, 1967), and smallest peak deceleration force (Reilley et al., 1965).

B. Separation of lamps on the same vehicle side.

1. Vertical separation. Mortimer (1970) found the widest tested separation (6") to result in lowest displacement threshold and highest subjective effectiveness rating. However, in a later study by Mortimer and his co-workers (Mortimer et al., 1973), different separations of brake and turn signals (2, 8") did not yield different subjective effectiveness nor different subjective brightness ratings. On the other hand, wider separation resulted in better identification of signals. Moore et al. (1958) found that within the range tested (3½-8"), the widest separation of brake and turn signals resulted in shortest reaction time to turn signals.

The only results favoring narrow separation came from the University of California (1968). In this study subjects gave higher subjective visibility ratings to narrower spacing (3.5 vs. 7") in the daytime condition while there were no differences in the nighttime condition.

2. Horizontal separation. The studies in this review dealing with horizontal spacing (Mortimer, 1969; Mortimer, 1970; Transport and Road Research, 1976) all report that the widest separation led to best performance. The dependent variables used were perception of one vs. two lights (Mortimer, 1969), displacement threshold and

subjective effectiveness (Mortimer, 1970), and percent missed signals (Transport and Road Research Laboratory, 1976).

Overall, the results suggest that within the limits tested, widest spacing (both of lamps on different sides and of lamps on the same side) is generally best.

II. POSITION

There is a scarcity of systematic investigations regarding effects of position of rear lights on driver's performance. The present review includes three such studies (Crosley, 1966; Moore, 1952; Rockwell and Safford, 1968), all dealing with the question of optimal mounting height. However, some studies concerned primarily with the effect of spacing (e.g., Moore et al., 1958) are also relevant here.

Crosley (1966) found shorter reaction times to brake lights which were mounted at roof-line height as opposed to lights in a normal position. Rockwell and Safford (1968) report no difference in headway changes (in an overtaking situation) between conditions with high (57½") and low (29") mounted lights. However, their results indicate that the high mounted lights appeared closer than the low mounted lights. In contradiction to the later finding, Moore (1952) reports that a high-mounted light (48") appeared further away than a low-mounted light (24").

As far as specific recommendations are concerned, Olson (1975) suggests high-mounted signal lamps and Crosley (1966) argues for high-mounted auxiliary brake lamps. Similarly, Moore et al. (1958) recommends turn signals to be mounted at driver's eye-level. On the other hand, Cole et al. (1977) are concerned about the increased occurrence of glare from lights mounted at eye-level. Consequently, they recommend that all rear lamps be mounted rather low (400-800 mm).

Finally, Mortimer (1970) recommends the following mounting heights: (a) tail lamps at 15-25", supplemented by additional tail lamps located as high as possible, (b) stop lamps at 15-30", and (c) turn signal lamps at a height not below that of the low-mounted tail lamps.

III. INTENSITY

A. Absolute level of lamp intensity.

Several studies report that increased intensity led to better detectability of lights whether measured by visibility distance (Lindae, 1965; Moore, 1952; Moore and Smith, 1966) or number of observers detecting a flashing signal (Cook, 1969). Furthermore, the highest intensities tested resulted in most efficient detection of closure (Parker et al., 1964; Reilley et al., 1965), fastest initiation of car control movements (Rockwell and Safford, 1966) and lowest peak deceleration force magnitude (Reilley et al., 1965). In terms of subjective evaluation, higher intensity is reported to have higher attention-getting value (Domas, 1975).

There is contradictory evidence on the effect of the intensity of lights on their apparent distance. Moore (1952) found that more intense signals appeared nearer, while Rockwell and Safford (1968) report no effect of intensity on perceived distance.

B. Intensity differences among different rear lamps.

Attwood (1977) found no effect of changing the turn signal intensity from 125 to 200 cd (keeping other rear lamps unchanged) on reaction time to different rear signals. Mortimer's results (1970) indicate the difference in reaction time to be rather small (0.05 sec.) between systems with turn signal intensity of 35 cd and 91 cd, respectively. On the other hand, increased intensity differences among lamps were found to result in more veridical identification of different signals (Forbes, 1966; Mortimer, et al., 1972; Rockwell and Safford, 1966). A report by Fiat argues, however, that light intensity changes "cannot be appreciated if the previous intensity was not known (Fiat, 1976, p. 13)."

In general, thus, high intensity of rear light signals coupled with a high ratio of signal to tail lamp intensities is desirable. However, high intensity levels result in discomfort glare (Forbes, 1966; Lindae, 1965; University of California, 1968) and disability glare (Cook, 1969). Since the problem of glare occurs primarily at low ambient levels, some researchers recommend dual intensity systems (e.g., Automobile Manufacturers Association, 1967; Mortimer, 1970) with the higher level for daytime use, or even triple intensity systems (e.g., University of California, 1968) with the highest level for fog conditions.

The optimal intensity values vary with changes in other parameters, such as color (e.g., Mortimer et al., 1973) and size of the lamps (e.g., Forbes, 1966; Mortimer, 1970). With this qualification in mind, the following are some specific recommendations for optimal candlepower levels:

Tail lamp: (min/max)	3/12	(Automobile Manufacturers Association, 1967)
	4/15	(Mortimer et al., 1973)
	10/30	(Cook, 1969; Projector et al., 1973)
	.25/-	(Moore, 1952)
	2/20	(Cole et al., 1977)
Stop lamps: (min/max)	250/750	day, 50/150 night (Automobile Manufacturers Association, 1967)
	300/-	day, 80/320 night (Mortimer et al., 1973)[1]
	100/300	(Cook, 1969; Projector et al., 1969)
	200	(Cole et al., 1977
Turn signal lamps: (min/max)	300/900	day, 60/180 night (Automobile Manufacturers Association, 1967)
	425/-	day, 80/320 night (Mortimer et al., 1973)[2]
	100/300	(Cook, 1969; Projector et al., 1969)
	600	(Cole et al., 1977)[3]

[1,2]Mortimer et al. (1973) provide recommendations for various systems; these particular recommendations are for a system with green tail lamp, red stop lamp, and amber turn signal lamp.

[3]For a system with yellow turn signal lamp.

IV. COLOR[4]

Reaction time differences as a function of color of rear lamps were obtained by Campbell and Mortimer (1972), Mortimer (1969), and Mortimer (1970). Mortimer's results (1969) show that red color led to faster reaction time than either green-blue or amber of equal luminance. On the other hand Campbell and Mortimer (1972) and Mortimer (1970) report that a system with green-blue tail/turn lamps yielded shorter reaction times to various signals than a system with red tail/turn lamps. Finally, Allen et al. (1967), testing amber, green, red, and white lights, and Attwood (1977), testing amber and red turn signals, were unable to find any effect of color on reaction time.

Studies investigating the delay of car control movements (Campbell and Mortimer, 1972; Case et al., 1969) report no differences due to the color of rear lights. Similarly, no effect of color was obtained using the following measures: accelerator release and brake application frequencies (Campbell and Mortimer, 1972), closing rate and following distance (Rockwell and Banasik, 1968), and headway changes in overtaking situation (Rockwell and Safford, 1968).

Different colors are reported to require different levels of intensity for equivalent ratings of brightness, visibility, and effectiveness. The following are color orderings in terms of increasing intensity requirements:

Brightness:	green, red, amber, white (Mortimer, 1970) red, amber (Mortimer et al., 1973)
Visibility:	red, amber, white (Automobile Manufacturers Association, 1967)
Effectiveness:	red, yellow, white (Committee on Motor Vehicle Lighting, 1964) red, amber, white (Kilgour, 1960) red, amber (Mortimer et al., 1973)

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[4]The terms "yellow" and "amber" are generally used interchangeably.

In addition, a red light has a longer recognition distance than either a green-blue or amber light (Mortimer, 1969) and red turn signals result in more vertical identification of various rear signals than amber turn signals (Mortimer et al., 1973). Finally, a red light is reported to be perceived as being further away than either an amber, blue, blue-green, or green light (Rockwell and Safford, 1966; Rockwell and Safford, 1968).

Most of the research on color as a parameter of rear lighting system is in the context of choosing the optimal color for turn signal and for tail lamp. Increasingly more researchers prefer amber (yellow) over red for turn signal lamps (e.g., Automobile Manufacturers Association, 1967; Committee on Motor Vehicle Lighting, 1964; Campbell and Mortimer, 1972; Mortimer, 1970; Moore et al., 1958). In regard to the color of tail lamps, general consensus is for red (but see Campbell and Mortimer, 1972 and Mortimer, 1970 for examples of data supporting green tail lamps).

The question of the optimal color for tail and turn signal lamps is related to a more general issue of the desirability of color coding of rear signals. Several investigators recommend color coding (e.g., Case et al., 1968; Campbell and Mortimer, 1972; Mortimer, 1968; Mortimer, 1970). However, a strong case against color coding is made by Projector and Cook (1972) who argue that "(a) some anticipated difficulties have not been studied adequately and (b) known advantages are outweighed by the known disadvantages combined with disadvantages suspected but not yet adequately investigated (p. 141)."

CONCLUDING COMMENTS

This review deals exclusively with applied research. It is clear that applied research data have higher face validity than basic research data due to the more realistic conditions of the experimental set-up. However, as evidenced by the present review, several areas of interest have been rather scarcely investigated and research in other areas yields contradictory findings. Therefore, it is suggested that, until additional applied data are available, benefits would be derived from a review of basic research dealing with effects of spacing, position, intensity, and color on human performance. The already available basic data are likely to fill some of the void as well as reconcile some of the contradictory findings of applied research.

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