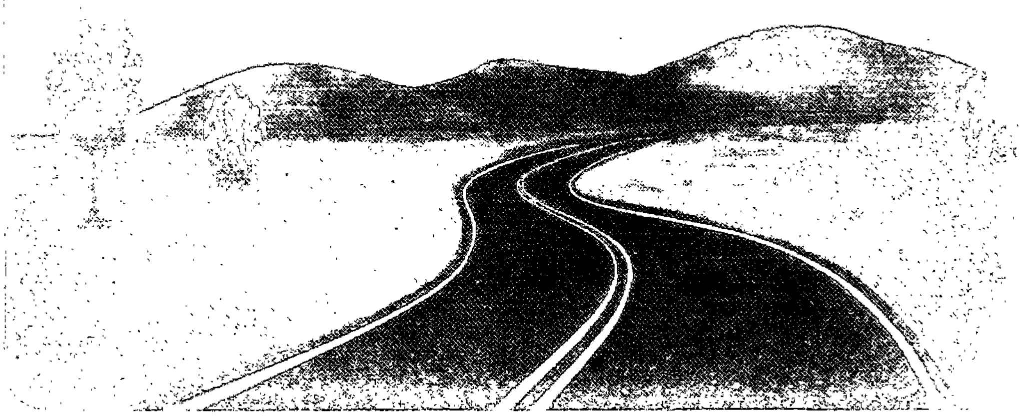
PB290-482

DRIVER'S VISIBILITY REQUIREMENTS FOR ROADWAY DELINEATION

VOL. I. EFFECTS OF CONTRAST AND CONFIGURATION ON DRIVER PERFORMANCE AND BEHAVIOR



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FINAL REPORT

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FOREWORD

The work reported herein was conducted under Contract DOT-FH-11-8824 to the Federal Highway Administration with Dr. Donald Gordon, of the Traffic Systems Division, Office of Research, serving as Contract Technical Manager. This study was part of the Delineation Task of a much broader FHWA effort, Project 1L, "Improved Traffic Operations During Adverse Environmental Conditions," managed by Mr. Richard N. Schwab of the Environmental Design and Control Division.

Systems Technology, Inc., served as the prime contractor on this study, with a major subcontract handled by Human Factors Research, Inc. R. Wade Allen served as Principal Investigator for STI and James F. O'Hanlon served in the same capacity for HFR.

The research reported herein was conducted during the time period of July 1975 through October 1977 and is documented in two volumes. Volume I covers the simulation and field test work conducted to define optimum and minimum visual roadway delineation treatments. Volume II documents a study to establish the lower saturation limit of yellow/white paint mixture that can still be distinguished from white.

The authors would like to extend their appreciation to the reports groups at both STI and HFR for a fine job in the production of these documents.

Charles F. Scheffey
Director, Office of Research

NOTICE

Technical Report Documentation Page

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16. Abstract

The overall purpose of this multiphased research study was to establish visibility requirements for roadway delineation that can be used to help establish the cost-effectiveness of a variety of delineation treatments. Given the visibility requirements developed here and subsequent cost/benefit analysis, a rational approach can be taken for the development, design, and maintenance of roadway delineation.

Two basic contract objectives were addressed in this research study: 1) experimentally determine the optimum and minimum visual roadway delineation treatments; and 2) establish the lower saturation limit of yellow/white paint mixture that can still be distinguished from white. These two objectives are somewhat independent and were pursued in two different research efforts which are documented in separate volumes of this report.

Two issues are addressed in this first volume: 1) the human factors requirements for adequate delineation visibility under adverse visual conditions of night, rain, and fog; and 2) the development of functional specifications for a methodology to assess highway marking contrast. The research on the above issues will provide guidance for delineation design and maintenance and quantification of driver performance and can be used in subsequent cost/benefit analysis studies.

A combined theoretical/experimental approach was taken in this research. A theory for delineation visibility and driver perceptual requirements was developed and tested in a laboratory simulation. Further validation tests were then conducted in an instrumented vehicle on the open highway. The simulation and field test results were compared and connected analytically through the use of the previously developed visibility theory, and a model was developed to quantify steering performance in terms of delineation contrast and configuration (i.e., line segment and gap lengths).

It was found that the quality of delineation under adverse visibility conditions depends on a combination of contrast and configuration. Conclusions are drawn about delineation contrast and configuration requirements, and suggestions are made on practical field techniques for measuring delineation contrast.

Volume II, Color Identification of Yellow Highway Paint as a Function of Yellow/White Pigment Mixture Ratio, is report number FHWA-RD-77-166 and is available from NTIS.

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EXECUTIVE SUMMARY

The overall purpose of this multiphased research study was to establish visibility requirements for roadway delineation that can be used as an element in the determination of the cost-effectiveness of a variety of delineation treatments. Given the visibility requirements developed here and subsequent cost/benefit analysis, a rational approach can be taken for the development, design, and maintenance of roadway delineation.

Two basic contract objectives were addressed in this research study:

- Experimentally determine the optimum and minimum visual roadway delineation treatments.
- Establish the lower saturation limit of yellow/white paint mixture that can still be distinguished from white.

These two objectives are somewhat independent and were pursued in two different research efforts which are documented in separate volumes of this report. A summary of each of the research studies is given below.

EFFECTS OF CONTRAST AND CONFIGURATION ON DRIVER PERFORMANCE AND BEHAVIOR (VOLUME I)

Background and Objectives

Two issues are addressed in this volume: 1) the human factors requirements for adequate delineation visibility under adverse visual conditions of night, rain, and fog; and 2) the development of functional specifications for a methodology to assess highway marking contrast. The research on the above issues documented in Volume I of this report will provide some guidance for delineation design and maintenance and quantification of driver performance and can be used in subsequent cost/benefit analysis studies.

The specific objectives addressed in this first volume are as follows:

- Develop dependent variables sensitive to roadway delineation treatments.
- Establish visibility requirements for roadway delineation.
- Determine luminance-contrast requirements for delineation.
- Develop functional specifications for a practical test methodology suitable for assessing roadway marking contrast.

Approach

The above objectives were achieved through three phases of work: 1) literature review and development of a theory for delineation visibility and driver perceptual requirements; 2) driving simulator tests designed to validate the previously developed theory over a wide range of visibility and delineation configuration conditions; and 3) in-vehicle field tests designed to measure driver performance during actual open highway driving. The theory and experiments are based on sound human factors principles associated with driver visual characteristics, perception, and vehicle steering control behavior. The work on each phase may be summarized as follows.

Theory. A theory for delineation visibility was developed based on human visual characteristics, atmospheric visibility properties, and the photometric properties of light sources and road surface conditions. Driver visual characteristics require minimum (i.e., threshold) contrast levels for detecting delineation targets (e.g., line segments). Delineation visual range is limited under adverse visibility conditions due to increasing contrast thresholds with distance and decreasing apparent contrast due to environmental effects. Perceptual theory and past research indicate that driver's require a minimum visual range for adequate steering control, and the visibility theory developed here quantifies the manner in which various adverse visibility factors limit this visual range.

Simulation. A driving simulation experiment was conducted to establish the relationship between performance, visual range, and delineation configuration. The simulation study resulted in the derivation of a configuration visibility parameter which is able to quantify the combined effect of limited visual range and delineation configuration (i.e., line segment and gap size) on driver steering control.

Field Test. In-vehicle tests on the open highway employed an instrumented van. These tests measured driver performance capabilities in an actual driving scenario over a range of adverse visibility and delineation conditions. Driver steering performance was established as a function of road marking contrast under clear night driving conditions. Under night rain conditions the efficacy of raised pavement markers on driver performance was also demonstrated.

Conclusions and Recommendations

The simulation and field test results were compared and connected analytically through the use of the visibility theory developed earlier. A model was developed to quantify steering performance in terms of delineation contrast and configuration, and conclusions and recommendations resulting from the research and analysis were as follows.*

Dependent Variables Sensitive to Roadway Delineation. In the simulator tests lane position variability, preferred speed, and driver rating were all found to be similarly sensitive to delineation configuration and visual range. In the field tests lateral lane position variability was found to be sensitive to delineation contrast. Driver physiological response was also found to be sensitive to rain conditions which affect delineation visibility.

*It should be noted that these results relate primarily to the driver's ability to laterally control his vehicle along a delineated pathway (steering control), as opposed to speed control and/or stopping which is primarily evoked by signing, signals, traffic and other obstacles on the roadway.

In addition to the above variables, various measures of the driver's dynamic response obtained in the simulation have given a great deal of insight into the manner in which adverse visibility restricts the driver's perception of automobile path and motion information required for steering control. These perceptual restrictions have been quantified in terms of the driver's dynamic steering behavior in response to random disturbances and path commands (i.e., road curvature). Combinations of reduced visibility and delineation configuration (i.e., intermittent dashed or dotted lines) tend to induce increased time delay in the driver and impair his perception of road curvature.

The above effects appear to be related to the apparent intermittent or sampled nature of delineation under reduced visibility conditions. Driver time delay increases at slower speeds, due to decreased sampling frequency, even though vehicle dynamic lags decrease with speed. This effect induced a somewhat compelling urge in some subjects to speed up in order to increase their information rate, which is a rather insidious phenomenon if true for real-world driving, since it might encourage drivers to maintain speeds with associated stopping distances exceeding their visual range.

Visibility Requirements for Roadway Delineation. The driver's ability to steer his vehicle along a delineated pathway is dependent on the visual range and configuration of the delineation, vehicle speed, and road geometry. Delineation provides the visual perceptual input for driver steering control actions. Driver steering performance depends on the quality and extent of the perceptual input. Steering performance degrades with decreased visual range. Steering performance also degrades as the segment-to-gap ratio of delineation is reduced, and the cycle length is increased.

Under adverse visibility conditions of night and/or fog, steering performance can be improved by increasing delineation contrast to achieve a longer visual range, and by improving the quality of the delineation configuration by increasing segment-to-gap ratio and decreasing the segment cycle length. Adding a solid right edge line gives a rather dramatic improvement in performance under adverse visibility conditions.

Steering performance also is affected by roadway geometry. In some cases delineation visual range may be restricted simply by roadway curvature, and in these cases, combined with prevalent adverse visibility conditions, high quality delineation configuration (i.e., higher segment-to-gap ratios and shorter cycle lengths) is indicated.

Rain effectively obscures painted delineation, and raised pavement markers which penetrate the water surface provide the only effective countermeasures.

Cost/benefit analysis must be performed in order to determine the cost effectiveness of various delineation treatments and maintenance schedules. Frequent restriping and high segment-to-gap ratios will maximize driver steering performance but are costly. A compromise must be struck between cost and performance, and this tradeoff can be determined through cost/benefit analysis using the performance models developed in this report and maintenance and wear data provided in previous research.

Further simulator and field test research and visibility analysis should also be conducted to determine if improved delineation visibility under adverse visibility conditions might actually degrade traffic safety by inducing higher vehicle speeds. Optimum delineation, while improving steering performance, might induce vehicle speeds with associated stopping distances which are in excess of typical obstacle detection ranges. This problem could be analyzed through a combination of simulator tests and visibility analysis, and verified with field measures of vehicle speeds under various visibility and delineation contrast and configuration conditions.

Further simulation research could be fruitfully conducted on variations of segment-to-gap ratios and delineation cycle lengths. Only certain selected cases were considered here, specifically the California Department of Transportation standard [9 ft (2.7 m) segments and 15 ft (4.8 m) gaps] and the old Manual on Uniform Traffic Control Devices guideline [15 ft (4.8 m) segments and 25 ft (7.6 m) gaps]. Further research should include the new FHWA guideline [10 ft (3.0 m) segments and 30 ft (9.1 m) gaps].

Luminance-Contrast Requirements for Delineation. Results of this study indicate that delineation contrast should be maintained above a value of 2 (dimensionless) for adequate steering performance under clear night driving conditions. Contrast is defined by the relationship

$$C = \frac{L_T - L_B}{L_B}$$

where L_T is the target (delineation) luminance and L_B is the background (road surface) luminance. Contrast is a dimensionless quantity because of the cancellation of numerator and denominator quantities.

For areas with frequent additional adverse visibility conditions (i.e., fog), delineation contrast should be maintained at even higher values. There is a tradeoff here between maintenance costs and improved driver performance, however, and a specific contrast increase cannot be stated without appropriate cost/benefit analysis. This research has shown that practically achievable levels of road-to-delineation contrast are not much greater than 12, however, so the contrast range is somewhat limited.

A cost/benefit analysis should be conducted on the cost effectiveness of maintaining given levels of delineation contrast. The performance models developed in this study can be used as metrics of steering performance, and maintenance data and costs can be derived from previous research. Also, as suggested above, further simulator and field research and visibility analysis should be conducted to determine whether improved visibility range due to higher contrast will induce higher vehicle speeds, which in fact could reduce traffic safety.

Measuring Roadway Marking Contrast. The above recommended lower bound on contrast of 2 implies a practical measurement problem that can probably be handled with a hand-held instrument. Another possibility involves a vehicle-mounted scanning diode array device. The details and qualifications on these measurements are discussed in the main report text.

A study should be conducted to compare the contrast measurements of various practical field photometers with the precision spectra photometer used in this study. Various commercially available hand-held spot photometers and possibly a prototype diode scanning device suggested in the text should be compared under actual field conditions with a laboratory photometer used as the standard of comparison. The study should consider a range of road surfaces and markings in various stages of wear. The measurements should be made with and without artificial illumination sources and include variations in source and measurement angle in order to evolve the simplest acceptable technique for conducting a field maintenance test. Finally, it might be possible to develop a crude observational technique under night conditions with a headlight illumination source. This approach would involve simply counting visible delineation segments and using a criterion based on the configuration visibility parameter developed in the simulation experiment.

COLOR IDENTIFICATION OF YELLOW HIGHWAY DELINEATION PAINT AS A FUNCTION OF YELLOW/WHITE PIGMENT MIXTURE RATIO (VOLUME II)

The Yellow Paint Problem

It is now standard practice in the United States to color-code highway lane delineation so that vehicles moving in the same direction are separated by white lines, and vehicles moving in opposite directions are separated by yellow lines.

The yellow paint in current use has several drawbacks which would be alleviated by dilution of the yellow lead chromate pigment content. Due to its lower reflectance and more rapid darkening with age, yellow paint is usually less visible than white paint, especially at night and in adverse weather; yellow pigment is also more toxic and more expensive than white pigment.

The purpose of this research was to determine how much the yellow paint can be diluted by white without causing drivers to misperceive it as white under actual driving conditions.

The results of this study indicate that yellow paint can be diluted with white paint up to 50 percent white pigment (by weight) without losing yellow color identity under lighting conditions where color is usually visible.*

By replacing half of the yellow pigment in yellow highway paint with white pigment, a cost savings of more than one million dollars could be realized annually in the U. S., while also improving visibility and reducing toxicity of the paint.

Cost Savings

Dilution of yellow paint would substantially reduce the extra cost of yellow painting, since yellow paint is approximately 15 percent more expensive than white. For example, assuming 50 percent white dilution, 15 percent higher cost for yellow paint, and an annual use of 5 million gallons for yellow delineation, the current extra cost for yellow delineation (as opposed to all-white delineation) is $2,250,000 per year. By adding 2 gallons of white paint (containing 1 lb/gal titanium dioxide pigment) for each gallon of yellow (containing 2 lb/gal lead chromate pigment), the extra cost of yellow delineation would be only $750,000, a 67 percent direct cost savings of $1,500,000 per year in the United States. Other indirect savings would result from better visibility and safer driver performance.

Improved Contrast and Visibility

By replacing 50 percent of the yellow pigment with white pigment, the visibility problems inherent in current yellow paint can be reduced. Yellow delineation is initially less reflective than white, and darkens more rapidly with exposure after painting. Due to lower brightness contrast with the

*There are many instances of adverse viewing conditions in which even 100 percent yellow delineation cannot be discriminated from white. Drivers recognize that delineation color coding may not be functionally visible under conditions of night lighting, glare from oncoming headlights, rainfall, and so on. The degree of dilution becomes academic under adverse conditions where even 100 percent yellow could not be identified. In night rain conditions this is almost always the case.

pavement, yellow markings are typically not as visible as white under adverse driving conditions such as night lighting, rain, and with windshield degradation due to road film, veiling luminance, icing, interior fogging, glare, and so on. (Only in exceptional cases would the additional color contrast of yellow markings improve visibility. For example, under snow conditions, fog conditions, or with very light colored pavement, the contrast of color as well as the contrast of brightness may give a yellow line greater visibility than a neutral white line.)

Experimental Details

Absolute color judgment is much more difficult than judgments of one color compared with another. Thus, in some cases a white reference strip was placed in the field of view to make the perception of yellow easier, as on a highway with a white edge line at the shoulder. Color perception varies greatly with distance and with the type of illumination available; a sample which looks distinctly yellow in one light may look pure white in another, in the presence of glare, etc. Thus there was the need to test color naming under a variety of lighting conditions and viewing distances.

The maximum white dilution which can still be reliably distinguished as yellow was determined under conditions which closely approximated the driving situation. A graduated series of paint mixtures ranging from 100 percent yellow to 100 percent white (yellow/white pigment weight ratios) were applied to 8 ft × 4 in. (4.2 m × 10.2 cm) strips of thin sheet metal, simulating highway delineation stripes. These test strips were painted with the assistance of California Department of Transportation paint crews, using standard airless spray equipment and glass-bead blower. Yellow/white color judgments were made by 20 subjects observing the sample strips from the driver's seat of a parked vehicle at distances of 30, 60, and 90 ft (9.1, 18.3, and 27.4 m), both with and without a 100 percent white reference sample in the field of view, under various day and night lighting conditions: high sun, low sun, headlights only, headlights plus mercury vapor, headlights plus sodium vapor, headlights plus tungsten illumination, headlights plus oncoming headlight glare.

The visual distance and angular size of the samples, the optical effect of the retroreflective glass beads, and the use of actual luminaires in an outdoor setting provided field test validity in the data.

The experimenter presented samples in an exploratory sequence to find the breakpoint at which the subject would switch from a white response to a yellow response. When this threshold or breakpoint was found, it was confirmed by repeated presentation of test strips on either side of the breakpoint. The threshold or breakpoint value recorded for each combination (reference/distance/lighting) was the percent white pigment in the most diluted test strip which was reliably identified as yellow.

Individual subjects' thresholds were remarkably consistent for most combinations of reference, distance, and lighting. In the main experiment, a total of 556 threshold values were obtained, 480 with night lighting conditions and 76 with daylight conditions.

Summary of Results

For each dry weather lighting condition, the average values of maximum permissible white dilution (percent) which can be reliably identified as yellow were: high sun = 93 percent white dilution, low sun = 90 percent, headlights plus mercury vapor luminaire = 61 percent, headlights plus tungsten luminaire = 57 percent, headlights alone = 51 percent, headlights plus sodium vapor luminaire = 46 percent, headlights with oncoming headlight glare = 38 percent. The night lighting averages were each based on 96 threshold determinations (6 thresholds each by 16 subjects). The mean value for all five night conditions (N = 480 threshold values) was 50 percent white dilution, with 0.95 confidence limits between 47 percent and 53 percent dilution. None of the judgments obtained at 30 ft (9.1 m) viewing distance fell below 50 percent dilution; thus even under the most difficult conditions (glare), subjects could reliably identify a 50 percent diluted yellow/white mixture at a 30 ft distance.

The summary averages for each night lighting condition are conservatively weighted by inclusion of data obtained at the more difficult 60 ft

(18.3 m) and 90 ft (27.4 m) viewing distances. The 50 percent mean value of 480 thresholds for all five night conditions combined is a conservative general guideline for maximum white dilution since it includes the more difficult sodium vapor and glare data.

Recommendations

As a general guideline for dilution of yellow paint with white, use a 50:50 yellow/white pigment weight ratio. To provide at least 1.3 lb/gal (.156 kg/l) total pigment for hiding power and protection of the paint, use at least (.078 kg/l) 0.65 lb/gal yellow (medium lead chromate) and at least 0.65 lb/gal (.078 kg/l) white (titanium dioxide). For example, this pigment content can be obtained by mixing 2 gal (7.6 liters) white paint (1 lb/gal (.12 kg/l) pigment with each 1 gal (3.8 liters) of yellow paint (2 lb/gal (1.24 kg/l) pigment); alternatively, paint with premixed pigment specifications may be obtained from the manufacturer.

For maximum white dilution, tailor yellow mixture dilutions for each section of highway as a function of the lighting conditions and the presence of other white delineation. For maximum delineation visibility, increase contrast by underpainting with black.

Conduct color identification testing of highway delineation materials with fully reflectorized samples at viewing angles which will occur in the actual driving environment. Use of non-reflectorized samples at higher than normal viewing angles may tend to underestimate the pigmentation required for correct color identification in night driving conditions, since the desaturating effect of glass bead reflection is an important factor.

SECTION I

INTRODUCTION

This report documents a multi-phased study concerned with a human factors analytical-experimental investigation of the visibility requirements of roadway delineation. The nature of the delineation experiments is inevitably keyed to the driver's needs and to the measurement of quantities sensitive to the satisfaction of those needs. In principle, the driver requires delineation for both long and short distance viewing, the first to provide adequate warning for stopping, obstacle avoidance, merging lanes, etc., and the second to provide for guidance and control. The guidance and control requirements are of primary concern here and are perhaps the most difficult to define. This is because of the many complex interactions between the elements of the driver's visual field and the environment and because of the vagaries of the driver's perception of appropriate cues from the surround and their application to vehicle control.

The specific objectives of this research were as follows:

- Develop dependent variables sensitive to roadway delineation treatments.
- Establish visibility requirements for roadway delineation.
- Determine luminance-contrast requirements for delineation treatments.
- Develop functional specifications for a practical test methodology suitable for assessing roadway marking contrast.

In order to achieve these objectives we performed a series of driving simulator and in-vehicle field tests designed to measure driver behavior, driver reaction and driver/vehicle system performance over a wide range of delineation treatments. The experiments were based on sound human factors principles associated with driver visual characteristics, perception, and vehicle steering control behavior.

In the following section (II) we discuss the various human factors principles used to guide the experimental design and interpret results. Visual characteristics and perception are reviewed in order to establish a rational basis for evaluating delineation visibility, and the effect of adverse visibility factors such as rain and fog is discussed. Section II concludes with a review of driver steering control behavior and a model which is subsequently used for measurement and analysis of simulator data.

A simulator experiment was conducted to measure driver steering performance under a wide range of delineation configurations and visibility conditions. The approach, methods, and results are discussed in Section III. A detailed description of the simulator is given in Appendix A, and the measurement technique and some detailed results on driver steering control behavior are further elaborated in Appendix B. The simulator allowed a wide variety of test conditions and measurements to be accomplished that could not otherwise have been accommodated. As discussed in Section III, the effects of delineation configuration and visual range on driver steering behavior and performance have been established, and a metric has been developed that seems capable of describing these effects.

Field test experiments were performed to complement and validate the simulator study and to include various effects that could not practically or reliably be duplicated in the simulation. The methods and results for these tests are described in Section IV. Details of the instrumented test vehicle are presented in Appendix C; further detailed field results and statistical analysis are given in Appendix D and photometry performed to document field visibility conditions is reviewed in Appendix E. The field tests gave good reliable results on the effects of delineation contrast change due to both wear and rain, and allow some definitive statements to be made about contrast requirements.

In Section V we compare the simulation and field test results in order to develop requirements for delineation configuration and contrast. Good tie-in between the two experiments is established which then leads to a potential contrast specification. Section V is then concluded with a discussion of functional requirements for field photometry approaches that would allow delineation contrast to be determined in a practical manner.

Finally, Section VI provides a compact and integrated summary of the conclusions of all phases of the study.

SECTION II

FUNDAMENTALS

A. OVERVIEW

Visual perception is critical in automobile driving to define the desired path and current status of the vehicle and the surround. Roadways are marked or delineated in order to enhance the driver's visual perception, and vehicle and roadway lighting systems are provided to counteract the effects of adverse visibility conditions (i.e., night, rain, fog, etc.). In designing delineation and lighting systems, key considerations are the driver's perceptual requirements for vehicle navigation and control, and the effect of various environmental factors on the visibility of required visual cues. This section addresses the above considerations, with primary concern with the visual cues required for steering control along an unobstructed path, as opposed to factors associated with speed control or stopping distance.

Under reduced visibility conditions there are a variety of factors that can influence driver performance. The important considerations are illustrated in Fig. 1. Illumination sources (sun, headlights, etc.) and elements of interest in the visual field (roadway delineation, signs, traffic, etc.) determine the characteristics of the visual field. The important features from the driver's viewpoint are geometric properties of size, shape and texture, and photometric properties such as luminance, reflectance, and color. The visual scene photometric properties are altered by atmospheric attenuation and scattering. Scattering is the more important effect, which acts to reduce contrast and desaturate colors.[1] Both effects increase with the density of atmospheric particles (e.g., fog, rain) and the distance over which an observation is made.

[1]Middleton, W. E., Vision Through the Atmosphere, University of Toronto Press, 1952.

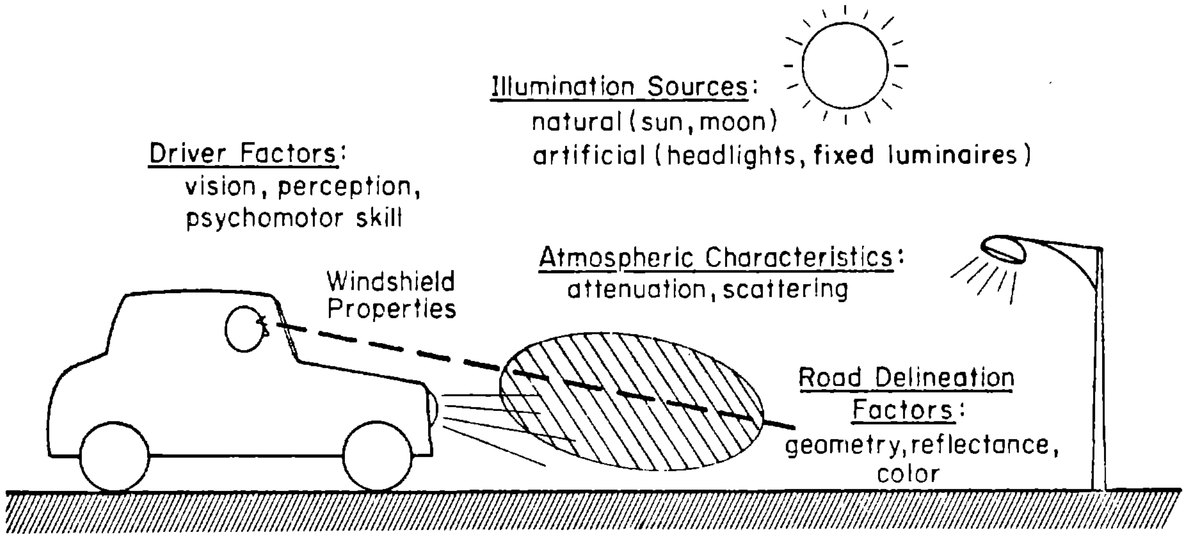

Figure 1. Factors Influencing Driver Steering Control Under Adverse Visibility Conditions

Driver psychophysical and behavioral characteristics are, of course, the final link in the chain of effects which determine steering performance. The pertinent driver characteristics can be broken down into three categories: 1) visual sensitivity; 2) recognition and perception; and 3) control. The visibility or detectability of scene elements depends on the psychophysical properties of the eye and the photometric and geometric properties of the elements of interest. Visibility factors are further elaborated on in Article B. Given that a feature, say a dashed line, is visible, the driver's perceptual processes can then derive useful information from which to control the car. Perceptual possibilities and requirements are discussed in Article C. Finally, driver control requirements, characteristics, and models useful for data measurement and analysis are considered in Article D at the end of this section.

B. VISUAL CHARACTERISTICS

Visibility of highway delineation depends upon the fundamental sensitivity of the driver's visual system to luminance and contrast. Only when the luminance and contrast of a delineation exceeds threshold values can the driver use his perception of form, motion, and distance as the input basis for control of a vehicle on a roadway. The purpose of this article is to discuss luminance and contrast sensitivity, the general luminance characteristics of delineation in roadways, and their implications for laboratory simulation and on-the-road testing of the adequacy of delineation treatment visibility. To detect an object or roadway characteristic, the luminance of the detail of interest must be sufficiently lower or greater than the general background luminance to create a detectable contrast with the background. Because of the capability of the eye to adapt to a luminance range of 10^9 times (!), the detection of contrast at a given luminance level becomes the most important characteristic for specifying the visibility of an object.

The contrast of an object is defined as the difference between target and background luminance divided by background luminance:

$$C = \frac{L_T - L_B}{L_B} \tag{1}$$

which is a dimensionless quantity due to the cancellation of numerator and denominator units. Visual contrast thresholds (i.e., minimum detectable contrast) depend on background or adaptation luminance and target size. The relationship between these variables was empirically determined in a series of classical experiments,[2] and the results are summarized in Fig. 2. As noted, contrast threshold decreases with greater background luminance (better detection during the day) and increases with target size (bigger targets are easier to detect). In the lower right-hand corner of Fig. 2a the threshold contrast curves become straight lines such that the product of contrast and stimulus area is constant for a given background luminance. In this region target detection is a function of target intensity only and is independent of target size.[1] This is the "point source" region which is pertinent to the detection of retroreflectors.

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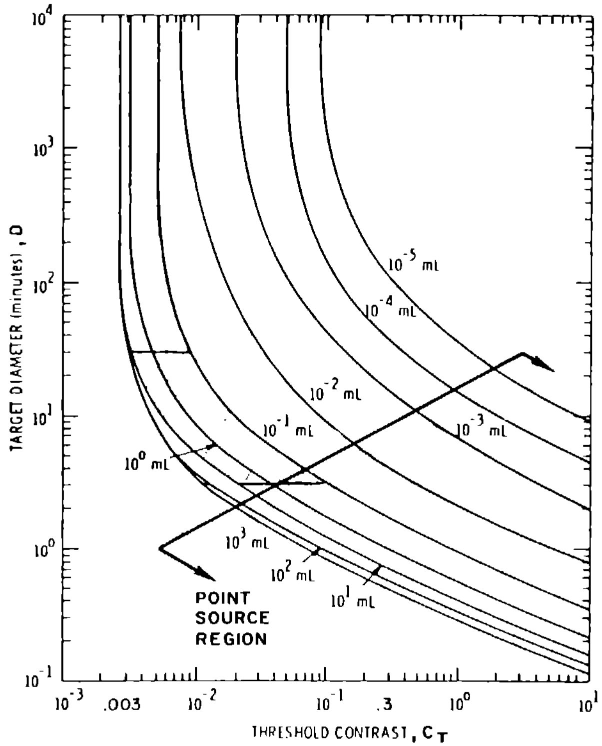
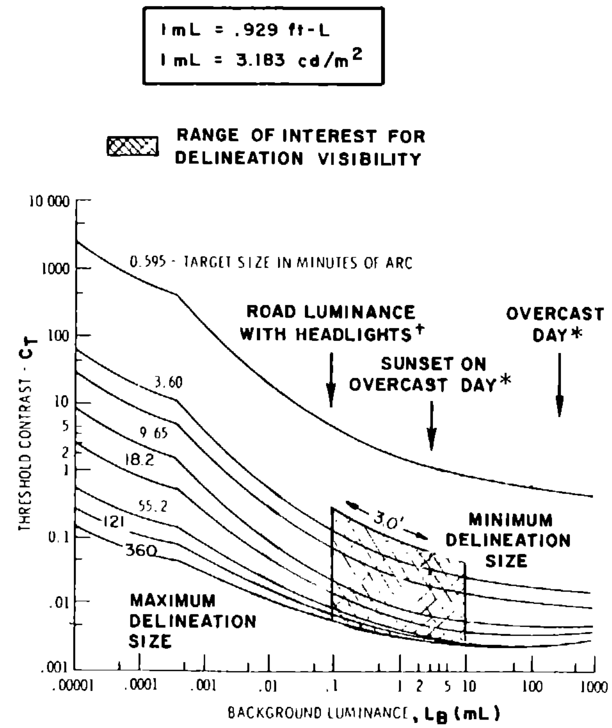
[2]Blackwell, H. R., and J. H. Taylor, "Survey of Laboratory Studies of Visual Detection," presented at the NATO Seminar on Detection, Recognition, and Identification of Line-of-Sight Targets, The Hague, The Netherlands, 25-29 Aug. 1969.

[1]Middleton, Vision Through the Atmosphere.



a) Target Size as a Function of Contrast Threshold for Various Background Luminance Levels



b) Relation of Threshold Contrast to Background Luminance for Various Target Sizes

*Middleton (Ref. 1)
†Richards (Ref. 3)

Figure 2. Visual Contrast Threshold Characteristics for Unlimited Viewing Time

Some gross boundary conditions of interest for this research study have been blocked out in Fig. 2. Target size boundaries are derived from apparent lane stripe dimensions shown in Table 1. The near view (20 ft; 6.1 m) size is limited by car hood obstruction, and contrast thresholds are not very sensitive to target size beyond this level anyway. For the small end of the target size scale, seeing distances of much greater than 300 ft (91.4 m) are not important for steering control as will be discussed subsequently (Article D).

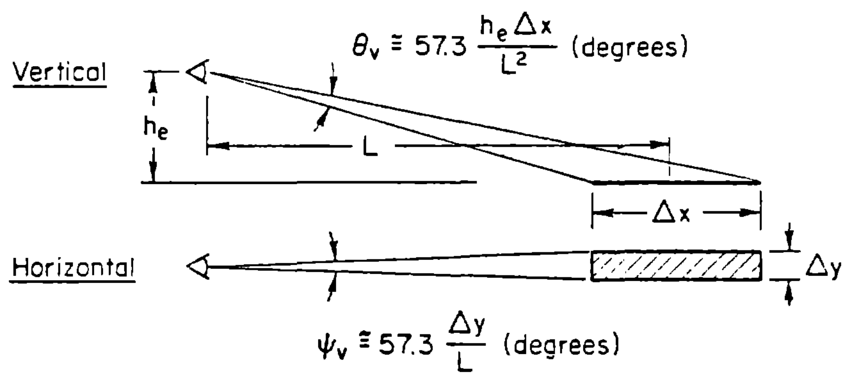
The range of interest for background luminance can be bounded on the low end by prevailing night illumination conditions. At night the roadway illuminated by headlights and fixed luminaires has a luminance range

TABLE 1. VISUAL ANGLE SIZE OF A LANE STRIPE, 4 in. × 15 ft (.10 × 5.56 m) AT VARIOUS ROAD DISTANCES FOR h_e = 4 ft (1.22 m)

MEASURE	DOWN-THE-ROAD DISTANCE, ft (m)					
	25 (7.62)	50 (15.2)	100 (30.5)	200 (61.0)	300 (91.5)	400 (122)
Vertical — θ_v (min)	330	82	21	5.2	2.3	1.3
Horizontal — ψ_v (min)	46	23	11	5.7	3.8	2.9
Equivalent Diameter[a] (min)	139	49	17	6.1	3.3	2.2

[a]The diameter of a circle of equivalent area to the delineation element.

Apparent angular size:



$$\theta_v \cong 57.3 \frac{h_e \Delta x}{L^2} \text{ (degrees)}$$

$$\psi_v \cong 57.3 \frac{\Delta y}{L} \text{ (degrees)}$$

from 0.003 to 4 ft-L (foot-Lamberts), with an average luminance in the range from 0.1 to 0.3 ft-L.[3] Note in Fig. 2 that, at the upper end of the luminance range, visual characteristics change only slightly beyond 10 ft-L. This background luminance level is a practical upper limit of simulation projection displays of interest in this study. The Blackwell data[2] suggest that simulation work can be conducted in the 10 ft-L range and still apply to daytime road luminances in the range of 100-1000 ft-L which would occur under fog or rain conditions.

The Fig. 2 data were collected in an ideal laboratory environment with young observers. For our application there are several real-world factors that tend to influence contrast thresholds. Driver-related factors include alertness in performing the detection task, target expectancy, and reduced acuity and contrast sensitivity with age.[3] Target-related factors include exposure time and apparent motion. In the case of delineation such as a dashed line, closely spaced elements would tend to point towards succeeding elements, thus increasing target expectancy.

Forward velocity results in apparent delineation motion and research with moving sine wave gratings have shown that contrast thresholds are actually at a minimum when the apparent frequency of motion (i.e., pattern elements/unit time past a fixed point) is in the region of 1-5 Hz.[4] If we consider the suggested national delineation cycle length guideline of 40 ft (12.2 m),[5] we can see that visual contrast sensitivity would be maximized in the speed range above 40 ft/sec (27 mph or 43.4 kph). The minimum threshold occurs somewhere in the region of 2.5 Hz [68 mph or 109 kph for the 40 ft (12.2 m) delineation cycle length!]. In conjunction

[3] Richards, O. W., "Vision at Levels of Night Road Illumination. XII. Changes of Acuity and Contrast Sensitivity with Age," American Journal of Optometry and Archives of the American Academy of Optometry, Vol. 43, No. 5, 1966, pp. 313-319.

[2] Blackwell and Taylor, "Survey of Laboratory Studies."

[4] Pantle, Allan, Research on the Recognition and Analysis of Complex and Dynamic Imagery, Aerospace Medical Research Lab., AMRL-TR-75-61, Oct. 1975.

[5] Manual on Uniform Traffic Control Devices for Streets and Highways, Federal Highway Administration, 1971.

with other factors this could possibly contribute to the relatively small speed reductions observed in fog.[6] Shorter dashed line cycle lengths, such as the California 24 ft (7.3 m) standard[7] would appear to be an effective countermeasure to excessive speed under reduced visibility conditions; the simulation experimental results in Section III seem to bear this out.

The contrast threshold levels given in Fig. 2 are very optimistic, being established for 50 percent target detection with expected targets under unlimited viewing conditions. Much higher levels are found in practice, however. For meteorological purposes, the minimum contrast threshold is normally taken as 0.02,[1] while the minimum threshold in Fig. 2 is noted to be approximately 0.003. In order to account for various practical or "field" viewing conditions, previous investigators have applied contrast multipliers to the Fig. 2 data. Since the vertical scale is logarithmic, the curves can simply be translated up (i.e., higher contrast threshold) to account for various effects. Blackwell, et al.,[8] have recommended a field factor of 15 for the roadway visual task. Hills[9] found a factor of 4 appropriate for the detection of taillights, disk objects, and pedestrian dummies. In more directly relevant research, Bhise, et al.,[10] found the detection of delineation-like targets (i.e., horizontal lines) to be directly predictable from the Fig. 2 Blackwell data.

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[6]Kocmond, W. C., and K. Perchonok, Highway Fog, National Cooperative Highway Research Program Report 95, 1970.

[1]Middleton, Vision Through the Atmosphere.

[7]Traffic Manual, State of California, Business and Transportation Agency, Department of Public Works, 1971.

[8]Blackwell, H. R., B. S. Pritchard, and R. N. Schwab, "Illumination Requirements for Roadway Visual Tasks," Highway Research Board Bulletin No. 255, 1960, pp. 117-127.

[9]Hills, B. L., Visibility Under Night Driving Conditions, Australian Road Research Board, Report 29, Nov. 1975.

[10]Bhise, V. D., P. B. McMahan, and E. I. Farber, "Predicting Target Detection Distance with Headlights," presented at the Annual Meeting of the Transportation Research Board, Washington, D. C., Jan. 1976.

The definitive psychophysical experiment to determine delineation detection under various configurations (i.e., dash to gap ratios, cycle lengths, widths, solid edge lines, etc.), speeds, and visibility conditions still remains to be accomplished. However, based on the above discussion, appropriate delineation contrast threshold multiplying factors for the Fig. 2 data probably lie in the region of 1-4 times. Given these threshold characteristics we can now discuss the effect of adverse visibility on delineation visual range. This is presented in the next article.

C. DELINEATION VISIBILITY

Under adverse visibility conditions we know that various environmental and/or lighting properties restrict down-the-road visibility due to contrast reduction, and this restricted "preview" has been shown to affect drive steering performance.[11] It is instructive to consider the nature of this restricted preview which occurs under various conditions.

For a uniform aerosol distribution (e.g., rain, fog) under daylight conditions, contrast decreases with range and particle density according to the simple Koschmieder law[1]:

$$C_R = C_o e^{-\sigma R} \qquad (2)$$

where

C_o = Inherent target (delineation) contrast, dimensionless

σ = Atmospheric extinction coefficient in inverse units of R (range)

C_R = Observed contrast at range R, dimensionless

[11] McLean, J. R., and E. R. Hoffmann, "The Effects of Restricted Preview on Driver Steering Control and Performance," Human Factors, Vol. 15, No. 4, Aug. 1973, pp. 421-430.

[1] Middleton, Vision Through the Atmosphere.

In Fig. 3, extinction coefficients are shown for various environmental conditions[1, 12, 13] to give some appreciation for this parameter. The data are plotted as a function of meteorological range, V_2,[1] which is a standard visual range calculation defined as the distance at which target contrast is reduced to 2 percent of the inherent target/background value:

$$\frac{C}{C_o} = e^{-\sigma V_2} = 0.02$$

Therefore

$$V_2 = 3.912/\sigma \qquad (3)$$

This measure does not take into account the Blackwell visual sensitivity data, but does provide a standard measure of visual range. As will be discussed subsequently, visual ranges on the order of 100 ft (30.5 m) and greater are adequate for good steering control,* so we are concerned with the lower right-hand corner region of Fig. 3.

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*We must reiterate here that the primary concern of this study is with the lateral guidance or steering control of vehicles along delineated pathways. The seeing distances required for delineation use in steering control[11] are much less than those typically required for minimum stopping distance.[14] Stopping is typically evoked either by traffic control devices such as signals or signs or by obstacles in the pathway. It is possible under conditions of low delineation-to-roadway contrast that delineation visual range might be on the order of 100 ft (30.5 m) or less, while the sight distance of signals or stoplights (illumination sources) could be much longer and perfectly adequate for the required stopping distance at a given speed. Here we will concern ourselves with the contrast and configuration of delineation required to permit adequate path guidance.

[1]Middleton, Vision Through the Atmosphere.

[12]Ivey, D. L., E. K. Lehtipuu, and J. W. Button, "Rainfall and Visibility — The View from Behind the Wheel," Journal of Safety Research, Vol. 7, No. 4, Dec. 1975, pp. 156-169.

[13]Eldridge, R. G., "Haze and Fog Aerosol Distributions," Journal of Atmospheric Science, Vol. 23, Sept. 1966, pp. 605-613.

[11]McLean and Hoffmann, "The Effects of Restricted Preview."

[14]A Policy on Geometric Design of Rural Highways — 1965, American Association of State Highway Officials, 1967.

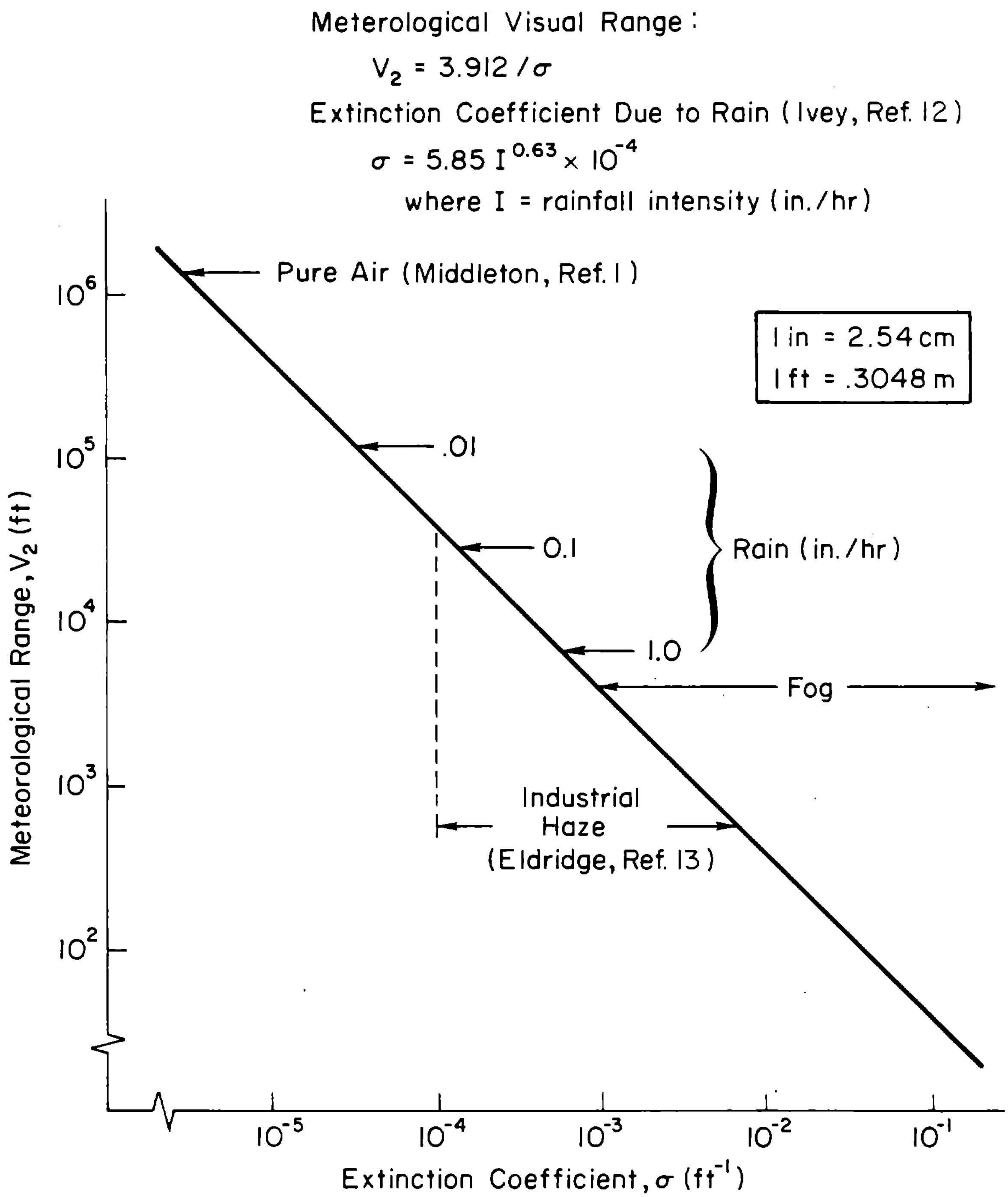

Figure 3. Extinction Coefficients for Various Atmospheric Conditions

Effects under nighttime conditions are somewhat more complicated. Illumination is then extremely non-uniform, being provided both by headlights and fixed luminaires which have complex distributions. Also, scattering, particularly backscatter from headlights, provides a complex distribution of veiling luminance in the visual scene. In general, the contrast of an object at night which determines visual detection is given by the expression:

$$C_R = \frac{L_T - L_B}{L_B + L_{BS} + L_G} \tag{4}$$

where

$L_{T,B}$ = Target and background luminance determined by headlight pattern and roadway and delineation reflectance

L_{BS} = Backscatter luminance which is a function of atmospheric scattering

L_G = General background luminance or glare due to other illumination sources

The effects of backscatter and non-uniform glare sources act as an equivalent extinction coefficient which is a function of range, such that contrast attentuation at night will be greater than that associated with Koschmieder's law.

The luminance terms in Eq. 4 can be expressed in terms of various independent variables depending on a given situation. For target luminance at the driver's eye:

$$L_T = \frac{\rho(\varphi) I_o(\psi, \theta) e^{-2\sigma R}}{R^2} \tag{5}$$

where

$\rho(\varphi)$ = Target reflectivity as a function of the illumination incidence angle, φ

$I_o(\psi, \theta)$ = Headlight illuminance as a function of displacement from the horizontal (ψ) and vertical (θ) optical axes

In this case light is scattered both going to and returning from the target, accounting for the doubled exponent in Eq. 5 over Eq. 3.

The addition of the headlighting has also added another photometric effect as illustrated in Fig. 4. The headlight illuminates the fog, thus causing a veiling luminance in front of the target. The total backscatter (L_{BS}) must be computed by accumulating (i.e., integrating) the backscatter contributions along the driver's line of sight to the target of interest. The amount of scattering is a function of the scattering angle and the headlight illuminance characteristic. The scattering function is fairly stable over a range of fog types[15,16] and the function given in Ref. 15 is probably adequate for the current discussion.

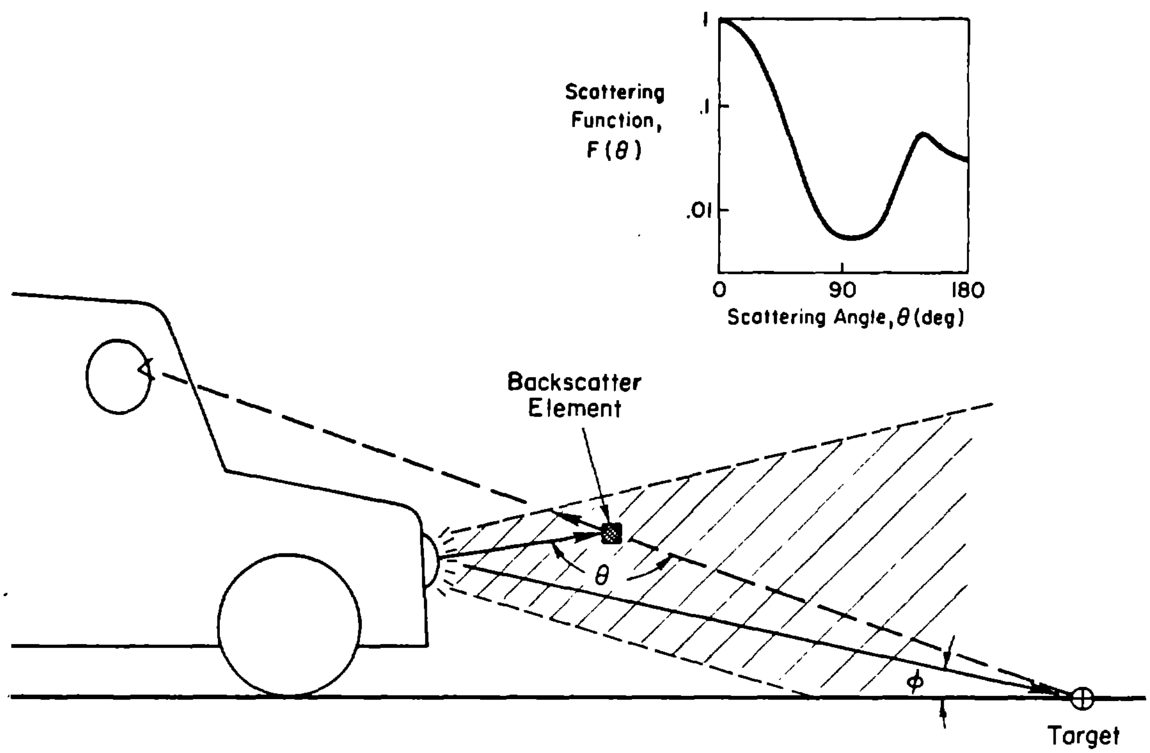

Figure 4. Veiling Luminance Due to Headlight Backscatter

[15]Spencer, D. E., "Scattering Function for Fogs," Journal of the Optical Society of America, Vol. 50, No. 6, June 1960, pp. 584-585.

[16]Winstanley, J. V., and M. J. Adams, "Point Visibility Meter: A Forward Scatter Instrument for the Measurement of Aerosol Extinction Coefficient," Applied Optics, Vol. 14, No. 9, Sept. 1975, pp. 2151-2157.

A final photometric effect which is of importance is that of glare sources such as those created by the headlights of oncoming traffic. The effect of such glare sources is to add a veiling luminance to the visual field. Building on the work of previous researchers, Schmidt-Clausen and Bindels[17] have established a refined model for the equivalent brightness of a number of glare sources:

$$I_G = K_G \sum_{1}^{n} \frac{I_{Gi}}{\beta_i^{2.2}} \qquad (6)$$

where

I_G = Glare source illuminance

β = Glare source angle from the line of sight

K_G = Constant

The above expression describes a "disability" glare in that it acts to reduce visual performance.

The Blackwell contrast detection threshold data of Fig. 2 can be interpreted in delineation visibility terms by defining an equivalent target size for delineation elements as given in Table 1. If equivalent delineation target size is computed as a function of range and a given background brightness is assumed, the required contrast for detection of typical delineation elements can be determined. Examples of these for delineation element lengths of 9 and 15 ft (2.7 and 4.6 m) are plotted in Fig. 5. Because the equivalent target size decreases with range, the contrast threshold increases with distance as shown. The magnitude of the effects is somewhat different, however, depending on the source of illumination as discussed below.

Consider first the situation with natural illumination which is relatively constant over the visibility distances of concern here. In Fig. 5a

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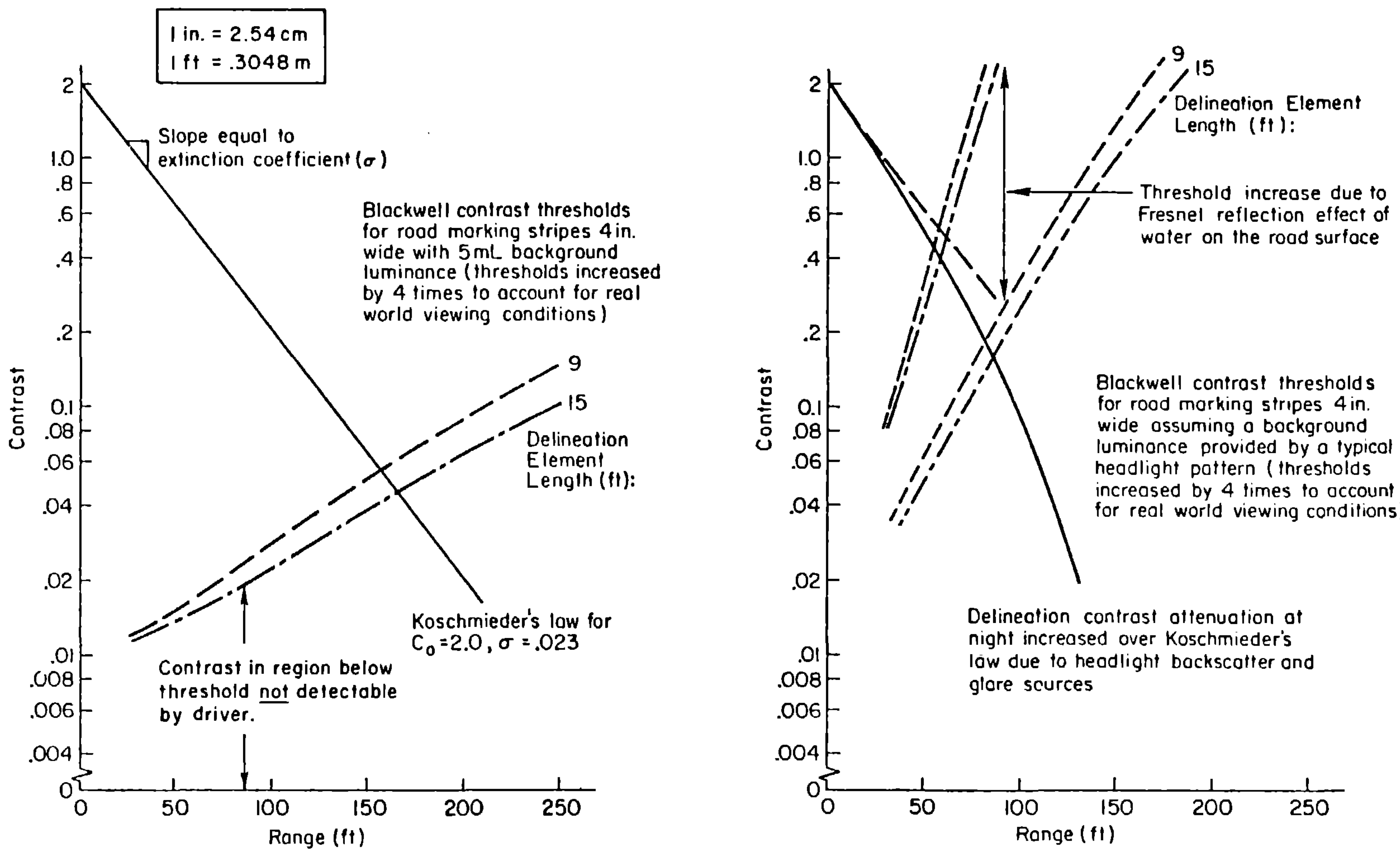
[17]Schmidt-Clausen, H. J., and J. T. H. Bindels, "Assessment of Discomfort Glare in Motor Vehicle Lighting," Lighting Research and Technology, Vol. 6, No. 2, 1974, pp. 79-88.



a) Daylight Illumination

b) Headlight Illumination

Figure 5. Delineation Visibility Under Natural (Daylight) and Night (Headlighting) Conditions

driver detection thresholds have been plotted for a worst-case daytime road luminance level (5 ft-L). (This level would occur at sunset on an overcast day[1] or even earlier in heavy fog conditions.) Koschmieder's law (Eq. 2) plots as a straight line on the logarithmic coordinate of Fig. 5a as shown, and the point at which the apparent delineation contrast recedes below the driver's detection threshold defines the delineation visibility range.

Now let us consider visibility conditions at night under headlighting conditions. Headlights provide extremely non-uniform illumination which results in decreasing pavement luminance as a function of distance down the road as shown for typical conditions in Fig. 6. We can use these

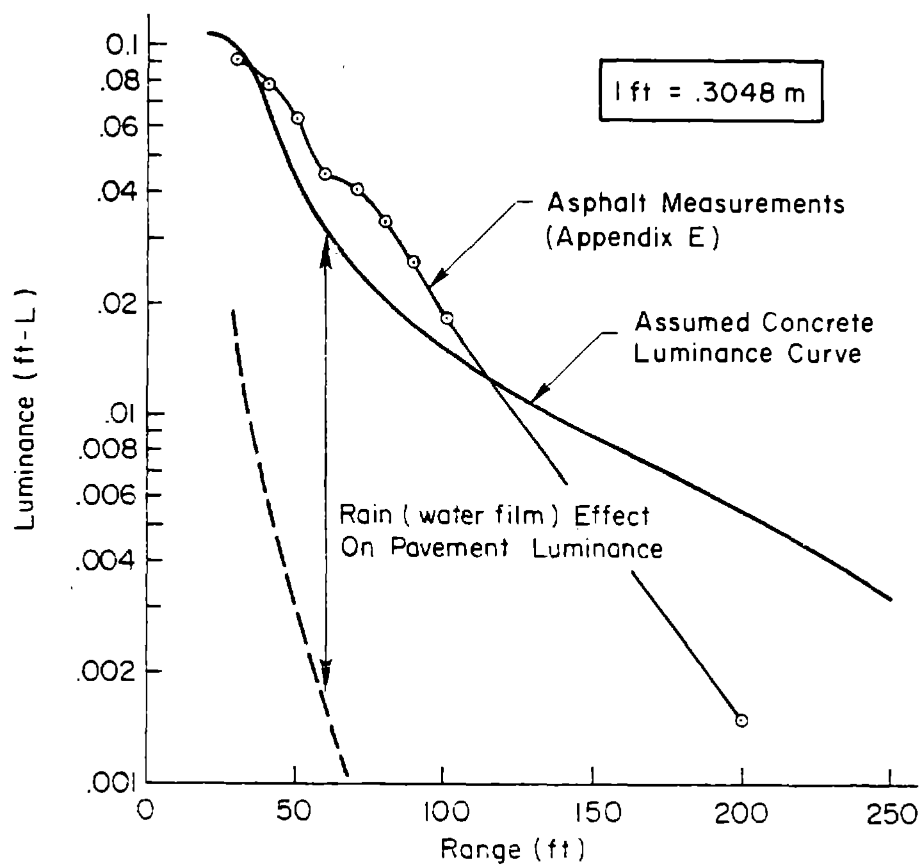


Figure 6. Roadway Luminance for Typical Headlighting Characteristics

[1]Middleton, Vision Through the Atmosphere.

levels as background luminance in order to determine Blackwell contrast threshold levels for delineation as shown in Fig. 5b. Note the appreciable increased differential threshold relative to daytime conditions because of the rapidly receding level of pavement luminance under headlighting conditions. Apparent delineation contrast will decrease even more rapidly with range than Koschmieder's law, due to backscatter and glare effects as given in Eq. 4. The various night visibility effects then combine to give delineation visibility ranges well below those under similar daytime conditions as shown in Fig. 5.

One final consideration that is important here as background for our field experiments (Section IV) is the effect of rain. The air/water interface on an inundated road causes high Fresnel reflection of the headlight illuminance as shown in Fig. 7.[18] This effect drastically reduces the amount of roadway luminance returned to the driver as shown in Fig. 6, which then leads to increased contrast thresholds as shown in Fig. 5b. Of course, the wet roadway also increases the reflected glare from opposing headlights, luminaires, etc., and during the day causes reflections of the visual surround. These additional factors cause equivalent glare and/or veiling luminance effects and are not easily illustrated in the Fig. 5 plot.

Although the visibility factors illustrated in Fig. 5 are plotted for some specific conditions, they do lead to some general conclusions about delineation visibility. First, a combination of factors determines visibility range, including inherent contrast (C_o), atmospheric extinction (σ), illumination source, and size of road marking. Thus, a variety of conditions could yield the same visibility range; for example, low contrast road markings and moderate fog compared to high contrast markings and dense fog. Second, the intersection of delineation contrast with the inferred Blackwell contrast threshold implies a fairly sharp cutoff in visibility range which may not be unduly sensitive to variability factors such as between-driver differences, etc. Third, because of the logarithmic contrast scale

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[18] Grieser, D. R., C. E. Moeller, M. M. Epstein, and J. R. Preston, "Performance of High Visibility Wet-Night Highway Lane Dividers," Optical Engineering, Vol. 15, No. 1, Jan.-Feb. 1976, pp. 52-55.

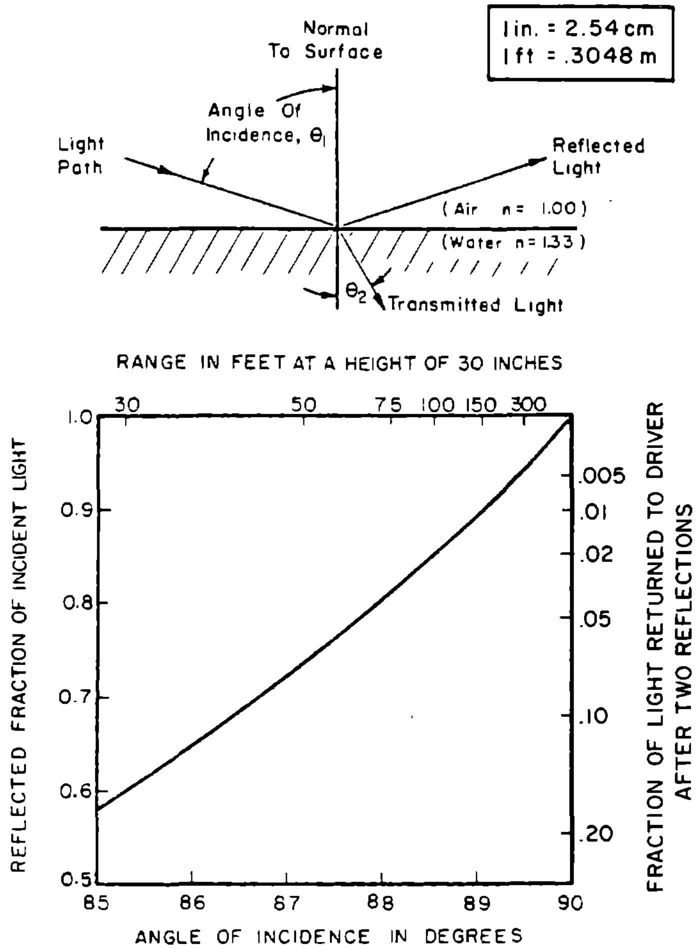

Figure 7. Fresnel Reflection for Unpolarized Light at an Air/Water Interface (Adapted from Ref. 18)

in Fig. 5, the plots can be translated vertically to determine the sensitivity of various effects. For example, moving the atmospheric attenuation plot up and down corresponds to changing the inherent contrast of the delineation (C_o), while translating the contrast threshold curve corresponds to multiplying factors applied to Blackwell laboratory data (Fig. 2) to account for real-world conditions such as observer attention, exposure time, age, etc.[19] A relative displacement of the atmospheric and threshold curves by a factor of 2 changes the visibility range by

[18] Grieser, "...Wet-Night Highway Lane Dividers."

[19] Duntley, S. Q., J. I. Gordon, J. H. Taylor, et al., "Visibility," Applied Optics, Vol. 3, No. 5, May 1964.

about 10 percent, while a similar change in the atmospheric extinction coefficient (i.e., the slope of the Koschmieder relationship) would lead to approximately a 50 percent change in visibility range. This gives some feeling for the sensitivity of various parameters which influence delineation visibility.

It is obvious from the above discussion that delineation detection is affected by a myriad of factors, far too many to be considered in any consistent manner in a single study. This dilemma was obvious early in this program, and a concerted effort was made to uncover those few independent variables that directly affect the driver's steering control capability. As will be discussed further in the next article, one key variable is the apparent visual range of the delineation as perceived by the driver. Previous research has found that during daylight subjects tend to fixate and scan in areas about 75 ft forward of the vehicle.[20] Using lamps illuminating small areas at several distances from the driver, the same study also reported that a lamp aimed at about 75 ft (23 m) resulted in the best maintenance of velocity and lane position.

The concept of a delineation visual range is quite appealing, particularly under conditions of severe reduction in atmospheric transmission where this visual range would be quite definite as suggested by the Fig. 5 analysis. Based on these observations, simulator work in this study was conducted with visual range as an independent variable under the premise that delineation above detection threshold would result in adequate perception of available information content. In the field tests, driver observations were combined with photometry to determine delineation visual ranges. This avoided the subtleties and well-known experimental difficulties of various photometric conditions which combine to give equivalent visual ranges. The extremely complex psychophysical problem of delineation photometric thresholds must be left for future studies.

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[20] Rockwell, T. H., R. L. Ernst, and M. J. Rulon, "Visual Requirements in Night Driving," NCHRP Report 99, 1970.

D. PERCEPTION AND DRIVER/VEHICLE SYSTEM GUIDANCE REQUIREMENTS

Given that a feature (e.g., dashed line) is detected, the driver's perceptual processes can extract information from the feature. As discussed in the previous article, adverse visibility conditions can reduce visual range, and the question now to be considered is how reduced visibility might affect driver perception of vehicle path and subsequent control actions.

An abstraction of the driver's perceptual task is illustrated in Fig. 8, a perspective view of a single lane bounded by dashed lines. With forward motion in a straight line the driver's visual scene appears to expand from a perspective vanishing point at infinity. Theories have been advanced for a focus or center of expansion perception of motion.[21] The center of expansion is the only point in the visual field that is apparently stationary, and it would provide a direct cue for the car's path angle. Thus, when

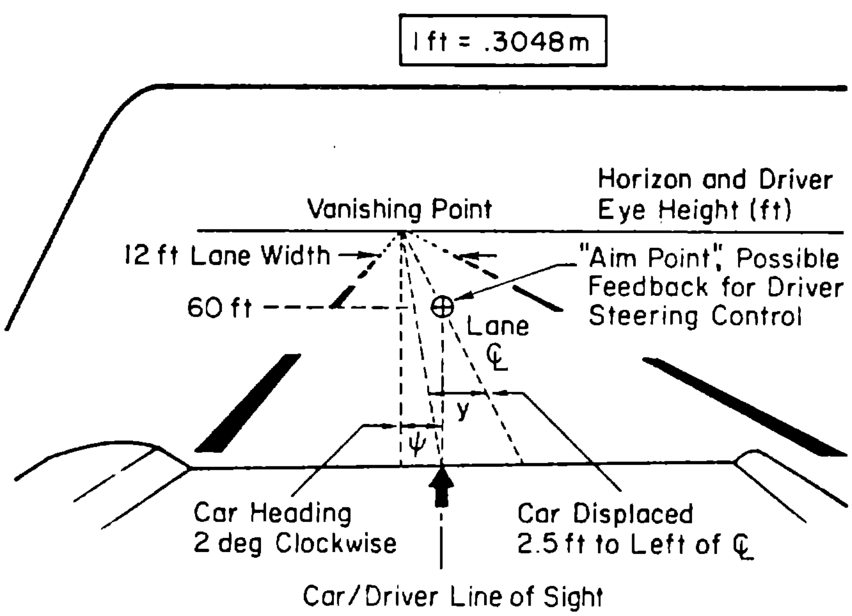

Figure 8. Driver's Perspective View of a Single Delineated Path Illustrating an Aim Point Control Law

[21]Gibson, J. J., "What Gives Rise to the Perception of Motion," Psychology Review, Vol. 75, 1968, pp. 335-346.

forward view is reduced by adverse visibility, direct perception of path angle is denied the driver according to the focus of expansion theory. This theory has some problems, however. As Gordon[22] notes, for curved paths the center of expansion lies at the center of curvature, which is at right angles to the path of the vehicle. Furthermore, Palmer[23] has found that the center of expansion in visual fields expanding at various constant rates of expansion can only be perceived with 1-6 degrees of visual angle, which is much too coarse for vehicular control.

In a perspective motion field the streamers themselves play a more important role in the views of Calvert,[24] who emphasized their role in both directional and longitudinal control of aircraft on the final approach, and of Gordon,[22] who considered terrestrial vehicles. The streamer theory states in essence that the driver perceives motion from objects in the visual field streaming across his field of view. Although the streamers emanate from the center of expansion, Gordon believes that it is the streamers themselves, particularly those provided by roadway boundaries and lane markings, that underlie the directional cue rather than the center of expansion itself. He notes that all parts of the visual field, road borders, and lane markers move when the wheel is turned but no one part is essential for tracking and that the driver responds to a total situation (a gestalt concept), not to isolated or ranked cues. Streamer perception should be fairly robust in the face of reduced visibility, although reduced contrast would eliminate many subtle cues (e.g., road roughness, edge texture), particularly those available outside foveal vision where contrast sensitivity and acuity degrade.[25]

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[22]Gordon, D. A., "Perceptual Basis of Vehicular Guidance," Public Roads, Vol. 34, No. 3, Aug. 1966, pp. 53-68.

[23]Palmer, E. A., "Experimental Determination of Human Ability to Perceive Aircraft Aimpoint from Expanding Gradient Cues," Aerospace Medical Meeting, Preprint of Scientific Program, San Francisco, May 1969, pp. 176-177.

[24]Calvert, E. S., "Visual Judgments in Motion," Journal of the Institute of Navigation, Vol. 7, 1957.

[25]Haines, R. F., "A Review of Peripheral Vision Capabilities for Display Layout Designers," Proceedings of the SID, Vol. 16/4, Fourth Quarter, 1975, pp. 238-249.

Control theory analysis and research into land vehicle steering control have identified cues that must be perceived either explicitly or implicitly in order to give good, stable performance. The car's position relative to the delineated path is the most obvious of these. Various studies have also demonstrated that heading or path angle is essential to achieving stable control (as reviewed in Ref. 26). Thus, properly weighted components proportional to lateral position and heading must be present in the driver's steering wheel deflection if the car's path is to be regulated in the lane.

One intuitively appealing model for driver lateral control involves steering inputs based on an aim point down the road as illustrated in Fig. 8. The aim point angle is one way to combine lateral position and preview-range-weighted heading into a single control quantity. The dynamics of this simple control model, among others, have been analyzed previously.[27] For an aim point at a distance, x_a, a look-ahead or preview time constant dependent on vehicle speed, U_o, can be defined as follows:

$$T_a = x_a/U_o \tag{7}$$

McLean[11] has reviewed a number of driving experiments involving variations in restricted forward view and vehicle speed which found preview times (T_a) of 2 sec or greater. The results were quite variable, however, and it would be hard to conclude an average or typical preview time constant.

If there is a preferred look-ahead distance or time constant, then restricted visual range due to adverse visibility could interfere with this cue, and the visual ranges shorter than the preferred look-ahead distance would be expected to deteriorate performance.

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[26]McRuer, D. T., R. W. Allen, D. H. Weir, and R. H. Klein, "New Results in Driver Steering Control Models," Human Factors, Vol. 19, No. 4, Aug. 1977, pp. 381-397.

[27]McRuer, D. T., D. H. Weir, H. R. Jex, et al., "Measurement of Driver/Vehicle Multiloop Response Properties with a Single Disturbance Inputs," IEEE Transactions, Vol. SMC-5, No. 5, Sept. 1975, pp. 490-497.

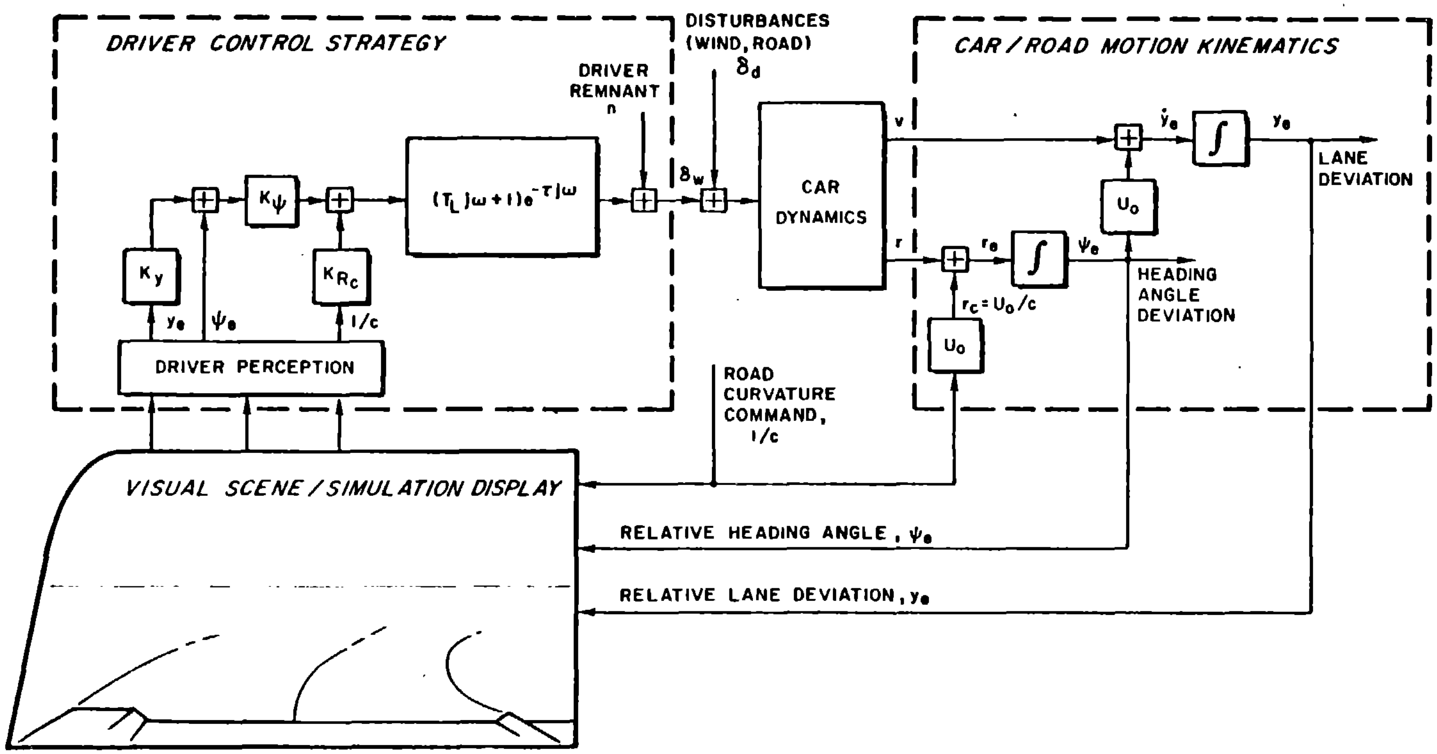
[11]McLean and Hoffmann, "The Effects of Restricted Preview."

Lane position and heading cues do not necessarily have to be perceived at a combined aim point, however. Referring again to Fig. 8, simple geometric analysis shows that for small angles the car's heading angle deviations with respect to the lane appear as horizontal translations of the visual scene. For car lateral position deviations with respect to the lane the road appears to rotate about its vanishing point at the horizon. Thus heading and lateral position are separately available from the perspective view _if_ a sufficient segment of this view is visible.

To gain further insight into driver perceptual requirements, consider the detailed driver/vehicle system dynamic model illustrated in Fig. 9. Here the vehicle model gives heading angle and lateral lane deviations (ψ and y) in response to driver steering commands (δ_w). The driver develops steering commands based on his perception of lane position and heading angle errors (y_e, ψ_e) plus an additional term proportional to perceived road curvature ($1/c$). The y_e and ψ_e perceptions and associated gains (K_y, K_ψ) are basically involved in regulation-only driver control, which is handled in a compensatory fashion. The added curvature term (KR_c) is a pursuit or feed-forward element needed to account for driver behavior on curved roads. It basically assumes the driver inserts an open-loop steering wheel command proportional to perceived path curvature. Some anticipation or driver lead (T_L) is applied to these perceptions to offset vehicle lag, and a time delay penalty (τ) is incurred by the driver due to basic neuromuscular characteristics and perceptual processing load. A final component of the driver's steering action is composed of remnant (n) which is basically noise or random variation in the driver's output uncorrelated with perceptual inputs.

The regulation or error correcting portion of the Fig. 9 model, involving only lane position and heading error feedbacks (y_e and ψ_e, respectively) has been shown to have good, stable control properties[28] and to be consistent

[28] Weir, D. H., and D. T. McRuer, "Dynamics of Driver/Vehicle Steering Control," _Automatica_, Vol. 6, No. 1, Jan. 1970, pp. 87-98.



Vehicle Motions and Roadway Commands:

- v = Vehicle lateral velocity normal to vehicle path
- r = Vehicle inertial heading rate
- r_c = Equivalent roadway heading rate at vehicle speed U_o
- r_e = Vehicle heading rate error with respect to the roadway
- δ_d = Equivalent disturbances to vehicle lateral motion

Perceived Quantities:

- y_e = Lateral lane position error
- ψ_e = Vehicle heading error with respect to the roadway
- $1/c$ = Road curvature (inverse radius of curvature)

Driver Dynamic Behavior:

- K_y = Driver gain applied to y_e
- K_ψ = Driver gain applied to the composite heading error $\psi_e + K_y y_e$
- K_{R_c} = Driver gain applied to road curvature perception
- T_L = Driver lead or anticipation time constant applied to perceptually derived steering commands to counteract vehicle response lags
- τ = Driver visual/motor time delay or response time
- δ_{sw} = Resulting driver steering wheel deflection
- n = Remnant (noise) or random time variations in driver steering action

Figure 9. A Driver/Vehicle Dynamic System Model for Analyzing Adverse Visibility Effects on Steering Control

with experimental measurements.[27,29] The road curvature perception was added specifically for this research study, and results in Section III will demonstrate its efficacy.

The Fig. 9 model can serve as the basis for some observations about driver visual perception requirements and potential effects of degraded visibility. Consider first the driver's use of the aim point concept illustrated in Fig. 8. Here reductions in visual range under adverse visibility conditions can eliminate the cues required to directly perceive the aim point. In this case the driver can extrapolate from the available cues or, alternatively, separately perceive lateral and heading error deviations. In either case, however, the driver is faced with an increased perceptual load. Past research has shown that increased perceptual load leads to increases in time delay (τ) and noise or remnant.[30,31] These effects should increase with decreased visual range.

When reduced visual range interferes with direct perception of the aim point, the lane delineation configuration then should become an important factor. Consider Fig. 8 with restricted preview. The driver needs adequate information to perceive ψ_e, y_e, and road curvature. If several delineation elements are visible, or single elements are of sufficient length, these variables should be directly perceivable. If element length is reduced, however, so that path direction is not readily indicated by a single element, then two components are needed to define direction and three to indicate curvature. In terms of the Fig. 9 model, a visual segment which

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[27]McRuer, et al., "Measurement of Driver/Vehicle....Response Properties."

[29]McRuer, D. T., R. H. Klein, et al., Automobile Controllability — Driver/Vehicle Response for Steering Control. Vol. I: Summary Report. Vol. II: Supporting Experimental Results, DOT HS-801 407 and HS-801 406, Feb. 1975.

[30]McRuer, D. T., and E. S. Krendel, Mathematical Models of Human Pilot Behavior, AGARDograph 188, Jan. 1974.

[31]Allen, R. W., W. F. Clement, and H. R. Jex, Research on Display Scanning, Sampling, and Reconstruction Using Separate Main and Secondary Tracking Tasks, NASA CR-1569, July 1970.

contains at least three elements is needed for development of the K_{R_c} feedforward, while at least two elements are needed for y_e and ψ_e to be estimated. Thus, the driver/vehicle system dynamics will depend strongly on the dimensions of the visual segment. As it is reduced, performance on curves will be degraded first (K_{R_c} reduced), followed by deterioration in lane position control (K_y), etc. For segmented delineation the driver's input information also becomes perceptually intermittent as the visual segment is reduced, and intermittency has been shown to lead to increased time delay (τ) and remnant (n) in the human operator.[31]

Besides providing insight into degraded visibility effects, the Fig. 9 model also serves as a paradigm for data measurement and analysis, as will be discussed in Section III and Appendix B. The driver control strategy parameters in Fig. 9 can be determined through Fourier analysis techniques[27] during driving tests involving regulation against disturbances, and following winding roads. This technique allows the perceptual/behavioral effects of adverse visibility to be determined simultaneously during a single realistic task (in situ as it were) rather than requiring a series of artificial tests to isolate each effect.

[31] Allen, et al., Research on Display Scanning.

[27] McRuer, et al., "Measurement of Driver/Vehicle...Response Properties."

SECTION III

SIMULATION EXPERIMENT

A. OVERVIEW

A simulation approach was taken to study the effects of adverse visibility on steering control over a range of conditions that simply could not be tested in the real world due to safety, economic, and logistic considerations. Because the effects under consideration are visual in nature, a fixed-base simulator with a relatively sophisticated visual roadway display was felt to be adequate for the purposes at hand. An existing fixed-base simulator[32] was upgraded with a projected roadway display and intensity control features required to simulate the adverse visibility effects discussed in Section II.

A variety of tasks and measures, some specifically developed for this study, was included in order to determine the effects of adverse visibility on driver/vehicle system performance (e.g., lane deviations), driver behavior, and driver subjective reaction. The performance measures tell us the consequences of adverse visibility and can be related to accident risk. Driver behavior is quantified by such model parameters as illustrated in Fig. 9. These behavioral measures give us insight into effects (e.g., perceptual, workload) on the driver which will allow the results to be generalized and extrapolated to cases not tested. Because of the human's adaptive capabilities, some conditions may not elicit measurable changes in performance. Increased adaptation demands invariably lead to some driver behavioral changes and increased workload, however, and workload changes can be measured with subjective ratings.

In the following article (B) the experimental method, setup, procedures, etc., are described. This is followed by results and discussion (C) and

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[32]Allen, R. W., J R. Hogge, and S. H. Schwartz, "An Interactive Driving Simulation for Driver Control and Decision-Making Research," Proceedings of the Eleventh Annual Conference on Manual Control, NASA TM X-62,464, May 1975, pp. 396-407.

concluded with a summary and discussion of the simulator results in Article D. The simulator itself is described in more detail in Appendix A, and the control model measurement and data analysis are elaborated in Appendix B.

B. METHODS

1. Setup

A fixed-base driving simulator was used to test the concepts discussed previously. The physical arrangement of the simulator is illustrated in Fig. 10. The simulator had a high quality, wide angle video projection display of roadway markings as illustrated. Display perspective and motion were correctly represented with respect to the driver's eye position, and the electronic display generator was designed to allow a variety of delineation configurations and visibility conditions. Apparent road motion relative to the cab was controlled by driver steering, acceleration, and braking actions through equations of motion mechanized on an analog computer.

Delineation configuration and visual range could easily be controlled from an experimenter's console. The mark and cycle lengths of dashed delineation lines could be independently selected in discrete steps. The range extent of the visual segment could be set continuously from zero to a maximum display generator range of 300 ft (91.4 m). Visual range was controlled by an electronic intensity function which smoothly decreased display delineation line luminance as a function of distance down the road. Desired visual range was set subjectively as described later. This gave the desired physical results directly and minimized the need to control or account for all the subtle photometric and subjective effects which determine threshold contrast.

2. Exploratory Tests

Before a formal design and test procedures were set up, a preliminary study was conducted to determine the various conditions and tasks which would cause measurable effects and to develop measures that would be

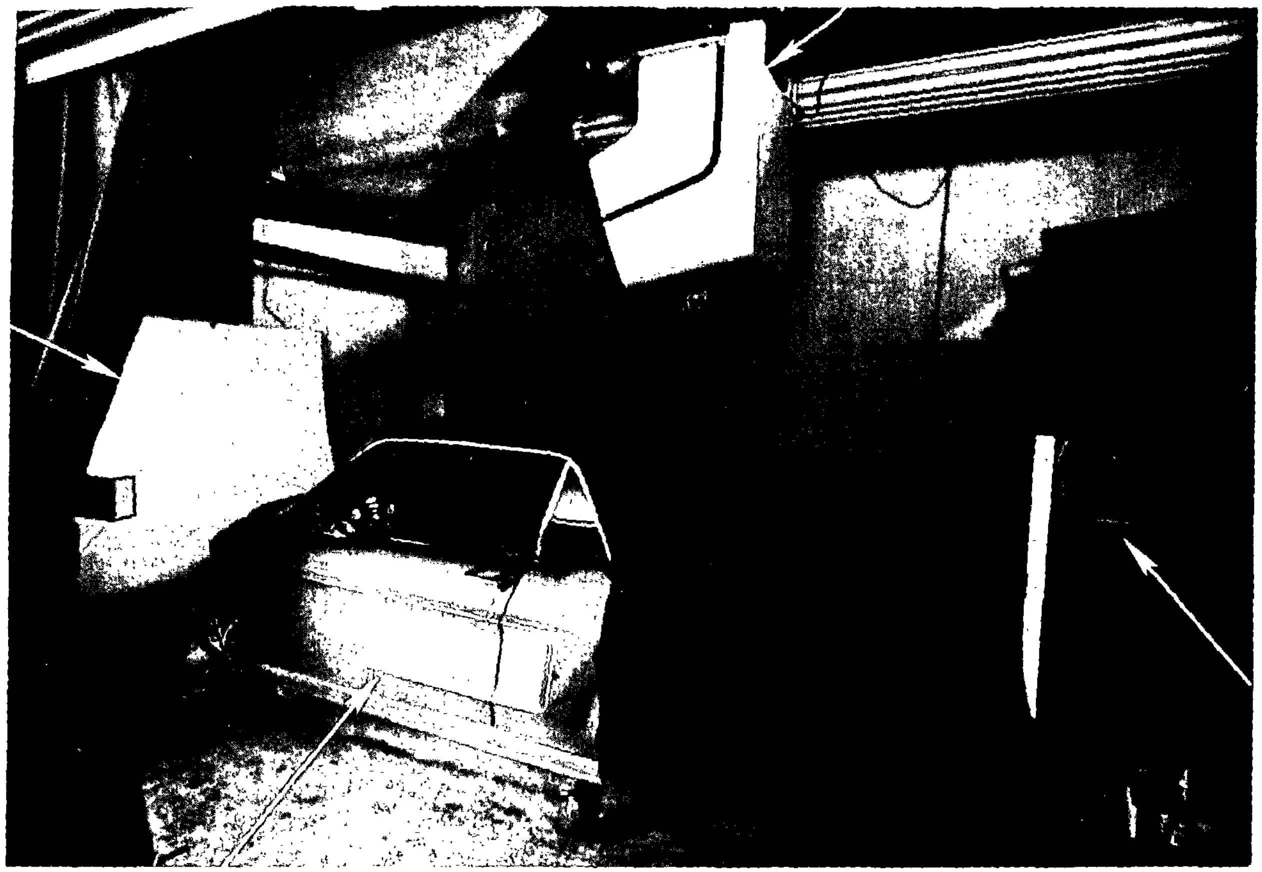

Figure 10. Driving Simulator Physical Arrangement

sensitive to these effects. Five subjects were given a short period to accommodate to the driving simulator under nominal conditions, then administered a variety of conditions including various visibility ranges and delineation configurations. Driving tasks involved steering around obstacles and through curves, and regulating against step input disturbances applied at the front wheel. Measurements included preferred driving speed and subjective comments, and the photometric (atmospheric) conditions were operationally defined by the maximum range at which the subject could detect the delineation. The following results were summarized from these tests:

a. As visibility range is reduced, delineation configuration or pattern becomes increasingly more important. Solid edge lines, longer dashes, and shorter cycle length can counteract some of the effect of reduced visibility.

b. Dashed lines lead to an interesting sampled data problem under reduced visibility conditions. The car hood restricts minimum forward view to approximately 20 ft (6.06 m) ahead of the driver's position; and when one dash disappears below the hoodline before a succeeding dash is visible through the fog, steering performance becomes very erratic. Thus, delineation gap length is a key delineation variable.

c. Long dashes can give some indication of road curvature even though only one dash is visible. Raised pavement markers are a limiting case and do not provide any inherent curvature information unless more than one element is visible.

d. Preferred speed decreases with reduced visibility, or at constant speed steering performance degrades. Both preferred and constant speed runs give sensitive measures of adverse visibility effects as does driver reaction or subjective opinion.

3. Experimental Design

Based on the exploratory tests we evolved the test matrix shown in Fig. 11. The matrix includes the important range of the three major variables of interest: visibility range, delineation configuration, and speed. The visibility range extends from close to the minimum possible for steering control (35 ft or 10.7 m) out to a distance beyond that required for

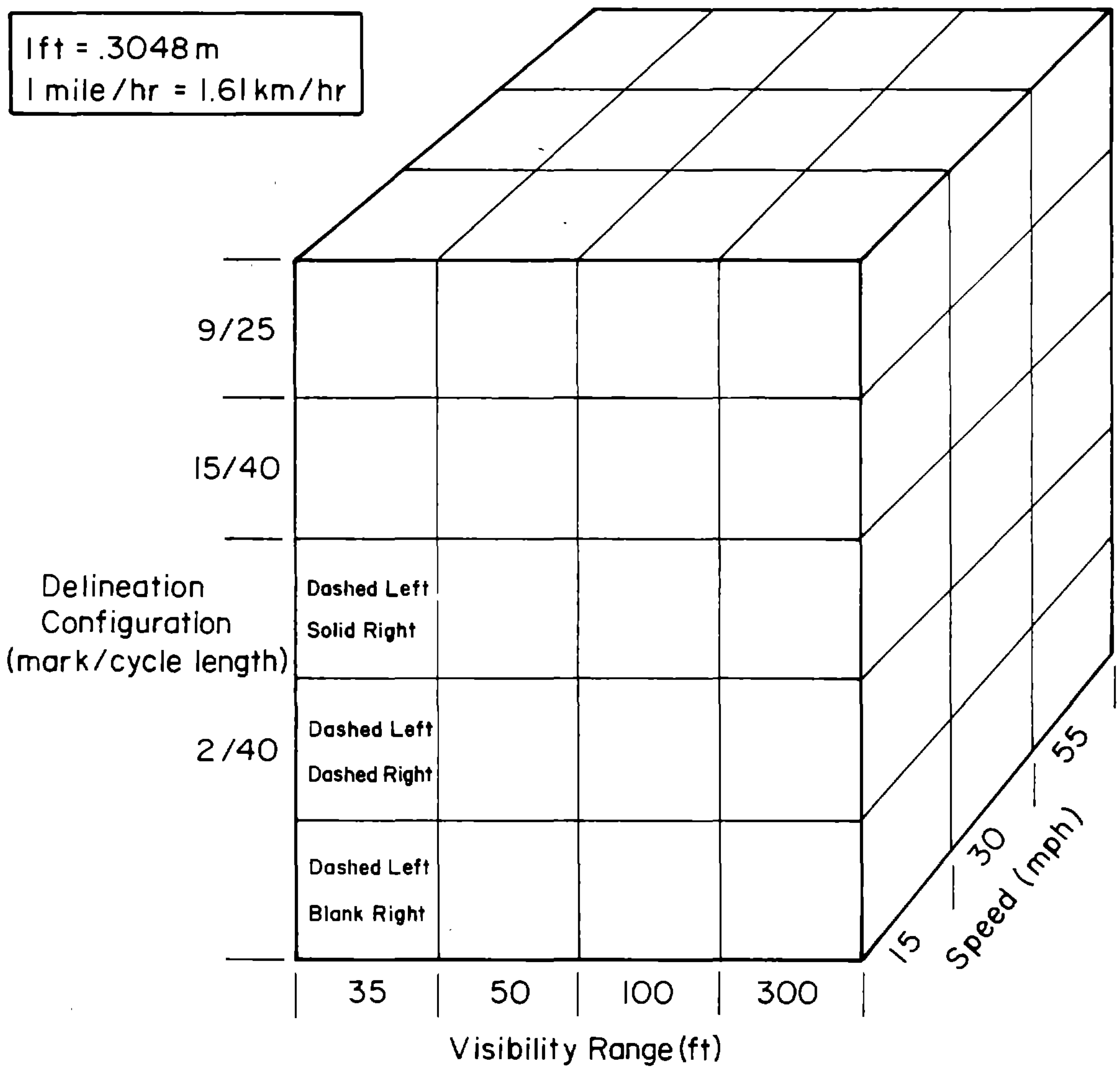

Figure 11. Simulator Test Condition Matrix

good control. Speed variations are covered from very slow to the current nationwide speed limit. Delineation configuration applies to a single lane delineated with left and right boundaries and covers a California standard with 9 ft (2.7 m) marks and 25 ft (7.6 m) cycle,[7] the national recommendation of 15 ft (4.6 m) marks and 40 ft (12.2 m) cycles*,[5] and a very short element spaced at 40 ft (12.2 m) meant to simulate retroreflective RPM's (raised pavement markers) which individually offer no directional cues. A further variation was applied to the right boundary of the RPM delineation which included either a solid, dashed, or blank (no right edge line) configuration. A solid edge line would presumably improve performance over that with dashed elements, while the lack of any edge line at all would degrade performance under adverse visibility. It was impractical to run all combinations of the factors shown in Fig. 11, so the combinations listed in Table 2 were selected to span the major dimensions, with emphasis on combinations likely to show degraded performance (i.e., higher speeds, shorter visibility ranges, and shorter delineation elements).

Based on the exploratory experiment results a configuration visibility parameter listed in Table 2 was developed to quantify differences between various combinations of delineation configuration and visual range. As illustrated in Fig. 12 the configuration visibility parameter has two components. The first, $(x_g + x_o)/x_v$, is related to the number of delineation elements visible. For $(x_g + x_o)/x_v > 1$ we see from Fig. 12 that delineation elements close to the car are obscured by the hood before the next element becomes visible down the road (hood visibility obstruction in the simulator was 19 ft or 5.8 m). The second factor, x_g/x_c, roughly quantifies the

*The Federal Highway Administration has since issued a new recommendation of 1:3 gment-to-gap ratio for broken line longitudinal pavement markings,[33] ich supersedes the MUTCD[5] recommendation for a 3:5 segment-to-gap ratio. The current recommendation for rural highways is 10 ft (3.05 m) se nts and 30 ft (9.1 m) gaps.

[7]Traffic Manual, State of California.

[5]Manual on Uniform Traffic Control Devices for Streets and Highways.

[33]"Change in Recommended Segment to Gap Ratio for Pavement Markings," FHWA Bulletin, Office of Traffic Operations, 31 May 1977.

TABLE 2. SIMULATION EXPERIMENTAL CONDITIONS

VISIBILITY RANGE ft (m)	SPEED mph (kph)	CONFIGURATION MARK/CYCLE LENGTH ft (m)	CONFIGURATION LEFT/RIGHT LANE EDGE CONFIGURATION[b]	CONFIGURATION VISIBILITY PARAMETER, C_V (Dimensionless)	PLOTTING SYMBOL[c]
300[a]	30	15/40	D/D	0.09	
100	30	15/40	D/D	0.28	
100	55	15/40	D/D	0.28	
100	30	2/40	D/D	0.54	
100	55	2/40	D/D	0.54	
50	15	9/25	D/D	0.44	
50	30	9/25	D/D	0.44	
50	55	9/25	D/D	0.44	
50	15	15/40	D/D	0.55	
50[a]	30	15/40	D/D	0.55	
50	55	15/40	D/D	0.55	
50	15	2/40	D/D	1.08	
50	15	2/40	D/S	1.08	
50	15	2/40	D/N	1.08	
50	30	2/40	D/D	1.08	
50	30	2/40	D/N	1.08	
50	30	2/40	D/S	1.08	
35	15	15/40	D/D	0.79	
35	30	15/40	D/D	0.79	

Note: 1 ft = 0.3048 m; 1 mi/hr = 1.61 km/hr.

[a]Baseline conditions repeated periodically throughout the experiment for each subject.

[b]D = dashed; S = solid; N = none.

[c]Categorized as follows:
3-sided symbols used for 15/40 (MUTCD Standard).
6-sided symbols used for 9/25 (California Standard).
4-sided symbols used for 2/40 (MUTCD Standard cycle length with short marks or RPM's).

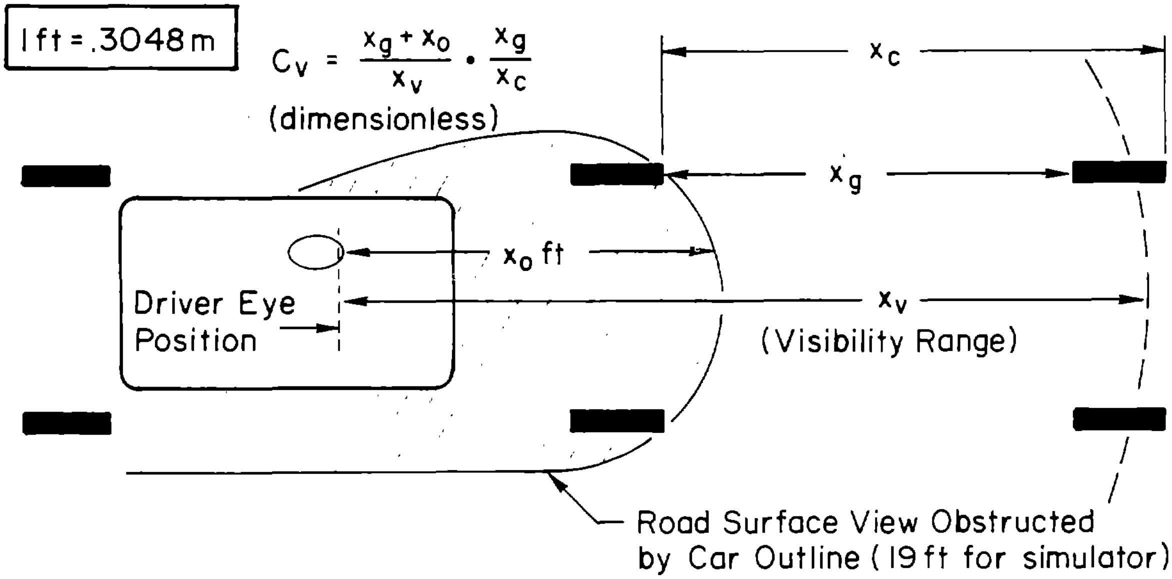

Figure 12. Configuration Visibility Parameter for Quantifying the Combined Effects of Delineation Configuration and Visual Range

proportion of available information when delineation elements are visible. These two factors are then combined into the visibility configuration parameter:

$$C_V = \frac{x_g + x_o}{x_V} \frac{x_g}{x_c} \tag{8}$$

C_V gives large values for poor visibility, large gaps, and large proportions of gap-to-cycle length ratio, and driver performance would be expected to deteriorate under these conditions. The configuration parameter therefore quantifies both the visual segment and intermittency aspects of the driver's visual scene. This parameter thus far only accounts for symmetrical delineation, however, and we will have to consider the performance effects to determine what influence the right edge line variations will have.

4. Procedures

Six licensed drivers with normal vision were selected as test subjects. Background on the subjects is given in Table 3. Prior to the formal testing/data-gathering experiments, each subject was given a brief introductory session that consisted of driving the test scenario twice through two baseline configurations involving visibility ranges of 50 and 300 ft (15.2 and 91.4 m). The purpose of this session was twofold: 1) to transition subjects' skills of everyday automobile driving to the fixed-base simulator environment; and 2) to introduce the subject to the general nature of the test plan and procedures. These initial sessions were intentionally short in order to minimize training efforts and avoid overlearning. By repeating the baseline configurations throughout the program, however, as discussed below, both short and long term training effects, if any, could be analyzed.

TABLE 3. SUBJECT BACKGROUND

SUBJECT	SEX	AGE	DRIVING EXPERIENCE (IN YEARS)	EDUCATION
A	M	29	17	B.S.
B	M	21	5	A.A.
C	M	33	17	A.S.
D	M	29	13	A.A.
E	F	41	24	H.S.
F	F	17	1	H.S.

Typically, each subject drove the entire test scenario in two or three days of concentrated testing. Each day was broken into four test sessions of one to one and a half hours each separated by a rest period. At the beginning and end of each day, the 300 ft (91.4 m) visibility baseline configuration was tested. At the beginning and end of each session, a baseline configuration was administered, either the 300 ft (91.4 m) or 50 ft (15.2 m) visibility condition. Baseline conditions were also periodically interspersed within the sessions. All configurations in the experiment were given to the subjects in a pseudo-random order. At no time was a subject aware of what conditions would be driven next.

In order to control for within- and between-subject variations in contrast thresholds and equipment variations, visibility distance was individually set for each condition according to the following procedure. The experimenter would initially set the visibility range, then ask the subject to position a line, which appeared across the roadway, to the point at which the delineation disappeared. The line position was controlled with a ten-turn potentiometer and was returned to zero between estimates. The experimenter would repeat this procedure several times, readjusting the visibility range between estimates in an iterative procedure until the desired visibility range, as indicated by the subject, was achieved.

5. Tasks and Measures

Three driving tasks and associated measurements were conducted for each experimental condition. One task required regulating against a random wind gust-like disturbance added in at the steering signal input to the vehicle equations of motion as illustrated in Fig. 9. This task required compensatory control behavior as the input could not be observed other than in its effect on vehicle motions. A second task involved following a winding road which allowed for pursuit control behavior if the visual scene provided for adequate curvature perception. Objective measures on the above tasks covered both driver dynamic behavior and driver/vehicle system performance. The details of the task inputs and measurements are discussed in Appendix B.

A third task required the subjects to follow an occasionally curving road as fast as they felt comfortable without having an accident. The measure in this situation was the driver's average or "preferred" speed. For all three tasks, the instructions to the subjects were to drive carefully, much as they would under actual adverse visibility conditions. The subjects were instructed to maintain a nominal position in the lane as well as possible, and in the case of the preferred speed run to slow down until they were able to achieve acceptable performance.

On all the above tasks, drivers were asked to express their reaction to, or subjective rating of, the various conditions encountered. Ratings were obtained via a scale marking technique[34] using the form shown in Fig. 13. These scales were designed to emphasize driver workload, compensation, and attentional demands. Each scale is fundamentally open ended and intended to be interval. No numbers are shown. When using the scale the subject shows his assessment by simply marking a location along the left-hand side. The adjectives and descriptive phrases are located to the right. It will be noted that these are not at equal intervals. Instead, their location along the equally spaced scale is nonlinearly adjusted in accordance with the techniques outlined by McDonnell.[35] This is the relative location of these words and phrases on an underlying interval psychological continuum. To the extent that this procedure is successful, rating data can then be treated as being on an interval scale. Means and variances of the numerical ratings are then unbiased estimates of driver opinions.

In rating a test configuration the subject was instructed not to rate the dynamics of the vehicle or of the display field, but instead to rate the present condition relative to a best condition. This procedure ensured that the ratings were directly related to changes in the visual scene.

C. RESULTS

1. Baseline Conditions

In order to observe any time trends (due to, e.g., learning, fatigue) during the experimental time frame, two conditions from the test scenario were chosen as "baseline" configurations and were repeated periodically throughout the experiment. These configurations were identical in roadway delineation, the MUTCD[5] recommended 15 ft (4.6 m) segments and 25 ft (7.6 m)

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[34] Guilford, J. P., Psychometric Methods, New York, McGraw-Hill, 1954.

[35] McDonnell, J. D., Pilot Rating Techniques for the Estimation and Evaluation of Handling Qualities, Air Force Flight Dynamics Lab., AFFDL-TR-68-76, Dec. 1968.

[5] Manual on Uniform Traffic Control Devices.

DATE/TIME	RUN NUMBER	SUBJECT	CONFIGURATION

CROSSWINDS

CONTROL COMPENSATION AND ANTICIPATION

- EXCELLENT — Minimum compensation (effort, anticipation) required to maintain desired (attainable) performance
- GOOD — Mild compensation required
- FAIR — Moderate compensation required
- POOR — Significant compensation required
- NEARLY UNCONTROLLABLE — Excessive control demands., cannot maintain adequate control

ATTENTION DEMANDS AND CONCENTRATION REQUIREMENTS

- COMPLETELY UNDEMANDING — Very relaxed, comfortable
- MOSTLY UNDEMANDING — Relaxed
- MILDLY DEMANDING
- DEMANDING
- VERY DEMANDING
- COMPLETELY DEMANDING — Maximum concentration

WINDING ROAD

CONTROL

- EXCELLENT
- GOOD
- FAIR
- POOR
- NEARLY UNCONTROLLABLE

ATTENTION

- COMPLETELY UNDEMANDING
- MOSTLY UNDEMANDING
- MILDLY DEMANDING
- DEMANDING
- VERY DEMANDING
- COMPLETELY DEMANDING

ROAD WITH CURVES

CONTROL

- EXCELLENT
- GOOD
- FAIR
- POOR
- NEARLY UNCONTROLLABLE

ATTENTION

- COMPLETELY UNDEMANDING
- MOSTLY UNDEMANDING
- MILDLY DEMANDING
- DEMANDING
- VERY DEMANDING
- COMPLETELY DEMANDING

COMMENTS:

Figure 13. Subjective Rating Form

gaps, but differed in visibility range. One simulated clear viewing conditions (300 ft or 91.4 m of displayed roadway in our simulator), while the second had a visibility range of 50 ft (15.2 m).

In Fig. 14 rms lane deviations during the wind gust and winding road tasks are plotted for four repetitions of the good (300 ft or 91.4 m) and poor (50 ft or 15.2 m) baseline visibility conditions. Statistical analysis of the experimental design shown in Table 4 was performed using Analysis of Variance (ANOV) procedures. Trends between the repeated baseline trials were not significant, thus indicating stable performance throughout the test sessions. This could be interpreted as little or no learning, fatigue, set changes, etc. The visibility effect on σ_y was only significant for the winding road data ($p < 0.05$). The standard deviation for the variance component of the highest order interaction (configuration × subject × replication) is plotted in Fig. 14 ("σ from ANOV") and indicates good run-to-run repeatability both within and between subjects.

The wind gust task occurs on a straight road, and the lack of significant effect of visibility on lane deviations is consistent with previous field research.[11] On the winding road the reduced preview causes increased

TABLE 4. EXPERIMENTAL DESIGN FOR ANALYSIS OF VARIANCE OF SIMULATOR BASELINE DATA

VARIABLE	LEVELS	POPULATION SIZE
Visibility	50 ft; and 300 ft	2
Subjects	Six licensed drivers	Infinite
Training/ Fatigue	Four replications spread throughout 2 data sessions	4

[11]McLean and Hoffmann, "The Effects of Restricted Preview."

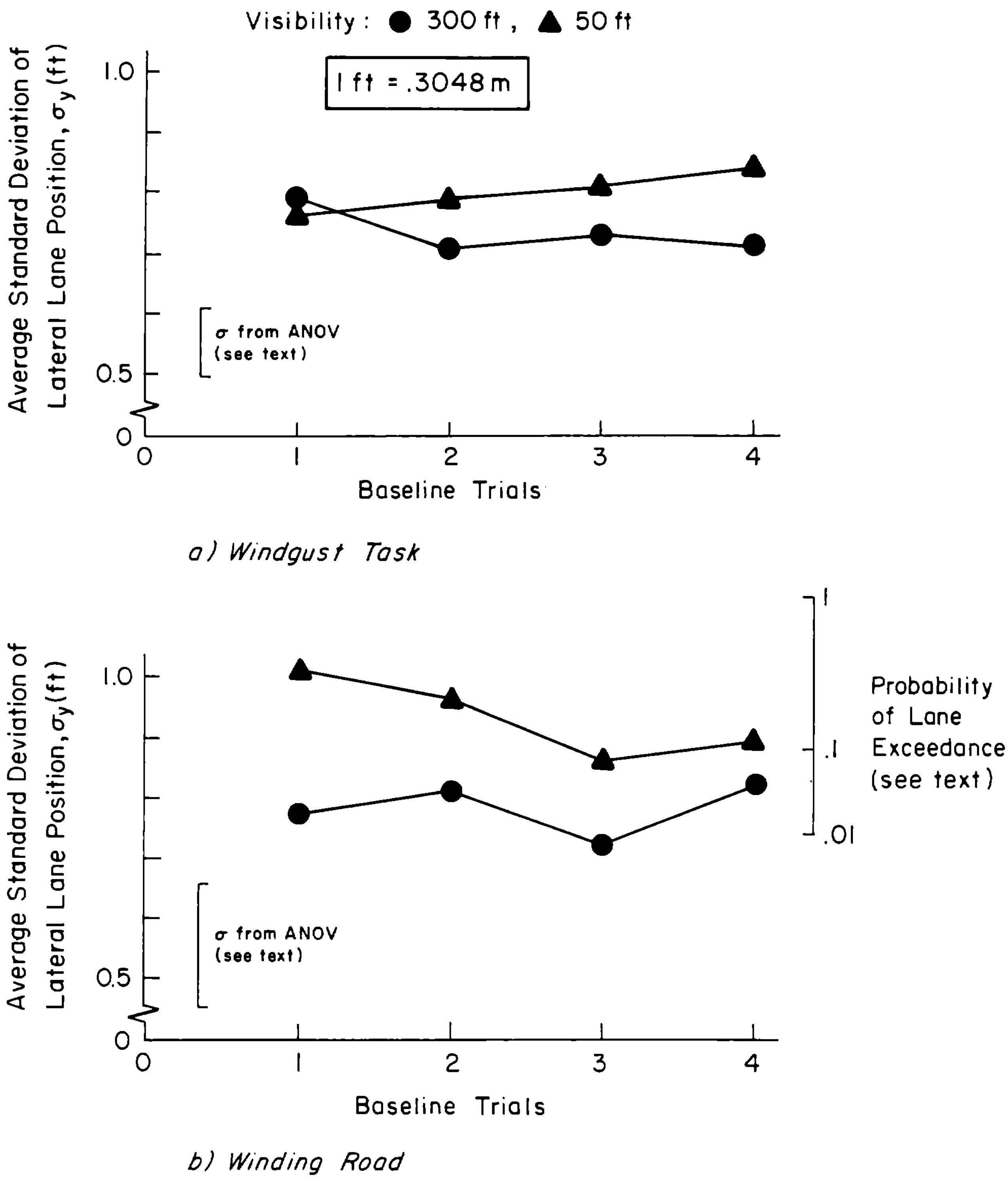

Figure 14. Effects of Visibility Baseline Conditions on Lateral Lane Position Performance in Two Simulator Tasks. Data Averaged Over Six Subjects. Repeated Baseline Trials Spread Out Over Two Data Sessions

wander in the lane, however, which leads to a sensitive change in the probability of lane exceedance which can result in increased traffic conflicts. The probability of lane exceedance in Fig. 14 was computed assuming a Gaussian distribution of lane deviations, a 12 ft (3.7 m) lane width and 6 ft (1.8 m) vehicle width.

Driver reaction to reduced visibility is illustrated in Fig. 15. Here we see that the attentional demand measure (subjective rating) reported by the driver increases appreciably as visibility is reduced, while the speed which drivers are willing to maintain on a curved road decreases. Statistical analysis shows the visibility effect to be highly significant ($p < 0.001$) with no change over the four repeated baseline runs. The underlying variability of the driver reaction measures obtained from the ANOV interaction variance is also shown in Fig. 15. The standard deviation is about 10 percent of the rating scale length for the two top plots in Fig. 15, which is consistent with previous work involving subjective ratings from the human operator.[35] These data corroborate those of Fig. 14 in showing the data to be reliable and with no indication of time trends due to learning or fatigue effects.

Comparison of treatment effects to the underlying data variability shows that driver subjective reaction measures are more sensitive than the performance measure, σ_y. In fact, for the crosswind task there was no significant treatment effect on lane deviations while there is an obvious effect on task difficulty as far as the driver is concerned. It would appear from these results that the driver is a more sensitive measuring instrument in response to the visibility treatment than objective performance measures.

2. System Performance

In Fig. 16 lane deviations for the wind gust and winding road tasks averaged over subjects are plotted both as a function of the visibility configuration parameter, C_V, and fixed speed, U_o, under which these tests were

[35]McDonnell, <u>Pilot Rating Techniques for...Handling Qualities</u>.

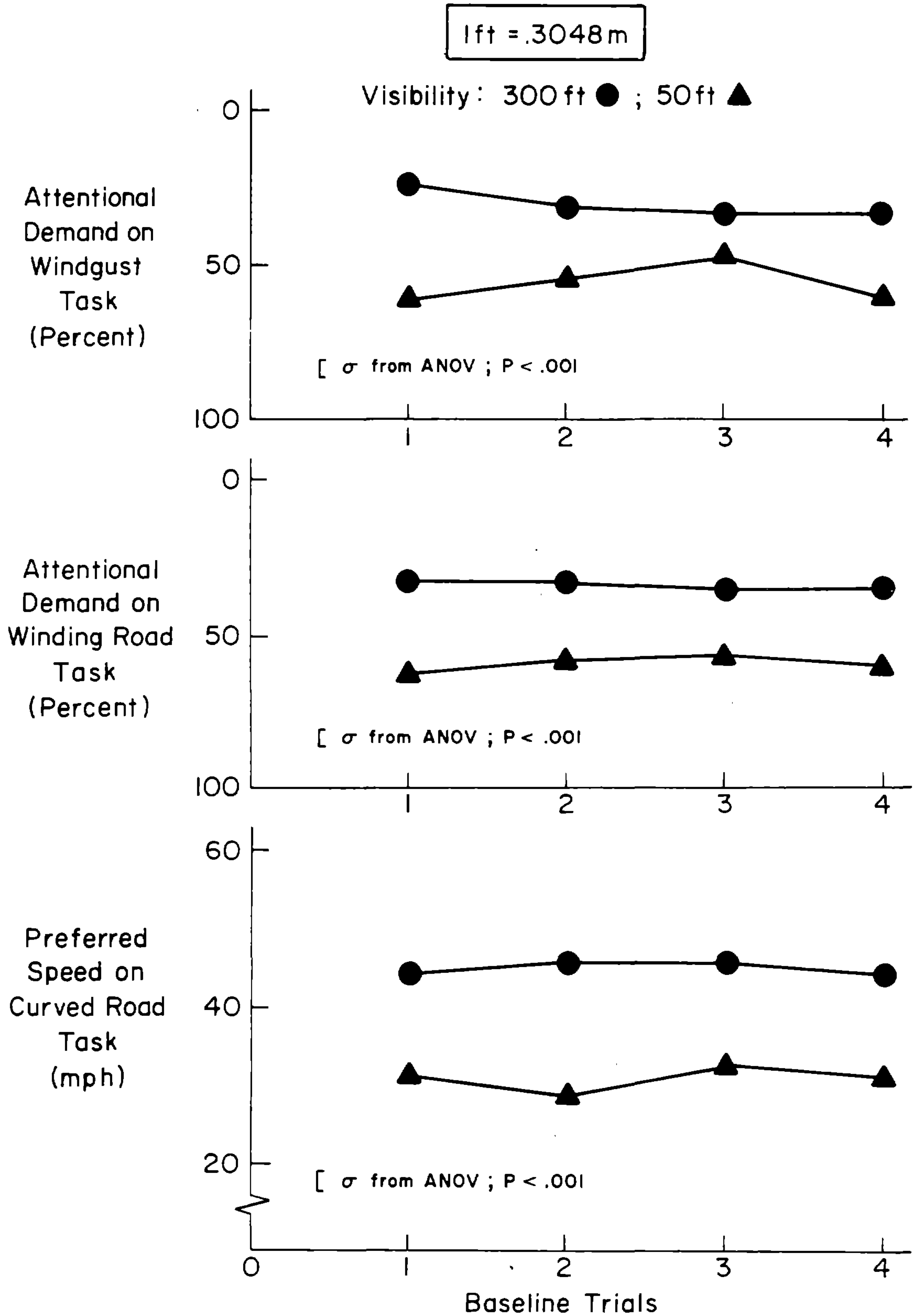

Figure 15. Driver Reaction to Reduced Visibility Conditions. Data Averaged Over Six Subjects

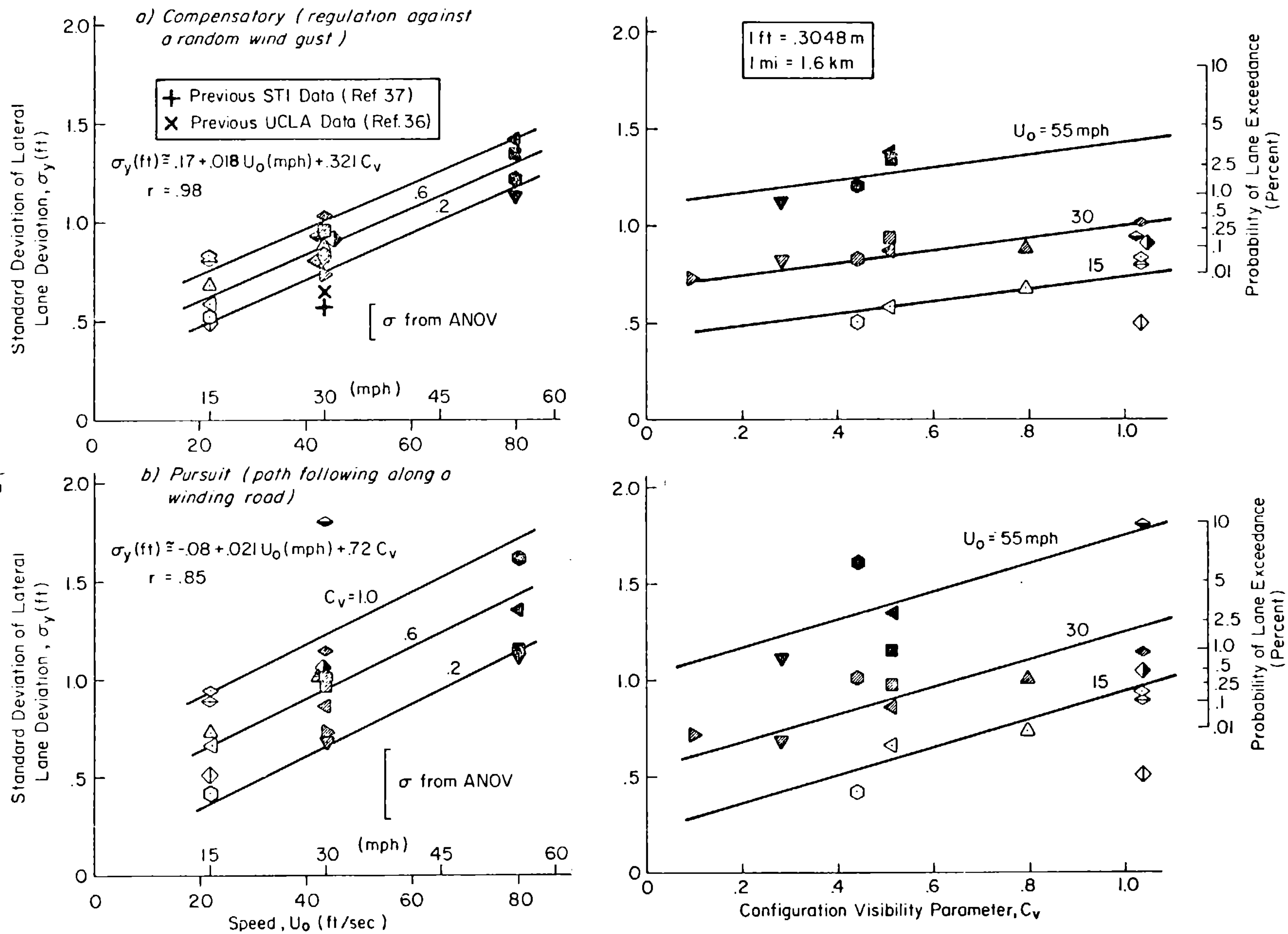

Figure 16. Lane Dispersions as a Function of Speed and Configuration Visibility Parameter

run. Lane dispersions were found to be linearly related with a high correlation to both C_V and U_o according to the relationship:

$$\sigma_y = a_o + a_1 U_o + a_2 C_V \qquad (9)$$

The coefficients for this relationship were computed using data for all the symmetrical delineations (left and right dashed lines), but excluding the solid or no right edge line conditions. The Eq. 9 coefficients and correlation coefficients are given in Fig. 16.

The σ_y plots and regression relationships show that speed sensitivity for both tasks is similar, but the winding road task is more than twice as sensitive to adverse visibility and configuration changes. The right-hand scale on the Fig. 16 plots shows the sensitivity of lane dispersions to the probability of lane exceedance. It is apparent that both speed and visibility/configuration changes can appreciably change the probability of exceeding the lane edges, which provides a measure of accident risk.

Consider now the reliability and validity of the lane dispersion data. An Analysis of Variance was performed on the data with subjects and configurations as variables. The differences between configurations were highly significant ($p < 0.001$), and the combined within- and between-subject variability is shown in brackets in Fig. 16. Thus, the reliability of the data is excellent. Also, the Eq. 9 regression relationship shows good linear correspondence, with linear correlation coefficients of $r = 0.85$ for the regulation and $r = 0.98$ for the path-following tasks, respectively.

To enhance confidence in the validity of the data, these results should be compared with past simulation and field test studies. To this end, average σ_y data from two previous simulator studies are indicated in Fig. 16. In the UCLA simulator[36] the driver was seated in an intact full

[36] Wojcik, C. K., and R. W. Allen, Studies of the Driver as a Control Element, Phase 3, Systems Technology, Inc., TR-2013-1, July 1971 (also University of California at Los Angeles, Rept. UCLA-ENG-7148).

sized sedan which was mounted on a chassis dynamometer. The dynamometer drum speed, controlled by the driver via the car's accelerator and brakes, determined the landscape velocity of a moving model landscape which was video projected on a large screen. The UCLA simulator thus provided a rich visual field which probably resulted in a very low value of C_V (i.e., less than 0.1) in addition to drive train sounds and power steering feel. Previous work on the STI simulator,[37] on the other hand, used a CRT display with two solid lane lines and no auditory cues. The solid lane lines probably also resulted in a low C_V.

In terms of validity with real-world driving it will be seen in Section IV that actual highway measurements of lane dispersion are on the order of 0.5 ft (0.15 m) or so, and previous field tests of individual driver dispersions have found similar levels.[38] There seems to be a lower bound threshold on lane deviations; and whether due to indifference or perceptual limitations, drivers do not hold lane position to much better than on the order of 0.5 ft (0.15 m). This value compares favorably with those shown in Fig. 16 for small C_V values.

The effects of right edge line variations are also illustrated in Fig. 16. Adding a solid edge line to the RPM delineation for the 15 mph (24 kph) case (◇) provided the most consistent effect. Judging from the data plot the solid edge line cases (◇, ⬗) could be given an equivalent C_V in the region of 0.4 to 0.6 and fit very nicely with the regression relationship. In fact, if we were to give the solid edge line cases a C_V averaged between the left and right lane boundary values we would end up with a value of about 0.5, since the C_V for a solid line is zero. The reason for the sensitivity of the RPM delineation to a solid edge line will become apparent when we discuss the sampling effects of intermittent delineation on driver dynamic behavior.

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[37] Allen, R. W., H. R. Jex, D. T. McRuer, and R. J. DiMarco, "Alcohol Effects on Driving Behavior and Performance in a Car Simulator," IEEE Trans., Vol. SMC-5, No. 5, Sept. 1975, pp. 498-505.

[38] Soliday, S. M., "Lane Position Maintenance by Automobile Drivers on Two Types of Highways," Ergonomics, Vol. 18, No. 2, 1975, pp. 175-183.

3. Driver Reaction

The test results discussed above were run at constant speed. In many of the poorer visibility situations (high C_V and/or high speed), however, the appropriate driver response is to slow down. This behavior option was tested for each experimental condition with a variable speed run involving path-following around discrete curves. The drivers were asked to drive as fast as they thought prudent without crashing, which would occur if the car was driven more than 2 ft (0.61 m) off the road boundary. These results are illustrated in Fig. 17, which shows that preferred speed under the various conditions as nearly a linear function of the configuration visibility parameter C_V with the exception of the solid edge line treatment. In that case the data would fall in line if they were assigned a C_V of 0.5, similar to the observation made for the performance data.

The preferred speed results have a fascinating tie-in with the fixed speed results of Fig. 16. If the driver is presumed to slow down when his lane deviations exceed a given level, $\sigma_{y_{max}}$, then Eq. 9 can be solved for the relationship between preferred speed and C_V:

$$U_{preferred} = \frac{\sigma_{y_{max}} - a_o - a_2 C_V}{a_1} \qquad (10)$$

If a maximum tolerable σ_y of 1.0 ft (0.30 m) is assumed (a lane exceedance probability of about 0.3 percent), and regression coefficients for the winding road task are used, the tolerable speed boundary shown in Fig. 17 results. This is quite consistent with the preferred speed data.

The reliability of the preferred speed data was quite good. Analysis of Variance showed the differences between configurations to be highly significant, and the combined within- and between-subject variability was on the order of 5 mph (8.0 kph).

The preferred speed runs provide an objective measure of the driver's reaction to combinations of adverse visibility and delineation configuration. As explained previously, drivers were also asked for this subjective

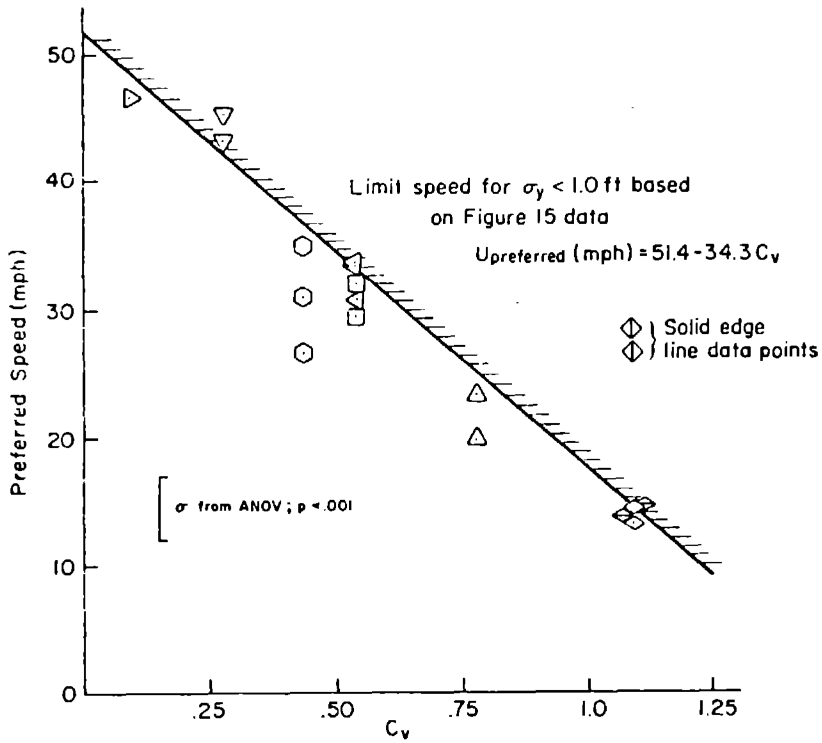

Figure 17. Driver Preferred Speed on a Curved Road under Various Delineation Configuration and Visibility Conditions; Data Averaged Over Six Subjects; Symbol Code Given in Table 1

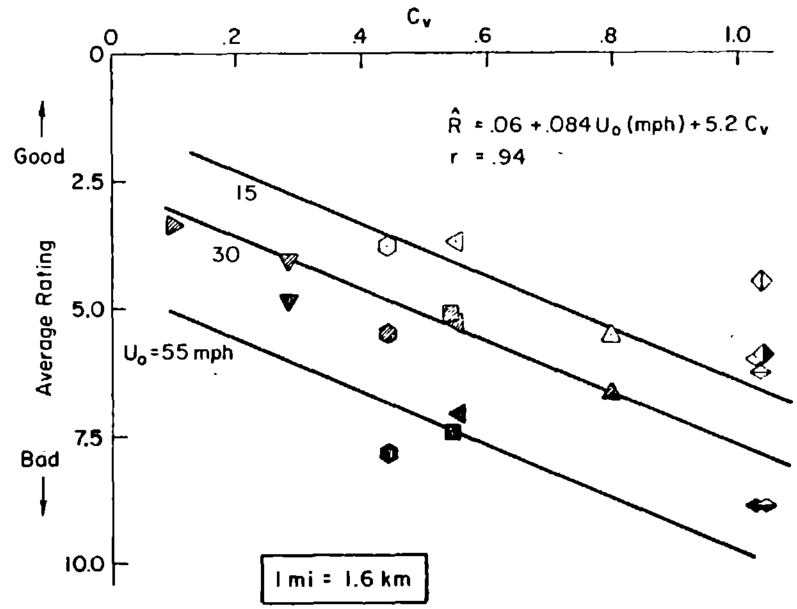

Figure 18. Driver Subjective Opinion as a Function of Speed and Configuration Visibility Parameter

reactions to the various conditions. As might be expected, the reaction on the preferred speed runs was fairly uniform, since the subjects had in effect control over the difficulty of a given situation through speed control. For the fixed speed runs there were highly significant rating differences between the various conditions as indicated by Analysis of Variance ($p < 0.001$). The four ratings for the fixed speed runs (e.g., see Fig. 15) were highly correlated, however, so an average was taken and is plotted in Fig. 18. A highly correlated linear relationship between the average rating and U_o and C_V was found as shown.

The regression coefficients for subjective rating appear to depend more strongly on U_o and C_V than did the performance relationship. Since the performance relationship agreed with the preferred speed runs, this indicates that even though drivers slow down to maintain an acceptable performance under adverse visibility, they still do not completely compensate for their subjective reaction to the condition.

Data for the right edge line treatments are shown in Fig. 18. A solid edge line (◇ and ⬗) led to much improved ratings over the other conditions, and as with the performance results, it appears that these conditions could be assigned a C_V of 0.5.

4. Driver Dynamic Response

The driver's dynamic response was analyzed in an attempt to obtain direct connections between delineation visibility and driver perception and response. To this end measurements for the complete model of Fig. 9 were obtained for a large number of the conditions listed in Table 2. A nonlinear regression program was used to fit the dynamic driver model to measured describing function data. The model fits were quite good and consistent with the expected describing function shapes. Procedures and data are given in Appendix B.

Model parameter means and standard deviations are given in Table 5 for the 300 ft (19.4 m) and 50 ft (15.2 m) baseline visibility conditions run at 30 mph (48.3 kph). The major consistent effect of decreased visibility

TABLE 5

DRIVER MODEL PARAMETERS FOR BASELINE VISIBILITY CONDITIONS
AVERAGED OVER REPEAT RUNS ON SIX SUBJECTS

a. Compensatory (Wind Gust Regulation)
n = 24 total runs

Visibility	Parameter	T_L (sec)	τ (sec)	K_ψ (rad/rad)	K_y (rad/ft)
300 ft*	Mean	0.471	0.526	0.195	0.022
	σ†	0.148	0.073	0.045	0.0078
50 ft	Mean	0.483	0.620	0.169	0.0251
	σ†	0.279	0.139	0.045	0.0096

b. Pursuit (Curved Path Following)
n = 22 total runs

Visibility	Parameter	T_L (sec)	τ (sec)	K_ψ (rad/rad)	K_y (rad/ft)	K_r (sec)	K_{R_c}/ℓ
300 ft	Mean	0.247	0.422	0.174	0.0387	0.176	0.84
	σ†	0.223	0.136	0.057	0.029	0.063	
50 ft	Mean	0.241	0.540	0.244	0.0218	0.180	0.86
	σ†	0.194	0.140	0.089	0.0140	0.071	

*1 ft = 0.3048 m
†Includes within and between subject variance for six subjects.

on the baseline compensatory and pursuit driving tasks was an increase in driver time delay (τ) of about 0.1 second. The driver's lead or anticipation time constant, T_L, remained quite constant with decreased visibility, as did the curvature perception gain, K_{R_c}, for the pursuit task. Table 5 also shows the dimensionless quantity K_{R_c}/ℓ (where ℓ is the vehicle wheelbase), which indicates the quality of open-loop control present in the pursuit operation (see Appendix B). K_{R_c} = 1 is ideal pursuit, while K_{R_c}/ℓ = 0 amounts to compensatory control with no active open-cycle element.

Model parameter data for all the visibility/configuration conditions reduced were analyzed in a variety of ways as discussed in Appendix B. Figure 19 illustrates how adverse visibility combined with configuration changes affects curvature perception. Here we see that the curve perception parameter K_{R_c}/ℓ decreases as a function of the configuration visibility parameter, C_V.

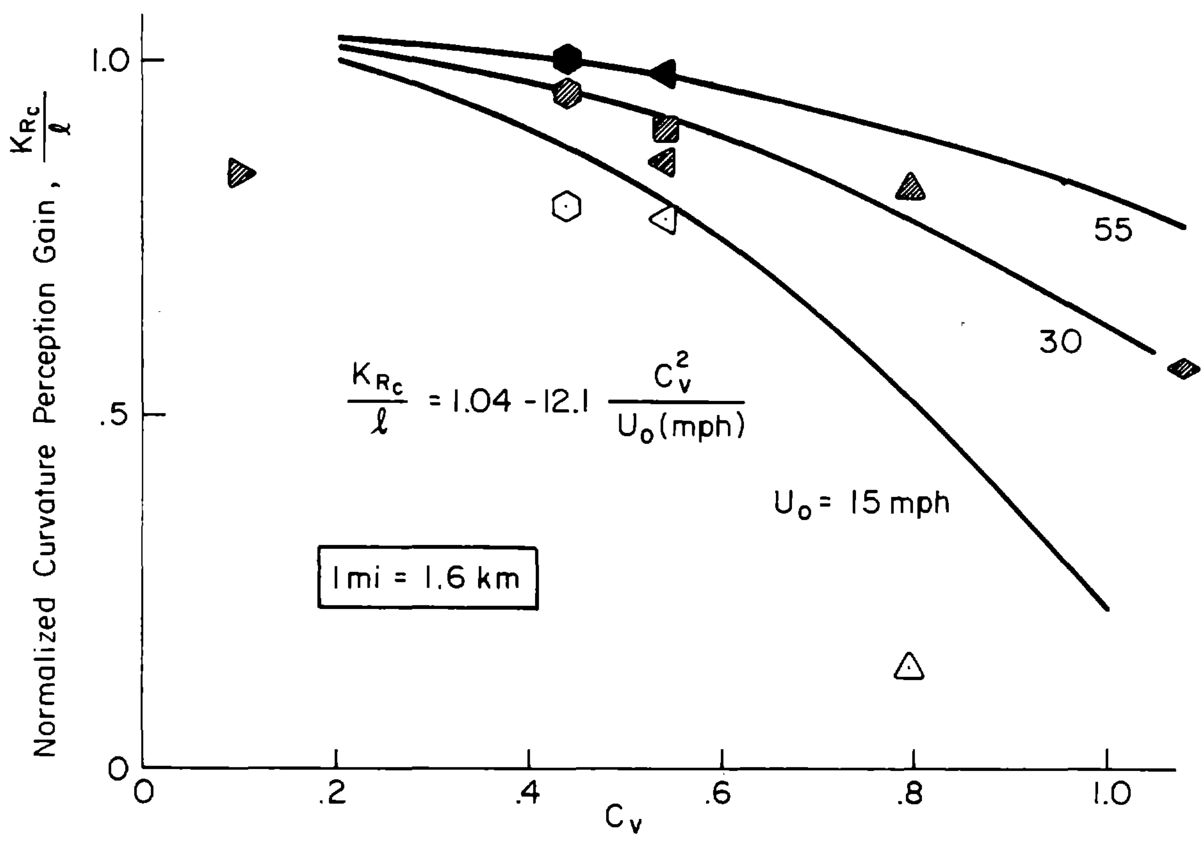

Figure 19. Effects of Adverse Visibility and Delineation Configuration on the Curvature Perception Parameter

For the wind gust regulation task, crossover model measures of driver behavior[30] were routinely obtained as discussed in Appendix B. Data are plotted in Fig. 20. In Fig. 20a there is only a small effect of speed (U_o) or visibility (C_V) on the driver's heading error gain (K_ψ, see Fig. 9). The inverse of the driver's lateral lane error gain (K_y) can be interpreted as an equivalent dynamic look-ahead distance.[27] The Fig. 20b plot of these data shows a strong dependence on C_V, with shorter distances apparently associated with restricted visual range (i.e., higher C_V values). There is little apparent speed dependence, however, suggesting that look-ahead distance is a more pertinent perceptual variable than the look-ahead time constant of Eq. 7 (Section II-D).

Equivalent time delay, τ_e (driver transport delay τ combined with the vehicle heading response lag), is affected by both speed and configuration visibility parameter C_V as shown in Fig. 20c. The increase in effective time delay with increase in C_V suggests that driver perceptual load increases with reduction in the visual segment. Past research has postulated that τ_e increases are associated with an increase in driver lead equalization requirements and/or with the presentation of sampled information.[31] In this case some driver lead (T_L in Fig. 9) is used to offset the vehicle lag. But, the vehicle lag increases with speed, whereas the effective time delay decreases with speed; so this "explanation" is in the wrong direction. The sampling time interval of the dashed lines is given by

$$T_s = \frac{x_c}{U_o} \tag{11}$$

where x_c is the delineation cycle length. Change in human operator τ_e is proportional to sampling interval,[31] so the variation of τ_e with both speed and C_V is in the right direction. Accordingly, we attribute the τ_e changes

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[30] McRuer and Krendel, Mathematical Models of Human Pilot Behavior.

[27] McRuer, et al., "Measurement of Driver/Vehicle...Response Properties."

[31] Allen, et al., Research on Display Scanning.

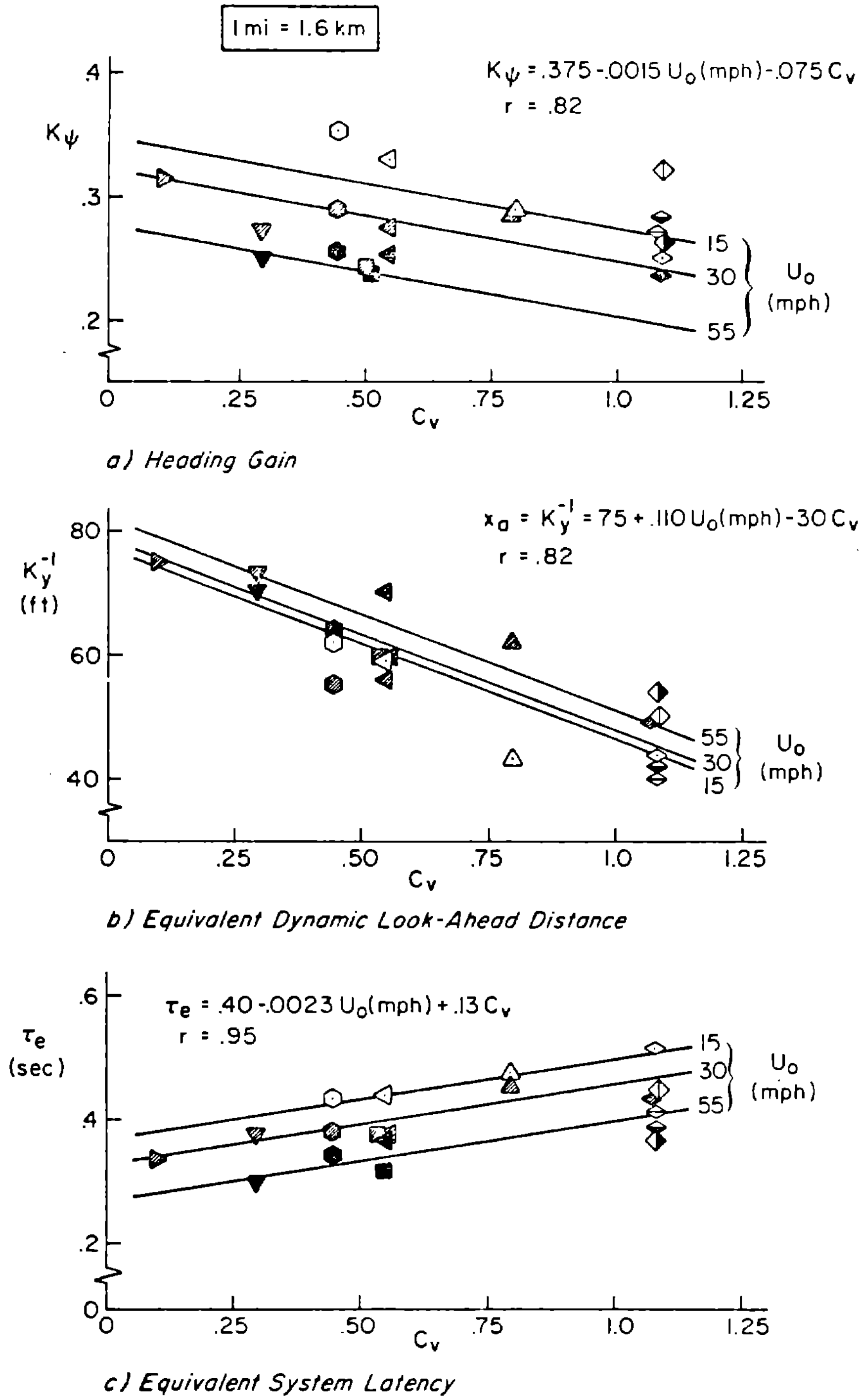


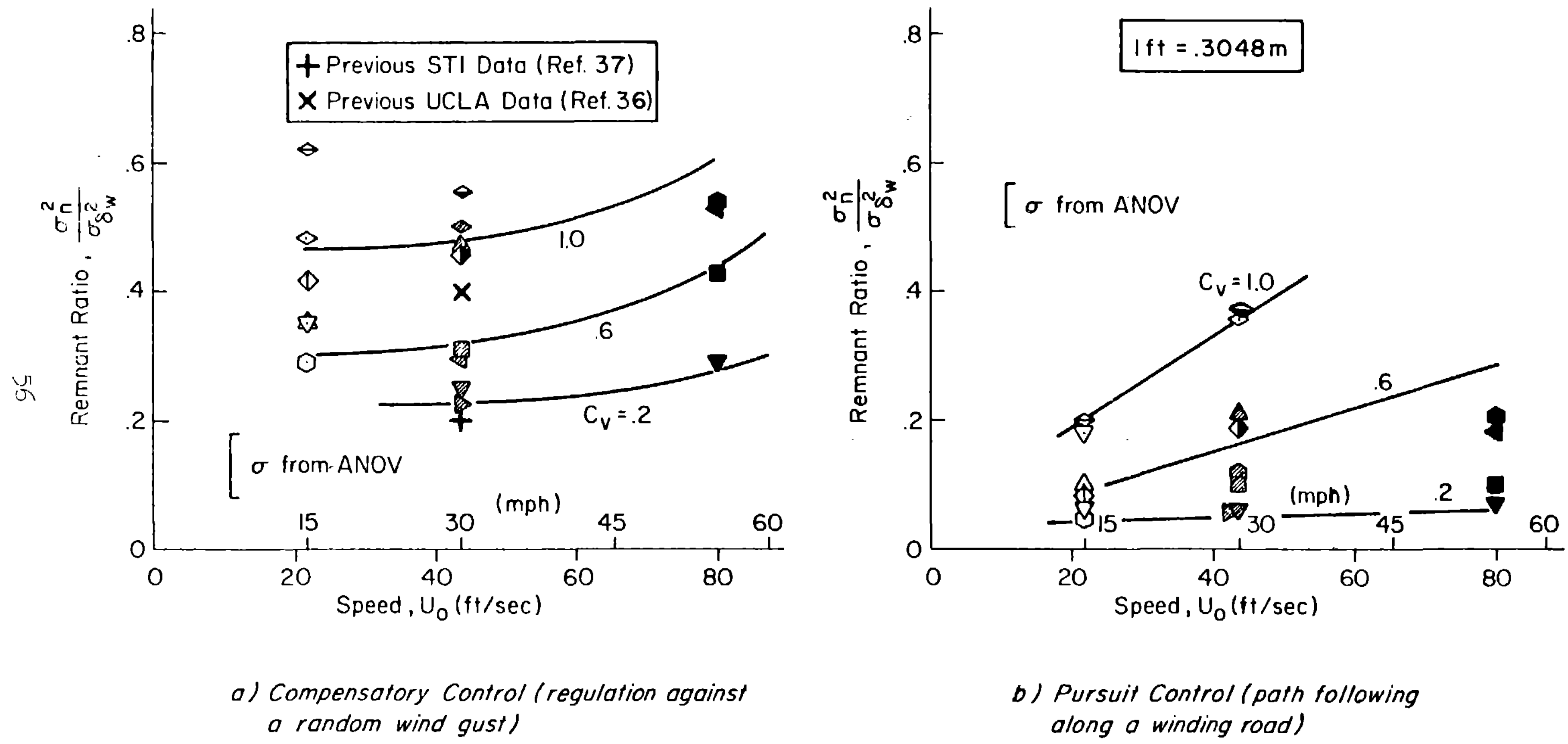
Figure 20. Driver/Vehicle System Extended Crossover Model Parameters for Compensatory Task

primarily to sampling processes associated with the delineation dashed lines and speed.

An interesting observation was made during the experiment which adds further credence to the idea of delineation sampling time interval. Under poor visibility (50 ft, 15.2 m), short delineation marks, and slow speed conditions (15 mph, 24 kph), some subjects reported a compelling desire to speed up in order to increase the frequency of lateral control information. As indicated in Eq. 11, increasing speed decreases the sampling interval T_s. A similar effect could be obtained by reducing the delineation cycle length x_c, and in critical locations this might be an effective means for inducing lower speeds under adverse visibility conditions.

The sampling process which affects the driver's time delay should also have some influence on the noise or stochastic component of his steering actions. In Fig. 21 we show the proportion of noise or remnant that is uncorrelated with the driver's actions in counteracting wind gusts or steering along a winding road. There is a tendency for driver noise to increase both with configuration parameter and speed.

The intermittency of delineation apparently affects driver remnant; however, this effect is increased at higher speeds (i.e., higher delineation sample rates) in contrast to the time delay penalty (Fig. 20c) which decreased with increasing speed. These two contrasting effects on driver behavior explain the relatively consistent effect of speed on performance under adverse visibility shown in Fig. 16. At low speeds, the slow intermittency of delineation causes appreciable increases in driver time delay which degrades performance; while at high speeds, driver noise increases, which again degrades performance. Also note that for the curve-following data driver noise increases appreciably under the same conditions that led to reduced curvature perception (Fig. 19). Furthermore, the curve-following data show a proportionately greater configuration visibility parameter sensitivity, consistent with the Fig. 16 performance data. A final observation is that the solid edge line reduces driver noise over the dashed or no right lane line cases, which (as with previously discussed data) is consistent with a lower equivalent C_v.



a) Compensatory Control (regulation against a random wind gust)

b) Pursuit Control (path following along a winding road)

Figure 21. Effects of Visibility and Configuration on Driver Remnant; Data Averaged Over Six Subjects; Symbol Code Given in Table 2

D. SIMULATION SUMMARY AND DISCUSSION

Steering performance appears to be reliably affected by the combined effects of reduced visibility and delineation configuration. Measures of driver dynamic response behavior have given insight into the underlying perceptual effects which lead to performance degradation. A parameter for quantifying the combination of visual range and delineation configuration (C_V) was developed in Section II and has proven very useful for analyzing the simulation data. Driver lane dispersions show a linear relationship with C_V and speed, U_O. As noted previously, the regression relationships for the wind gust and winding road tasks had similar speed sensitivity. The constant terms in the two expressions were small and of opposite sign. With these observations we can state a summary relationship for the two tasks:

$$\sigma_y = 0.019U_o \text{ (mph)} + kC_V \qquad (12)$$

where k is a function of the command in the case of the curved road or disturbance in the case of the straight road input to the driver's steering task.

Driver reaction in terms of speed reduction on an occasionally curving road had a linear relationship with C_V (i.e., slower speeds for higher values of C_V), and the data proved to be consistent with the above performance relationship. If we hypothesize a maximum tolerable lane dispersion of 1 ft (.3048 meters) and use the constant for the winding road task (k = 0.72), we can express preferred speed as a function of the configuration visibility parameter:

$$U_{preferred} \text{ (mph)} = 51 - 34C_V \qquad (13)$$

Thus, for a C_V of about 1.4 the driver should come to a stop. This value of C_V would be equivalent to the short delineation used here (simulating retroreflective RPM's) with 40 ft. (12.2 meters) spacing and a visual range of approximately 40 ft (12.2 meters).

Providing a solid right edge line provided significantly improved performance over a dashed edge line or no edge line. In fact, the solid edge line appears to reduce the C_V value that would be computed for the left edge by a factor of two. The driver takes advantage of this by going faster, however. In fact, with the simulator data there appears to be a dilemma in that improvements in delineation (either increased contrast or improved configuration) lead to increased speed. Straighter roads would also lead to increased speed due to a low k value in Eq. 12. To the extent that drivers in the real world fail to reduce speed under adverse visibility conditions,[6] however, improved delineation would reduce lateral lane dispersions.

[6]Kocmond and Perchonok, Highway Fog.

SECTION IV

FIELD TEST EXPERIMENTS

A. OVERVIEW

Although the simulation experiment described in the last section allowed a great deal of control over experimental treatments and measures, simulation is still an idealization and abstraction of the real world. There is a variety of factors having established or suspected effects that can only be measured in field tests — for example, the rich visual scene with subtleties such as texture, photometric complexities such as headlighting patterns and pavement reflectance characteristics, motion cues, complex horizontal and vertical road curvature, the real-world risks in driving, etc. In order to account for some of these factors, field tests were conducted that would test delineation visibility factors in a real-world setting and provide tie-in validation data with the simulator tests.

The field tests were performed in two separate experiments. In the first field experiment we sought to measure critical aspects of drivers' lateral and longitudinal vehicular control over: a) a 40.5 mi (65.2 km) highway circuit which originally had different striping contrast levels on successive 4 mi (6.4 km) segments; b) again over the same highway circuit after the delineation had been allowed to degrade severely; and c) over the same highway after it had been repainted according to standard California Department of Transportation (Caltrans) procedures. A group of men and women differing in age over a wide range was employed as the subject/driver sample. Drivers were studied on two occasions — either experimental delineation and degraded delineation or degraded delineation and standard delineation — as they drove a specially instrumented vehicle for a prolonged period on the highway circuit.

The second field experiment was designed specifically to compare indices of driver lateral and longitudinal vehicular control under wet and dry conditions with lane-line delineation of either: a) striping plus reflective pavement markers; or b) striping alone. The selected treatments were on contiguous sections of the 52 mi (83.7 km) highway test circuit, so that it was possible to compare the same driver's reactions to the treatments under approximately the same climatic conditions. As before the interaction between delineation visibility and fatigue was studied by requiring the subjects to operate the vehicle over the highway circuit for prolonged periods in both wet and dry conditions. The section with striping alone fortuitously contained a significant subsection where thermoplastic delineation was applied instead of the usual paint as part of a Caltrans investigation of thermoplastic durability. This allowed a special comparison of paint and thermoplastic delineation effects on driver performance in wet weather.

The following article (B) discusses general experimental methods including the instrumented vehicle, measurements, and procedures. Details of the instrumented vehicle and measurements are further elaborated in Appendix C. Specific methods for the first experiment on delineation wear and contrast effects are given in Article C, followed by specific methods for the second or "rain effects" experiment in Article D. Data reduction and analysis procedures are reviewed in Article E, and key results are presented in Article F. More detailed results and analysis are given in Appendix D. Finally, this section is concluded with a summary and discussion of the two experiments in Article G.

B. GENERAL METHODS

1. Instrumented Vehicle and Measurements

The subject's vehicle was an extensively modified 1971 Dodge 3/4 ton (.68 tonnes) van. Basic structural modifications included an auxiliary gas tank to permit uninterrupted operation for the entire experimental driver period, a 2.5 KVA electricity generator to provide power for the apparatus, and an alternate hydraulic steering and brake system for use by the experimenter, who was seated behind the driver on the vehicle's midline. Foot pedal controls for the latter system were hidden from the driver's view by a housing and no mention was made to him concerning them.

Several vehicle-mounted sensors were employed to measure driver/vehicle variables of interest. A specially constructed electro-optical sensor mounted above the vehicle's left front wheel was used to continuously measure lateral lane position with a resolution of ±0.5 in. (1.3 cm). Vehicle speed was obtained from a tachometer tied in to the speedometer cable and was accurate to within ±0.5 ft/sec (0.15 m/sec). A potentiometer was employed to measure steering wheel deflections to within a ±0.5 deg resolution.

Electrophysiological variables were continuously recorded to obtain indices to driver psychophysiological status as affected by driving time and the various delineation treatments. The variables recorded were the driver's electroencephalogram (EEG) and electrocardiogram (ECG). From these were obtained the driver EEG power spectra from 18 sec epochs measured from the beginning of successive 1 min epochs during the runs and mean heart rate variability over successive 1 min epochs. These physiological measure have been previously shown to be sensitive to changes in the driver's psychophysiological status associated with changes in performance.[39] It was hoped here that they would reveal any changes in the drivers' arousal caused by having to operate the vehicle for a prolonged period while guided by delineation treatments that varied with respect to visibility, and would tie in with the subjective driver reaction data obtained in the simulation experiment.

The vehicle contained a double electronics rack for all data acquisition, processing, and electromagnetic tape recording (six channels on an Ampex 350). In addition, a response console containing 40 separate switches and several displays was mounted on a pedestal in front of the experimenter's seat. Use of the switches was registered as respective pulse codes on the tape, indicating the occurrence of certain highway and traffic events and driver errors.

[39] O'Hanlon, J. F., and G. R. Kelley, "Comparison of Performance and Physiological Changes Between Drivers Who Perform Well and Poorly During Prolonged Vehicular Operation," in R. R. Mackie, ed., Vigilance: Theory, Operational Performance, and Physiological Correlates, New York, Plenum Press, 1977.

More complete details on the vehicle instrumentation and measurements are contained in Appendix C.

2. Procedures

Subjects were recruited by advertising at local offices of the California State Department of Employment Development. No particular qualifications were required other than the possession of a valid driver's license. The 12 subjects selected for the first experiment ranged in age from 19 to 55 years (M ± SD: 29.2 ± 9.3; median = 28). Six men (ages 19-55) and six women (ages 19-35) were included. The 12 subjects selected for the second experiment ranged in age from 25 to 34 years (M ± SD: 28.7 ± 3.4; median = 28). Six men (ages 25-34) and six women (ages 25-34) were included. All subjects had held a driver's license for at least 3 years and had driven at least 15,000 mi (24,140 km) previously.

Subjects were paid $20 after completing two runs on separate days. They were informed beforehand that no deduction would be made if they elected not to complete a run for reasons of fatigue or illness; but, if they chose to quit for other reasons, they were paid at a rate of $2 per hour of work. One subject in the first experiment terminated after completing only half of a scheduled run due to fatigue. None withdrew for other reasons.

The subjects were fully informed of the nature of their task, but not the specific purpose of the experiment. They were further informed of certain specific requirements including the following:

a. To obtain adequate sleep on the night before each run (inadequate sleep was defined as losing more than 1 hr from the individual's normal sleep period).

b. To refrain from excessive physical exercise on the day of the run.

c. To refrain from the use of all non-medicinal drugs and alcohol on the day of the run (use of most medicinal drugs was allowed but the fact had to be drawn to the attention of the experimenter).

d. To refrain from the use of tranquilizing drugs from noon on the day of the test.

e. To refrain from smoking during the run, but not before.

Compliance with these regulations was checked from the subject's response to a 24 hr history questionnaire, administered just prior to each run. The first noncompliance was cause for run postponement; the second, for dismissal (it was never necessary to take that action).

All experiments were staged from a motel in the vicinity of a designated highway test circuit. Each subject arrived for each test run at between 1630 and 1730 hours. He was briefed with regard to the nature of the experiment and again cautioned that he was not to continue driving beyond the point of fatigue when he would ordinarily stop. Thereupon, electrodes were attached to the driver for electrophysiological recordings. He next assumed control of the research vehicle and drove to the test circuit in 15 to 30 min. He paused and rested for 5 min while initial resting physiological measurements were obtained and then entered the circuit between 1830 and 2030 hours. He drove in the outside lane, except when passing slower vehicles, attempting at all times to maintain a constant speed of 50 mph (80.5 kph). All runs were completed in darkness, and the subject was instructed to keep his headlights on low beams (see Appendix E for headlight isoluminance patterns). After completing half the circuit, he left the highway via an offramp and overpass and returned on the corresponding onramp to resume driving in the opposite direction. He repeated this maneuver at the origin, thereby completing one circuit. He completed each circuit without pausing but was required to stop at the point of origin to allow the experimenter to change reels of tape on the recorder and to perform any minor equipment adjustments that might be required. Usually this was accomplished in less than 10 minutes. Upon resumption of the run the subject continued as before, completing an integral number of circuits to a limit specified by the particular experimental design. Following completion of a run the subject paused at the point of origin for 5 min while final resting physiological measurements were obtained. Finally, he drove to the motel where he was dismissed after electrode detachment and a short debriefing.

C. SPECIFIC METHODS: FIRST EXPERIMENT, VARIATIONS IN DELINEATION CONTRAST

1. Highway Circuit

The circuit for the first experiment was over east- and westbound sections of Interstate Highway No. 80 (I-80) between the Colfax and Blue Canyon exits in Placer County, California. According to posted Caltrans highway mileage markers, the circuit extended from post-mile 80 Pla 53.36 (Blue Canyon Exit — East) to 80 Pla 33.00 (Colfax Exit — West). The terrain was generally mountainous, and the road grade was positive in the eastbound direction as shown in Fig. 22. Elevation at the western end was about 2400 ft (732 m) and at the eastern end, 5000 ft (1524 m). The circuit contained numerous vertical and horizontal curves.

The section of I-80 used in the experiment consisted mainly of two lanes eastbound and two westbound. Three eastbound traffic lanes, including a "truck lane," were present for about 1 mi (1.6 km) near the eastern end of the circuit where the upgrade was greatest. Opposing traffic lanes were separated either by median striping alone (throughout most of the westernmost quarter), by a median barrier, or by a wide greenbelt (throughout most of the easternmost quarter). The traffic lane surface was Portland cement (PC). That surface was well worn and discolored with occasional bituminous asphalt (AC) patches. Lane width was 12 ft (3.7 m), and the adjacent improved shoulder width was 8-10 ft (2.4-3.0 m). The shoulder surface was AC, and it too was worn, cracked, patched, and discolored. No edge line separated the outside traffic lane and the shoulder at the time of the experiment. Paddle delineators, mounting retroreflective elements, were present throughout the circuit next to the shoulder. Finally, a kind of informal delineation was provided by the presence of poles set both in the median and on the unimproved outside shoulder as a guide to snowplows.

There were standard mercury-vapor fixed luminaires above 11 offramps in each direction. Except at these locations, the highway was illuminated during the night only by vehicle headlights, and was generally quite dark owing to the rural nature of the terrain.

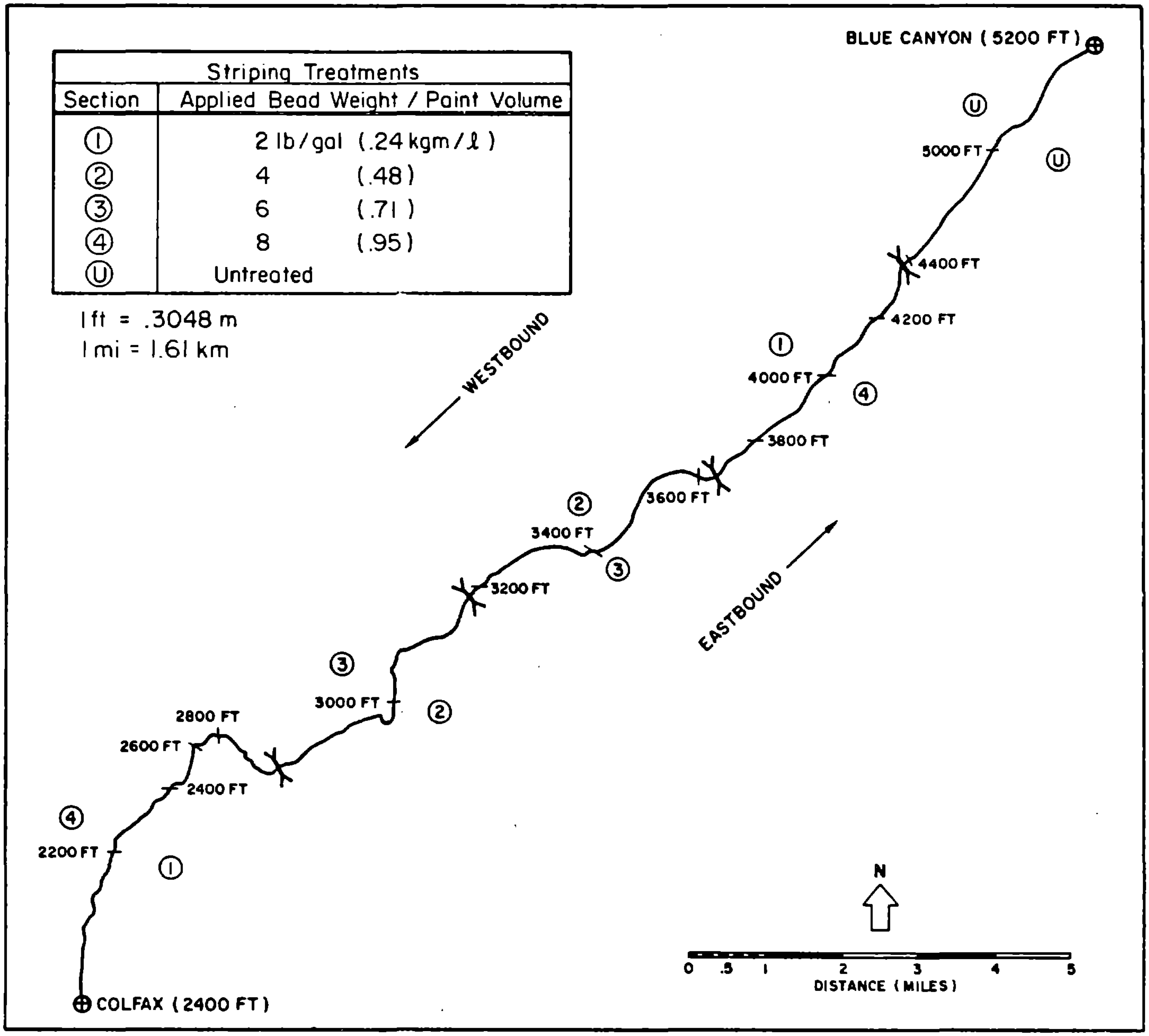


Figure 22. Highway I-80 Test Section for the First Experiment (Delineation Contrast Variations); Delineation Treatments (Circled Numbers) Defined in Table 6

2. Experimental Design

Two groups of six subjects participated in the first experiment. Subjects in both groups completed two runs. The first group made one run after the circuit had received a special lane-line delineation treatment, and the second run with degraded delineation. The second group made a run initially with the same degraded delineation, and then made a second run after the highway had been restriped according to standard Caltrans procedures. Each scheduled run consisted of two complete highway circuits.

3. Delineation

a. Special Treatment

The special striping treatment was applied to I-80 by Caltrans on 21-22 October 1975, under the supervision of project personnel. For this, the eastbound highway section was divided into four contiguous 4 mi (6.4 km) segments beginning at post-mile 80 Pla 33.00. This left the last 4.36 mi (7.0 km) segment of the eastbound section in its original, untreated condition. The parallel segment of the westbound section was also untreated. Treatment began in the westbound direction at post-mile 80 Pla 49.08. From there, the highway was again divided into four contiguous 4 mi (6.4 km) segments, ending at marker 80 Pla 33.00, the point of origin.

The striping treatment was applied for lane-line delineation between the first and second traffic lanes. It consisted of standard white titanium dioxide point (Caltrans PT-225) to which was added an amount of standard reflective glass bead (Highway Safety Spheres, Potter Industries, Inc.) that varied in incremental weight:volume steps between treatment segments. In the eastbound direction, the four successive mixtures contained 2, 4, 6, and 8 pounds of beads per gallon of paint (0.24, 0.48, 0.71, 0.95 kg/l, respectively). The same was true for successive mixtures applied in the opposite direction. All mixtures were applied by Caltrans personnel operating a conventional striping vehicle. Striping was applied in the conventional California broken line pattern with a 9:15 ft (2.7:4.6 km) line-to-gap ratio.

On 28-29 October, project personnel conducted a photometric assessment of the treatment segments, and on 30 October Caltrans conducted an analysis of the actual concentration of beads adhering to the paint after application.[40] Salient results are given in Table 6, and the full photometric record is provided in Appendix E.

Table 6 shows that considerably less bead remained on the road surface than had been originally applied; also, that photometric contrast measurements were related to the bead-to-paint ratios in a generally monotonic, but nonlinear, manner. The relationships between measured striping composition and both maximum and averaged contrast measurements at selected points in the treatment segments are shown in Fig. 23 for both east- and westbound sections of the I-80 circuit.

Several observations on the Fig. 23 data are pertinent here. First, the maximum achievable contrast levels for painted delineation with beads is on the order of 18 or less. Furthermore, average levels are on the order of 15 or less. From a practical standpoint, considering the nonlinear relationship between contrast and bead concentration in Fig. 23, average contrast levels on the order of 10-12 are to be expected. A Caltrans study[40] obtained driver subjective ratings over highway sites with varying bead concentrations and concluded that concentrations beyond 4 lb/gal (0.48 kg/l) achieved through an application rate of about 6 lb/gal (0.71 kg/l) led to wasted beads. The study also found that application rates of 4-6 lb/gal (0.48 kg/l to 0.71 kg/l) led to similar lane guidance ratings. Thus, taking all factors into account, a practically achievable average contrast level of about 12 appears to be reasonable for beaded paint delineation lines.

b. Worn Delineation

Runs conducted with the special treatment were concluded on 12 December with the beginning of snowfall on the I-80 site. Subsequent enforced use of tire chains, snow plowing, and road sanding continued to degrade the

[40] Russell, G. L., Optimization of Traffic Lane Delineation, California Department of Transportation, Report No. FHWA-TS-77-200, Dec. 1976.

TABLE 6. SPECIAL DELINEATION TREATMENT LOCATION AND COMPOSITION
1 mi = 1.61 km; 1 lb = .45 kg

TREATMENT SEGMENT		DISTANCE FROM CIRCUIT ORIGIN		CALTRANS MATERIAL MEASUREMENT		HFR PHOTOMETRY MEASUREMENT		
		BEGIN	END	RELATIVE MILEAGE	LB BEAD/ GAL PAINT	RELATIVE MILEAGE	MAXIMUM CONTRAST	AVERAGE CONTRAST
EASTBOUND	1	0	4.0	0.8 1.4 2.5 3.6	1.8 1.2 1.1 1.8 $\bar{M}$ = 1.47	0.8	5.3	3.72
	2	4.0	8.0	4.8 5.6 6.4 7.5	2.1 2.4 1.5 2.2 $\bar{M}$ = 2.05	5.3	5.1	3.89
	3	8.0	12.0	8.5 9.5 10.5 11.5	3.1 4.0 4.0 5.3 $\bar{M}$ = 4.10	10.7	15.9	11.0
	4	12.0	16.0	12.4 13.4 14.5 15.5	6.0 6.2 6.3 6.7 $\bar{M}$ = 6.30	13.0	17.1	14.5
WESTBOUND	1	16.8	12.0	15.4 14.5 13.3 12.4	1.2 1.1 1.0 1.2 $\bar{M}$ = 1.13	12.4	5.9	4.36
	2	12.0	8.0	11.6 10.5 9.4 8.6	1.7 1.0 1.6 1.5 $\bar{M}$ = 1.45	10.4	7.8	5.75
	3	8.0	4.0	7.2 6.3 5.6 4.3	4.0 4.0 4.2 3.6 $\bar{M}$ = 3.95	6.3	15.8	10.7
	4	4.0	0	3.4 2.5 1.4 0.6	7.7 6.4 5.7 6.6 $\bar{M}$ = 6.48	1.8	17.9	10.5

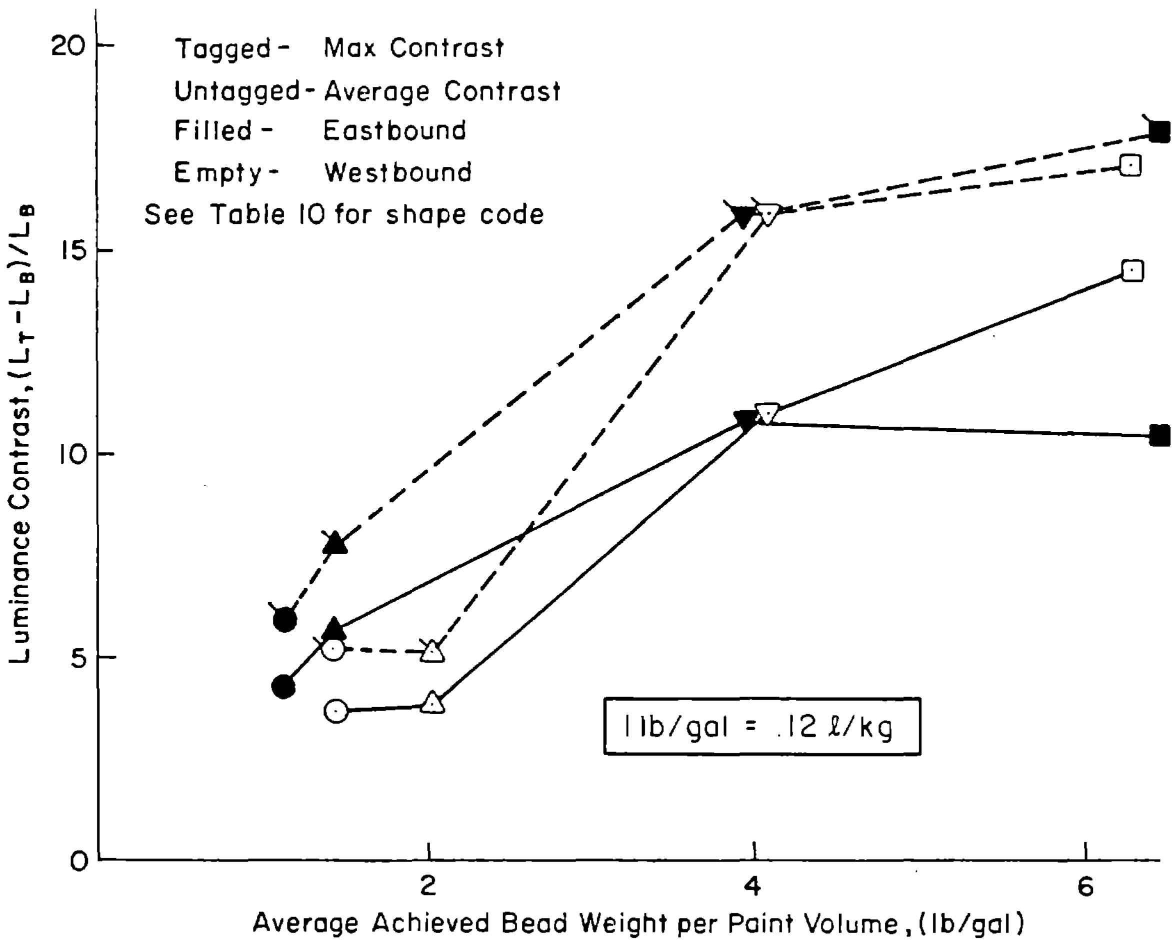


Figure 23. Average Contrast of Lane Line to Road Surface at Each Treatment Site as a Function of Average Bead Weight per Gallon of Paint

delineation through repeated snowfalls which ended in early March. Before restriping, another photometric assessment of the road was completed (16 March 1976) and the runs resumed (17-29 March). Restriping was then accomplished by Caltrans on 31 March.

The results of the photometric assessment of degraded striping were highly variable, indicating uneven wear patterns and residual differences among treatment segments. Nonetheless, only one measurement had a value exceeding 3.0, only 19.5 percent were about 2.0, and 41.5 percent were below the 1.0 level (see Appendix E).

c. Standard Delineation

The final series of runs was completed on 18-23 April. In restriping the highway, the applied bead-to-paint ratio was the Caltrans standard 6 lb/gal (0.71 kg/l). A limited series of photometric assessments was made at four of the previous photometry sites. Two sites were chosen for having what appeared to be delineation of the highest contrast on the circuit. The other sites were chosen for the opposite reasons. Values at the sites of greatest contrast ranged from about 4.0 to 10.0, whereas those at the sites of lowest contrast ranged from 1.0 to 4.0.

D. SPECIFIC METHODS: SECOND EXPERIMENT, RAIN EFFECTS

1. Highway Circuit

The circuit for the second experiment was over north- and southbound sections of Interstate Highway No. 5 (I-5) between the Central Redding and Lakeshore exits in Shasta County, California, as shown in Fig. 24. The posted Caltrans highway mileage markers at the southern (point of origin) and northern (turnaround) limits were post-mile 5 Sha 15.37 and 5 Sha 40.91, respectively. A critical point on the circuit occurred at post-mile 5 Sha 26.00, denoting the location of the Pit River bridge. Road surface delineation changed at this point from a combination of retroflectors and striping (south) to striping alone (north). This difference is described in the section that follows.

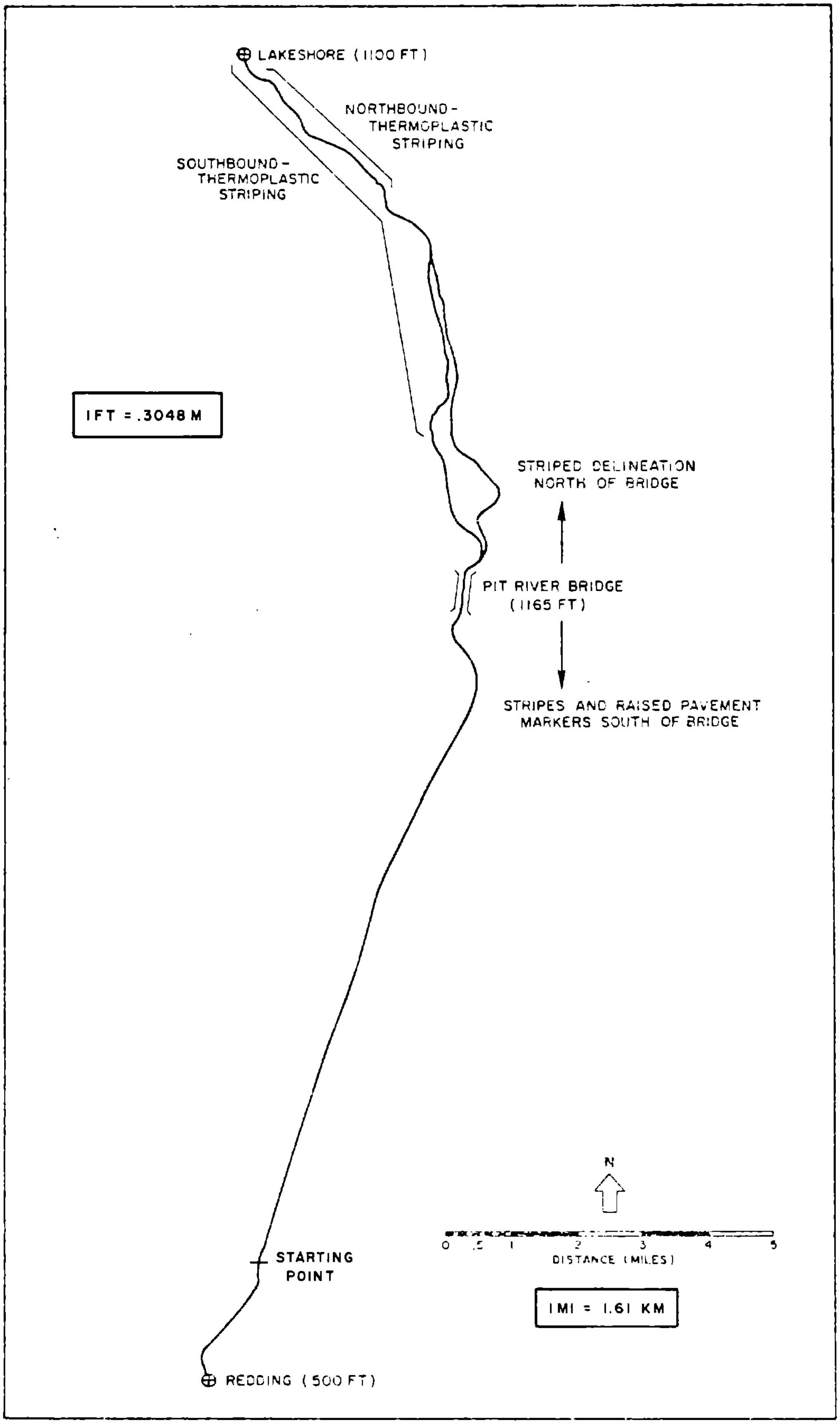


Figure 24. Highway I-5 Test Section for the Rain Effects Study

Roadway geometry and the nature of the surrounding terrain also changed markedly at the Pit River Bridge. South, the highway consisted primarily of straight and level tangents between a few wide horizontal curves. North, the highway contained frequent vertical and horizontal curves interspersed between straight tangents on up and down grades. The highway between Redding and the Pit River Bridge was 4-6 lanes, divided, through generally urban and suburban areas, with exits and entrances at 0.5 (0.8 km) to 1.0 mi (1.6 km) intervals. The highway north of the bridge was also 4-6 lanes, divided, and had exits and entrances at similar intervals. However, there the terrain was definitely rural and generally mountainous. The traffic lane surface was PC in good condition. Lanes were 12 ft (3.7 m) in width. The 10-13 ft (3.0-4.0 m) shoulder surface was AC.

2. Delineation

A yellow 4 in. (10.2 cm) median line and a white 4 in. (10.2 cm) edge line were generally present on the inner and outer shoulders at a distance of 2 in. (5.1 cm) and 1 ft (0.3 m), respectively, from the adjacent traffic lanes. Broken lane lines were always present with the usual 9 ft (2.7 m) segment and 15 ft (4.6 m) gap. Paddle delineators mounting retroreflective elements were set next to the improved outside shoulder at 1/10 mi (0.15 km) intervals except on the outside of curves having less than a 10,000 ft (3048 m) radius. There the paddles were set with a spacing which depended upon curve radius (r), according to the standard Interstate formula: $3\sqrt{r} - 50$.

South of the Pit River Bridge, reflective pavement markers (Stimsonite 88-yellow) were present on the inner shoulder with a 24 ft (7.3 m) spacing. Reflective (Stimsonite 88-clear) and ceramic nonreflective markers were used with striping for lane-line delineation. The former were spaced at 48 ft (14.6 m) intervals, in alternate striping gaps. Four of the ceramic markers were placed in each 9 ft (2.7 m) stripe with 3 ft (0.9 m) spacing. The vertical dimension of both types of markers was 3/4 in. (1.9 cm).

In the immediate vicinity of the bridge, the markers were intermittent due to occasional snowplow removal and irregular replacement. No markers were present north of post-mile 5 Sha 26.5.

On 19 December 1975, Caltrans installed thermoplastic (Cataphote Spray Plastic 0.075) lane lines from post-mile 5 Sha 37.0 to beyond the northern end of the circuit for the northbound traffic lanes, and from 5 Sha 32.5 for the southbound lanes. Measured thickness of the thermoplastic stripe varied between 0.06 (0.15 cm) and 0.10 in. (0.25 cm), which represented a 12 to 20 fold increase in line thickness, relative to the usual fresh paint stripe (0.005 in.; 0.013 cm).

3. Experimental Design

One of the reasons for selecting the I-5 circuit was the abundant rainfall expected from annual averages [i.e., 34 in. (86.4 cm) in Redding and close to 100 in. (254 cm) near the northern end of the circuit]. It was planned to run all 12 subjects at night under dry weather conditions in January 1976, then for the experimenter to reside in Redding and conduct another night run for each subject during the time of the expected heaviest rainfall (February-March). All runs were to consist of three complete highway circuits.

As it happened, northern California experienced a severe drought during the winter and spring of 1976. Across much of the test site the precipitation level at the time of the experiment's conclusion (12 April) was the lowest ever measured since the beginning of systematic recording in 1856. Consequently, only 8 of the original 12 subjects participated in both scheduled runs. Moreover, the cessation of rainfall during several runs caused their early termination. Four subjects completed three circuits in the rain; two more completed two circuits before the rain stopped; and the remaining two were unable to complete a single circuit in the rain. Data from the latter pair were dropped from the analysis.

Table 7 summarizes the runs conducted in the rain that provided data for analysis. Listed there are 24 hr rainfall recordings made by U. S.

TABLE 7. SUMMARY OF RUNS MADE UNDER RAIN CONDITIONS

DRIVER	RUN	DATE	CIRCUITS	TIMES	24-HR. RAINFALL* (in.; 0800-0800) SOUTH	NORTH	STRIPING VISIBILITY	OBSERVER'S COMMENTS REGARDING RAINFALL
			1	1947-2045			<50 - 125	Light--Very Heavy
11	21	2/25	2	2052-2153	1.3†	3.5	75 - 125	Light--Moderate
			3	2200-2353			<50 - 100	Moderate--Very Heavy
			1	1909-2005			50 - 125	Light--Very Heavy
17	22	2/26	2	2014-2109	1.0	.7	50 - 125	Moderate-- Very Heavy
			3	2124-2220			>300	Light--Stopping
			1	1942-2040			75 - 100	Moderate--Heavy
21	24	2/28	2	2046-2141	.8	.6	75 - 100	Moderate--Heavy
			3	2147-2247			<50	Heavy
			1	1847-1949			50 - 60	Heavy
19	37	4/7	2	2001-2058	2.1	2.9	50 - 60	Heavy
			3	2102-2209			<50	Very Heavy
22	38	4/8	1	2043-2145	1.5	1.0	50 - 100	Light--Heavy
			2	2150-2246			50 - 100	Light--Heavy
20	39	4/11	1	1958-2057	.5	.2	<50	Moderate--Heavy
			2	2101-2201			50 - 75 >300 (Briefly)	Light--Moderate--Stopping

*U.S. Department of the Interior Weather Stations: South — Redding; North — Shasta Dam

†1 in. = 2.54 cm.

Weather Stations near the two ends of the highway circuit. Because the spatial and temporal distribution of rainfall was highly variable over the circuit, these data are less instructive than the onboard experimenter's observations which are also listed. At the times of moderate to very heavy rainfall, the experimenter described the road surface as being completely covered with standing or running water.

4. Visibility of Delineation in the Rain

One attempt was made on 5 December 1975 to assess the photometric characteristics of the highway circuit in the rain (described as light-moderate). Two sites were surveyed, but the task proved to be exceedingly difficult. Striping visibility was restricted to below 100 ft (30.5 m), and it was difficult to find the target with the photometer even at closer distances. The few delineation contrast measurements that were obtained resulted in values of 1.65, dropping to 1.0, at ranges increasing from 50 (15 m) to 100 ft (30.5 m).

Further photometric assessments were initially planned, then cancelled when it became apparent that every opportunity had to be taken to ensure adequate driving data collection. Instead, it was decided to rely upon the onboard experimenter's estimation of the visible range of striping delineation as the index of striping visibility. He was readily able to accomplish this by counting successive visible lane-line segments, and multiplying their number by 24 ft (7.3 m), the lane-line repetition cycle. (The experimenter's estimate for rain runs is shown in Table 7.)

Retroreflector visibility range, both for pavement markers and paddle delineators, was always greater than 300 ft (91.4 m) at night under either wet or dry conditions.

E. DATA REDUCTION AND ANALYSIS

The six tracks of raw data tape were read simultaneously at four times recording speed by an Ampex 350, interfaced to a general purpose digital computer (Redcor RC-70). Analog signals were demodulated and digitized at 112 Hz. Digital information passed directly into the computer. Identifying information was added, and the data were compressed in the required format on 1/2 in. (1.3 cm) computer tape. The latter was read by a larger, second-stage computer (Varian V-73) which applied various error recognition, noise rejection, and signal conditioning algorithms to different variables. A disk file was created containing all of the data, identified with respect to experiment, subject, run, and portions of runs. Thereupon, an iterative series of editing procedures was applied. First, the digital information relating to spatial/temporal events which delineated various experimental treatments was listed. These were edited and corrections were made to the file. Next all analog information was printed in a strip chart format and the record was edited to eliminate sections of bad data. After these corrections had been added to the file, the data were grouped by experiment and by all independent variables; that is, subject, delineation treatment, weather conditions (I-5), direction of travel, and successive circuits.

Data collected on I-5 were further segregated, within each combination of treatment, direction, and circuit, into successive quarters of the distance traveled across the treatment segment.

Finally, the data present in the finest level of grouping were averaged to yield an array of scores in cells defined by all possible combinations of the independent variables for each of the dependent variables listed in Table 8. Empty cells were present as the result of the data lost for a variety of reasons (early run terminations, equipment malfunctions, experimenter errors, weather changes, etc.).

All of the available data were treated in a descriptive statistical analysis (see Appendix D). However, the loss of a large block of data, such as that collected over an entire highway circuit, forced the elimination of the subject from inferential statistical analyses. Isolated empty cells, resulting from data lost during a subject's traversal of a single treatment segment (I-80) or quarter of a segment (I-5), were filled by an average value obtained from the other subjects under the same conditions. This was done to permit the use of standard computer programs for analyses of variance (ANOV) but had no effect on ANOV results due to the subtraction of one degree of freedom for each artificial score in determining the value of the respective term of error variance.

TABLE 8

DEPENDENT VARIABLES FOR FIRST AND SECOND EXPERIMENTS

<u>VEHICULAR CONTROL</u>

Mean lateral position relative to lane-line (feet--right, positive)

Standard deviation of lateral lane position (feet)

Mean speed (mph)

Standard deviation of speed (mph)

<u>DRIVER PHYSIOLOGICAL STATUS</u>

EEG - Absolute and relative power within each of the following frequency bands: .5-2.0 (delta), 2-5 (low theta), 5-7 (mid theta), 7-8 (high theta), 8-12 (alpha), 12-16 (sigma), 16-30 (beta)

ECG - Mean heart rate and standard deviation of heart rate

<u>DRIVER ERRORS AS SCORED BY EXPERIMENTER</u>

Right lane drift frequency (drifts/mile)

Left lane drift frequency (drifts/mile)

Combined lane drift frequencies (drifts/mile)

F. RESULTS

Detailed analyses of the field test data are contained in Appendix D where the statistical significance (reliability) and generality of the various trends are established. This article presents the results that directly relate to the effect of delineation visibility on driver control performance, behavior, and reaction.

1. First Experiment (Delineation Contrast Variations)

a. Performance

In Fig. 25 the effect of good and bad (worn) painted delineation is shown on mean lane position, and lateral lane position variability. For the first subject group (subject grouping discussed in Article C) the results are quite consistent: subjects move closer to the center of the lane [3 ft (0.91 m) lane tracker position places the 6 ft (1.83 m) wide vehicle in the center of the lane] and experienced greater variability in their lane position control. These two effects are quite consistent if subjects are attempting to minimize the possibility of lane edge excursions. This effect seems to be borne out by the lane drift (lane edge excursion) data recorded by the experimenter as discussed below.

Some appreciable differences between Group 1 and Group 2 data are noted in Fig. 25. Mean lane position for Group 2 is not much different for the two paint conditions, and lateral position variability is worse for the worn paint condition only on Treatment Segments 2 and 3. There was considerable variability in the delineation contrast experienced by the second group under the repainted condition* which may account for some of the between-group differences.

*In retrospect, the photometric assessment of the highway as experienced by Group 2 during their exposure to the standard Caltrans pavement delineation was inadequate. This was mainly due to our misguided impression that "standard" meant "constant," so that striping contrast measurements at a few sites would be representative of the conditions over the entire circuit. This was not the case, as the measurements taken indicated that standard striping contrast varied over the range 1.0 to 10.0. A consequence of our error was that the regression analysis discussed later had to be based entirely upon data obtained from Group 1 for showing the relationship between vehicular lateral position variability and striping contrast.

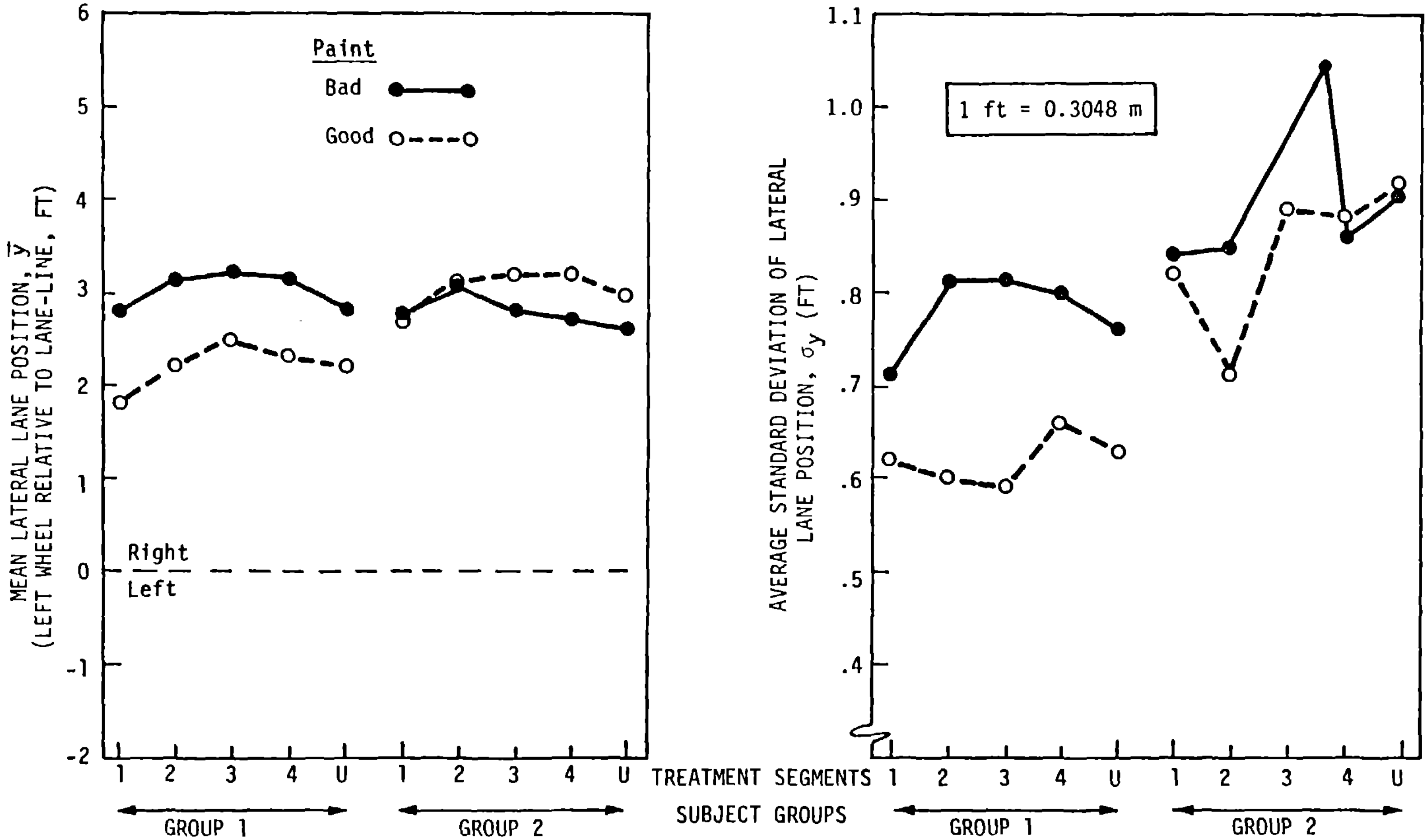


Figure 25. Mean Lateral Lane Position (Left) and Average Standard Deviation of Lateral Lane Position (Right) for Groups 1 and 2 Under Good and Bad Delineation Paint Conditions on Treatment Segments on the I-80 Circuit. (Delineation Treatment Segments Described in Section IV-C-1 and Figure 22, Subject Groups Described in Section IV-C-2.)

Experimenter-scored, right and left lane drift frequencies were tabulated for six subjects in Group 1 and for five in Group 2 who completed two circuits on I-80 when the condition of the striping paint was good and again when it was bad. These apparently inadvertent actions were relatively rare, and no drifts were recorded under many experimental conditions. Data are summarized in Table 9. Nearly all of the subjects permitted the vehicle to drift from the prescribed lane, more often to the right in the direction of the road shoulder than to the left into the adjacent traffic lane. Nonetheless, the paint condition had little effect upon right or left drifting tendencies. Actually, there was a slight reduction in the overall drifting frequency when the paint was bad.

Because the visual contrast of lane-line delineation was documented at representative sites in each of the treated segments after special striping had been applied and again after it had been badly worn (i.e., M1 and M2 photometric assessments listed in Appendix E), it was possible to analyze the functional relationships between lateral position variability and average log striping contrast.

TABLE 9

LANE DRIFT FREQUENCIES UNDER GOOD AND BAD PAINT CONDITIONS ON I-80 (N = 9)

	PAINT	
	GOOD	BAD
LEFT DRIFTS		
NO. DRIFTS	17	14
NO. SUBJECTS	2	6
RIGHT DRIFTS		
NO. DRIFTS	40	37
NO. SUBJECTS	8	8
ALL DRIFTS		
NO. DRIFTS	57	51
NO. SUBJECTS	8	9

For this analysis, the combined first and second circuit values of standard deviation of lateral lane position were included for all six subjects in Group 1. The Group 2 data were excluded because of the photometry problem discussed above. The data were grouped and averaged by Treatment Segments 1-4 in both directions and by paint conditions. Group means (±SD of individual scores) are shown in Table 10, along with corresponding data from the photometric site survey. The Table 10 data are illustrated in Fig. 26, where it is clear that lane deviations increase with decreasing delineation contrast.

The linear regression of average standard deviation of lateral lane position on log average striping contrast was determined from the above data using the method of least-squares. The linear correlation was significant and the regression relationship is shown in Fig. 26. Different symbols have been used in Fig. 26 to differentiate between the various course sections and directions. Note that for most of the course sections the trend between the good and worn striping data generally follows the slope of the regression line even though the data points are below or above the line (i.e., have different intercepts). The constant in the regression equation may have some portion that relates to other factors associated with each of the sections such as road geometry, and more of the data varieties could probably be explained in a multiple regression sense if there were a metric for quantifying average road curvature.

b. Driver Physiological Response

As shown in Appendix D, the EEG variables were generally insensitive to changes in all independent variables. The ECG variables alone showed some effect of repeated circuits. Moreover, mean heart rate was also significantly affected by treatments and directions. However, all differences among conditions were relative small, never exceeding 9 bpm for mean heart rate and 1.2 bpm for the standard deviation of heart rate.

TABLE 10

CONTRAST AND PERFORMANCE DATA USED FOR ANALYZING RELATIONSHIP BETWEEN LANE LINE CONTRAST AND LATERAL POSITION VARIABILITY

TREATMENT SEGMENTS		PLOTTING SYMBOL	AVERAGE STRIPING CONTRAST		AVERAGE (±SD) STANDARD DEVIATION OF LATERAL LANE POSITION	
			Linear	Log	Feet	Centimeters
Good Paint Condition						
EASTBOUND	1	○	3.7	0.57	.64 ± .15	19.5 ± 4.57
	2	△	3.9	0.59	.60 ± .14	18.3 ± 4.27
	3	▽	11.0	1.04	.62 ± .18	18.9 ± 5.49
	4	□	14.4	1.16	.69 ± .17	21.0 ± 5.18
WESTBOUND	1	●	4.4	0.64	.60 ± .13	18.2 ± 3.96
	2	▲	5.8	0.76	.61 ± .12	18.3 ± 3.66
	3	▼	10.7	1.03	.56 ± .13	17.1 ± 3.96
	4	■	10.5	1.02	.64 ± .16	19.5 ± 4.88
Bad Paint Condition						
EASTBOUND	1	○	1.4	0.13	.71 ± .13	21.6 ± 3.96
	2	△	2.4	0.38	.66 ± .14	20.1 ± 4.27
	3	▽	2.1	0.32	.77 ± .18	23.5 ± 5.49
	4	□	0.3	−0.52	.81 ± .32	24.7 ± 9.75
WESTBOUND	1	●	0.4	−0.35	.81 ± .19	24.7 ± 5.79
	2	▲	0.7	−0.13	.78 ± .11	23.8 ± 3.35
	3	▼	1.6	0.20	.89 ± .29	27.1 ± 8.84
	4	■	2.2	0.34	.85 ± .25	25.9 ± 7.62

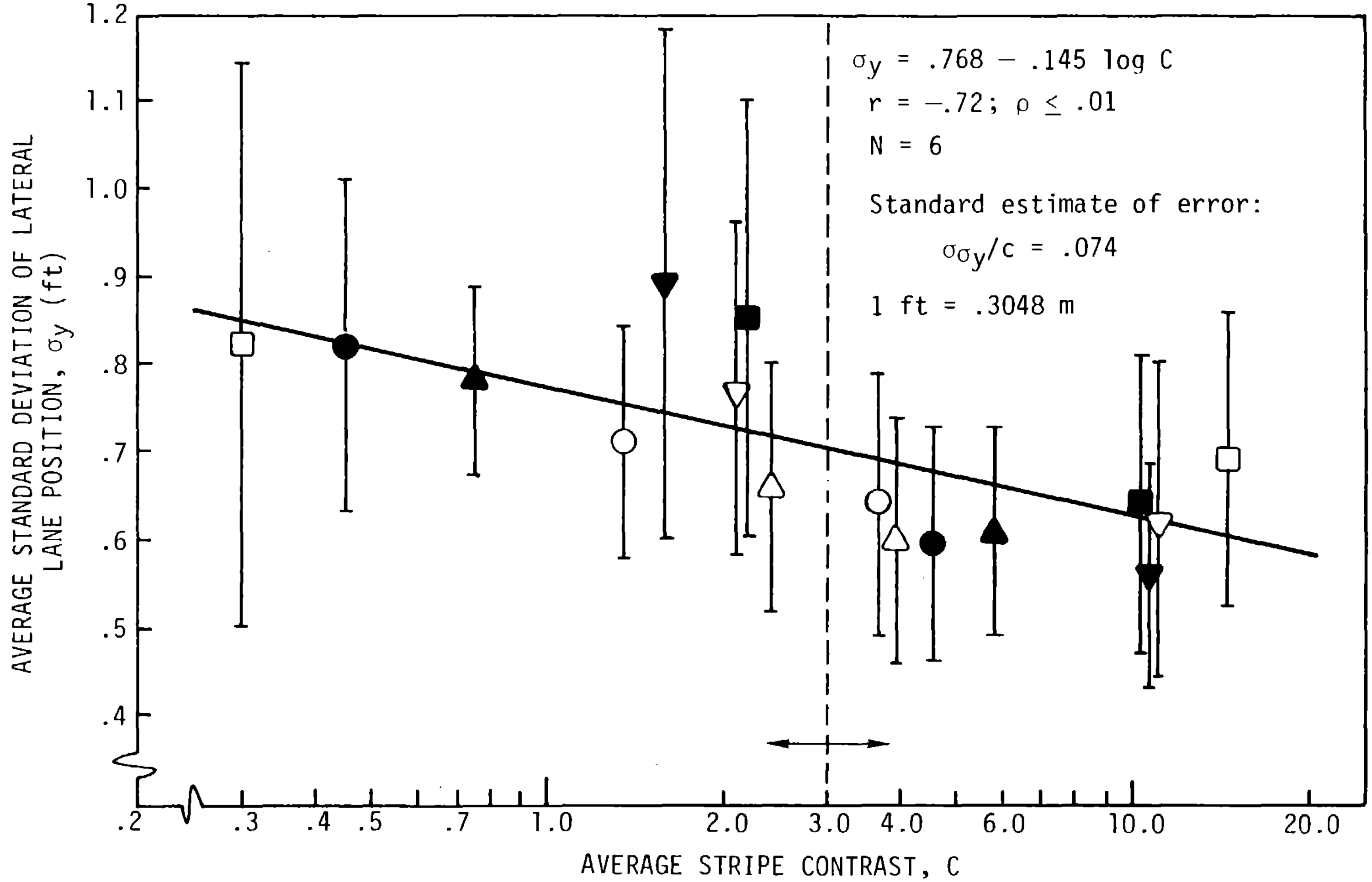


Figure 26. Average Standard Deviation of Lateral Lane Position as a Linear Function of Average Stripe Contrast for Good and Bad Delineation on the I-80 Circuit; Vertical Bars Indicate the Standard Deviation of Individual Scores (Plotting Symbols Defined in Table 10)

2. Second Experiment (Rain Effects)

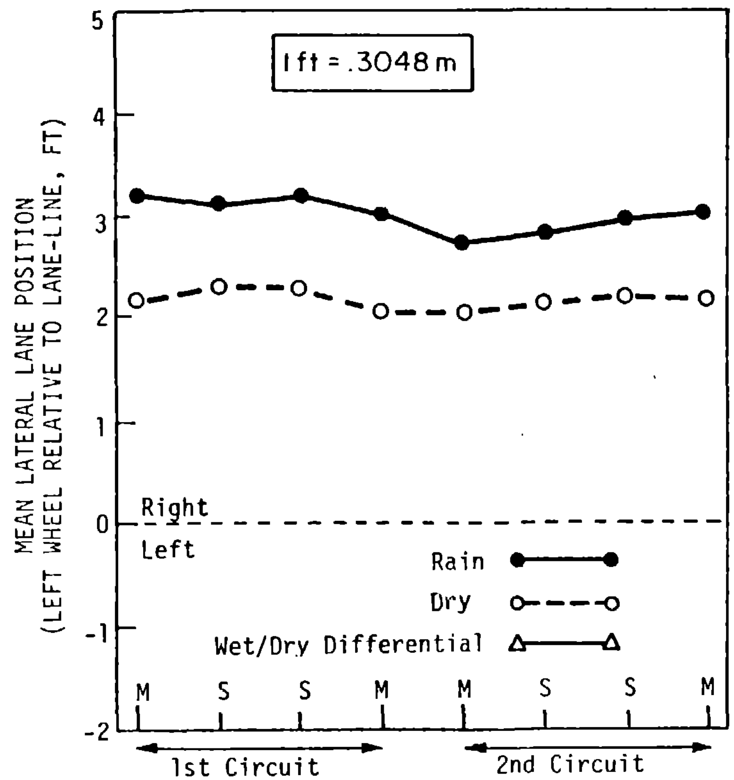
Rain had a significant effect on both mean lane position and lane variations as illustrated in Fig. 27. These results are similar to the first experiment in that the drivers center themselves in the lane when lateral deviations increase, presumably in order to minimize lane edge excursions. This strategy was not as effective in this experiment, however, as shown in Table 11. Left and right lane drift frequencies were tabulated for all subjects over both types of treatment segments and under both weather conditions on the I-5 circuits. There appeared to be a greater tendency for the occurrence of drifts on striping-alone segments than on segments with markers plus striping. Moreover, in wet weather there were more left drifts into the adjacent traffic lane by subjects operating on segments where pavement delineation was provided by striping alone.

The lateral lane position variability data in Fig. 27 show several effects. First of all, the road geometry differences described in Article II.D.1 probably primarily account for the dry run differences between the

TABLE 11

LANE DRIFT FREQUENCIES UNDER WET AND DRY WEATHER CONDITIONS ON I-5 (N = 6)

LANE DRIFTS	WET WEATHER		DRY WEATHER	
	MARKERS + STRIPING (M)	STRIPING ALONE (S)	MARKERS + STRIPING (M)	STRIPING ALONE (S)
Left Drifts				
Number of drifts	1	9	0	0
Number of subjects	1	3	0	0
Right Drifts				
Number of drifts	4	22	2	21
Number of subjects	1	2	1	4
All Drifts				
Number of drifts	5	31	2	21
Number of subjects	1	4	1	4



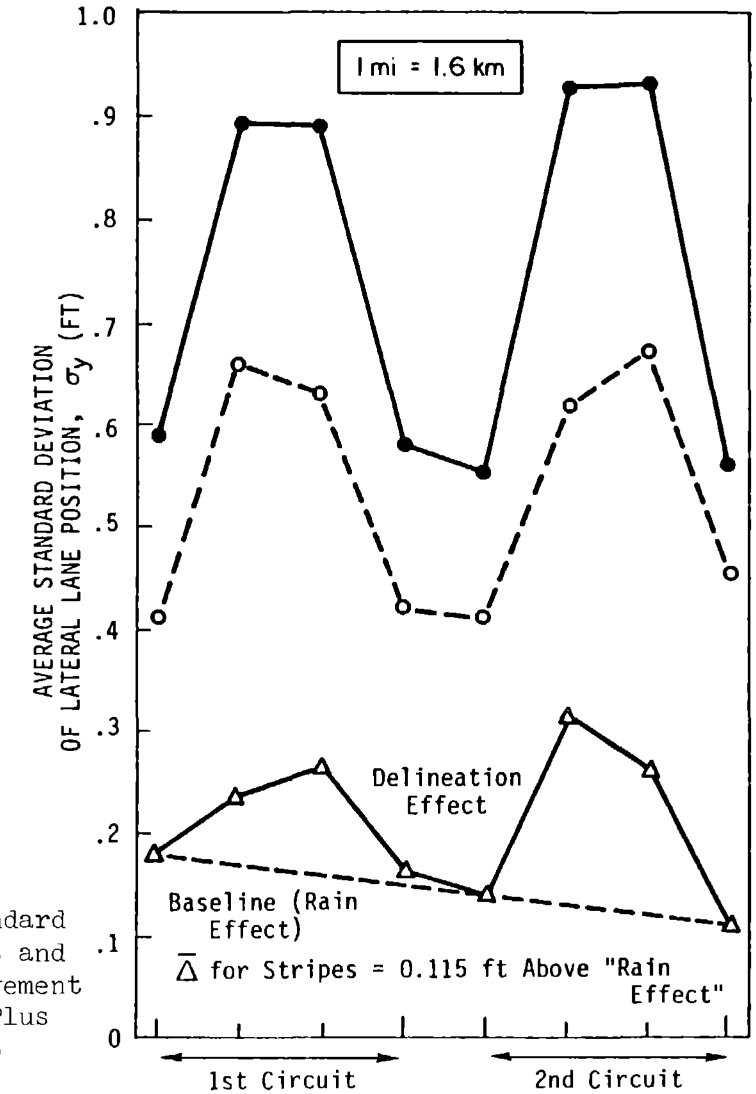


Figure 27. Mean Lateral Position (Left) and Average Standard Deviation of Lateral Lane Position (Right) Under Both Wet and Dry Weather Conditions, Over Treatment Segments Where Pavement Delineation Consisted of Either Raised Pavement Markers Plus Striping (M) or Striping Alone (S), on Two Successive I-5 Circuits

striping only (S) and marker plus striping (M) sections of the test circuit (i.e., the road had much greater curvature on the S section). Secondly, there is a general "rain effect" that seems to influence lane position variation on all parts of the test circuit. Finally, there is the differential effect of interest here, between the changes in lane position variability, wet and dry, for each delineation type. As illustrated by the differential data in Fig. 27, once the course effects and general rain effect are accounted for, there still remains a differential effect with steering control degrading most under the striping only delineation conditions.

b. Paint Versus Thermoplastic Effects in Wet and Dry Weather

The northbound and southbound sections of the I-5 circuit had alternating paint and thermoplastic lane-line delineation in the respective striping-alone treatment segments. To determine whether this change in delineation differentially affected lateral position variables under wet and dry conditions, the results were plotted as shown in Fig. 28.

Any advantage of thermoplastic delineation over paint in wet weather should be revealed by: 1) a reduction in lateral position variability; and possibly 2) an associated reduction in the lane-line/vehicle separation distance, relative to respective dry weather values. Thermoplastic striping was present exclusively in the northernmost quarter of the northbound segment and the northernmost half of the southbound segment. Paint delineation was present alone in the first two quarters northbound, and the last quarter southbound. The other quarters contained mixed thermoplastic and paint delineation. Inspection of the results shown in Fig. 27 indicated no differential effect of the two types of striping delineation on either lateral position variable in the two weather conditions, so no further analysis was conducted.

c. Driver Physciological Response

Several EEG variables were significantly affected by the factors studied on the I-5 circuit. Taken together, these effects indicated a strong

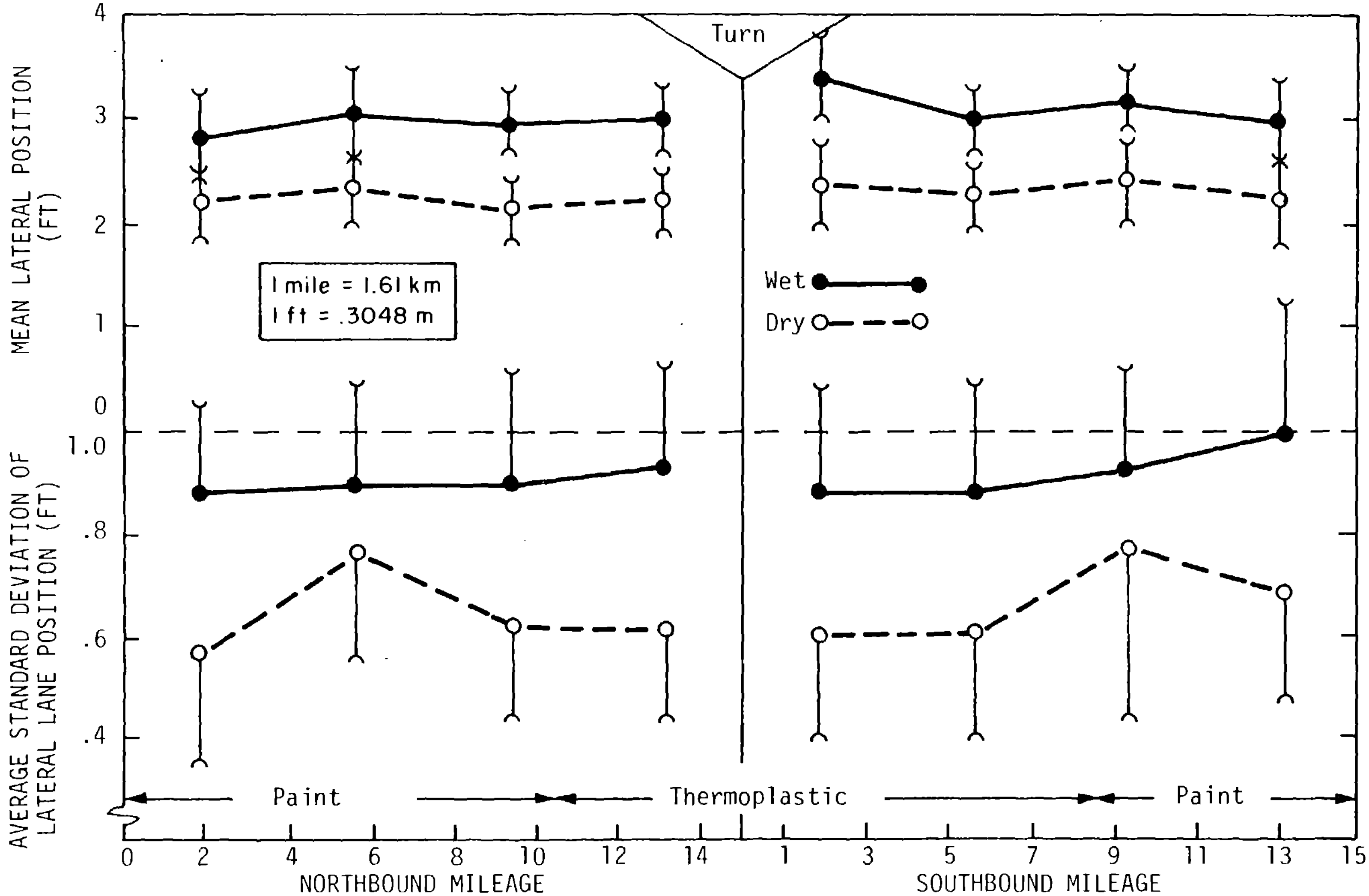


Figure 28. Mean Lateral Lane Position (Top) and Average Standard Deviation of Lateral Lane Position (Bottom) on Both I-5 Circuits Combined Under Both Wet and Dry Weather Conditions in Both Directions on Segments Where Pavement Delineation Consisted of Striping Alone, Either Paint or Thermoplastic, as Shown by Horizontal Arrows; Vertical Bars Indicate Standard Deviation of Individual Scores

correspondence between various EEG reactions and changes in vehicular control. The former are shown in Fig. 29.

It is apparent that a major redistribution of power within the EEG frequency spectrum occurred during exposure to striping alone on the second circuit in wet weather. Power shifted out of the lowest (theta) frequency band and into the highest (beta and alpha) bands. No comparable reactions were ever observed under dry weather conditions or on marker-plus-striping segments in wet weather. This is reflected in the ANOV results in Appendix D as significant effects of the interaction treatments × circuits × weather upon both theta and beta power. Such changes are widely understood to indicate a rather dramatic elevation in psychophysiological arousal, so it seems that the subjects had to exert greater effort for maintaining vehicular control when faced with that adverse combination of delineation, driving time, and weather.

G. FIELD TEST SUMMARY AND DISCUSSION

The analyses that were performed revealed several important effects of delineation visibility on vehicular control. When delineation visibility was reduced by either wear (I-80) or by a covering film of water (I-5), the drivers' reactions were generally as follows:

1. They shifted their vehicle's mean lateral lane position away from the leftware lane line and to approximately the center of their traffic lane.

2. Their lateral control performance deteriorated, as indicated by a substantial increase in the vehicle's lateral position variability. On I-80, this change was dependent upon road grade and curvature, being greater on downgrade curving roadways than on upgrades.

3. They did not reduce mean speed appreciably, except in the rain on I-5. Even there, the average speed reduction was only on the order of 2 mph (3.2 kph) under the worst visibility condition.

4. Their speed control seemed generally unaffected on I-80, although on I-5 the vehicle's speed variability was uniformly higher in the rain.

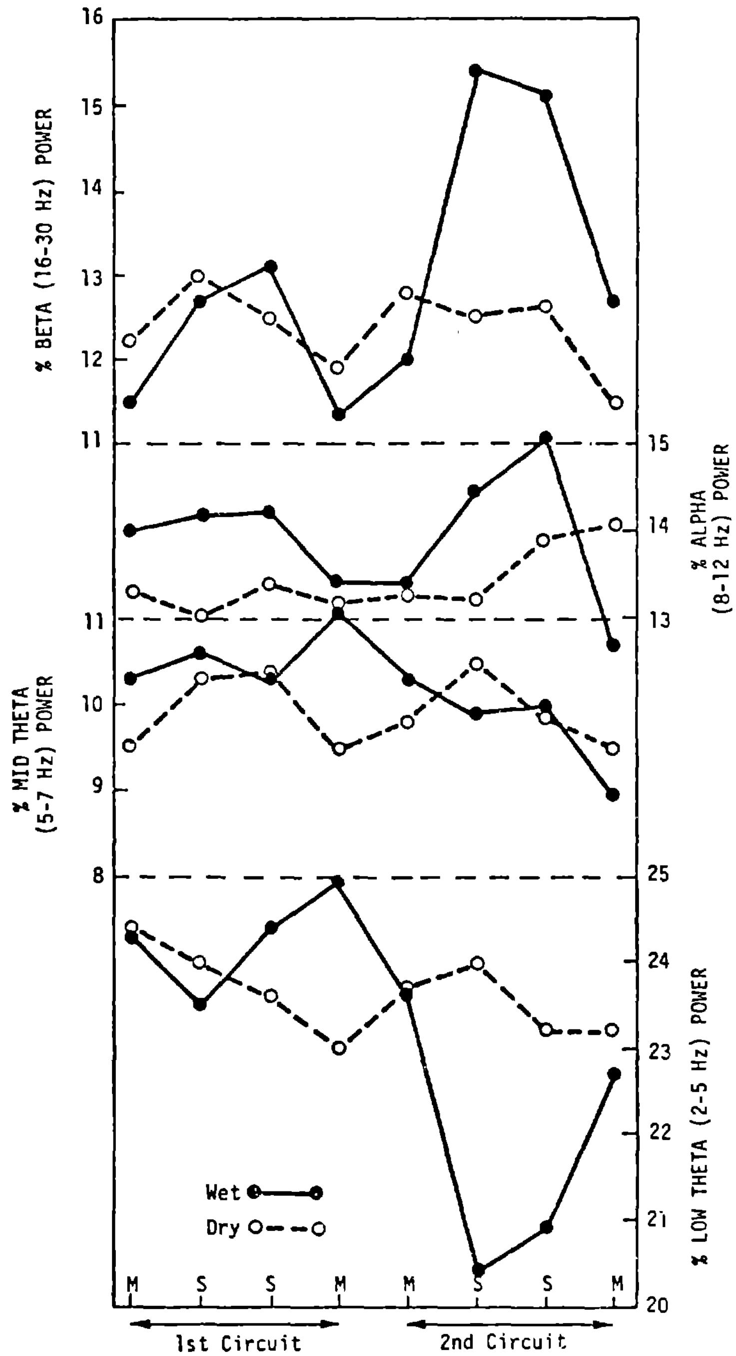


Figure 29. Mean Relative Power (%) Within Each of the Beta (16-30 Hz), Alpha (8-12 Hz), Mid Theta (5-7 Hz), and Low Theta (2-5 Hz) EEG Frequency Bands Under Both Wet and Dry Weather Conditions, Over Treatment Segments Where Pavement Delineation Consisted of Either Raised Pavement Markers Plus Striping (M) or Striping Alone (S) on Two Successive I-5 Circuits

The drivers' overall tendency to shift to a more central lane position under adverse visibility conditions may have been an attempt to compensate for their increased lane position variability. This agrees with the absence of any increase in the drivers' tendency to drift out of their lane on I-80, and only a slight increase in leftward drifting tendency on I-5, while tracking worn or wet pavement delineation.

The major result to emerge from the first experiment was the demonstration of a systematic relationship between pavement striping contrast and lateral position variability. That relationship was described in the regression analysis by a linear equation, expressing the average standard deviation of lateral lane position as a function of log striping contrast:

$$\sigma_y \text{ (ft)} = .77 - .14 \log C_{max} \tag{13}$$

The adequacy of this expression for describing the relationship may be judged from the magnitude of the associated correlation coefficient (i.e., −0.72). Moreover, the expression may serve as a highly practical model for predicting the probability of inadvertent vehicular excursions from traffic lanes as a function of striping contrast (as discussed in Section V).

Yet however adequate and useful the empirical equations might be, it is clear that the true relationship between delineation visibility and vehicular control cannot be linear. This is illustrated by the results of the first experiment. At neither extremes of contrast did the drivers react as might be expected if the relationship between lateral position variability and log contrast were truly linear. At the lower extreme performance was better, and at the upper extreme worse, than predicted by the equation. The true function is probably sigmoidal, bound at low delineation contrast levels by the drivers' compensatory use of visual cues besides pavement delineation, and at high contrast levels by the basic limit of human control capability.

The results obtained in the second experiment strongly indicate the efficacy of retroreflective pavement markers, and the inadequacy of striping delineation for guiding drivers in the rain. With only striping for guidance, the I-5 drivers' lateral vehicular control was even worse in the rain than was that for the I-80 drivers operating when striping contrast was 1.0 or less. Moreover, the I-5 drivers showed a concurrent and potentially dangerous combination of increasing lateral variability and decreasing mean distance from the lane-line over successive circuits on the highway. This occurred as they were showing rather unambiguous physiological signs of heightened arousal, and presumably greater effort. The evidence indicates that the I-5 drivers were exerting great effort, but were still losing control capability when required to operate in the rain with only striping for guidance. When they returned to a road segment where pavement markers were present with striping, their performance recovered and their psychophysiological status returned to its initial, normal level.

A final question arises from the I-5 results. Even in dry weather, the drivers controlled the vehicle with less lateral position variability when pavement markers were used with striping. Because of the highway delineation/geometry confounding mentioned earlier, we cannot conclude from this that the addition of pavement markers improves performance under all circumstances. Yet this is definitely a possibility. Drifts over the markers, in particular the more abundant ceramic type, produce strong auditory and proprioceptive feedback signals to the driver that he has lost some measure of vehicular control. The memory of such events may create an avoidance response to subsequent lane boundary exceedances. Future research, or perhaps a more detailed analysis of the present data base, might be aimed at answering the question of whether such an effect was responsible for the result reported here.

SECTION V

COMPARISONS AND RATIONALIZATION OF SIMULATION AND FIELD TEST RESULTS

A. OVERVIEW

In the previous three sections we have considered: basic fundamentals associated with driver visibility, perception, and control; simulation tests over a wide range of visibility and delineation conditions; and two field experiments which considered delineation contrast variations due to paint/glass bead condition and rain. In this section we will tie together the simulation and field test experiments and then draw conclusions about delineation contrast and configuration requirements.

In the following article (B) simulation and field test performance (lateral lane deviations) results are compared using the visual contrast thresholds concept discussed in Section II-B. The use of a few assumptions allows fairly satisfactory comparison between the laboratory and field experiments. Given the tie-in between the two experiments, we then consider the implications for specifying delineation contrast and configuration requirements in Article C. Then, presuming a contrast specification, we discuss the photometry requirements for assessing delineation contrast in Article D.

B. SIMULATOR AND FIELD TEST COMPARISON

In Section III the simulation performance results lead to an empirical relationship between lateral lane deviation, speed, and delineation visibility and configuration (Eq. 12, Section III.C.2). Ignoring speed effects this relationship can be expressed as

$$\sigma_y = b_1 + a_2 C_V \qquad (14)$$

where b_1 accounts for both speed and threshold effects, a_2 accounts for road geometry, and C_V includes visibility and configuration factors as defined in Fig. 12. C_V can be broken down into visibility components as follows:

$$C_V = \frac{x_g + x_o}{x_v} \cdot \frac{x_g}{x_c} = \frac{b_2}{x_v} \qquad (15)$$

where b_2 contains all the delineation configuration factors and x_V is the visual range of delineation cues. In the simulation study, one of the main independent variables was the visual range, x_V, while in the first field study measured delineation contrast quantified the experimental treatment. Thus, visual range must be expressed as a function of delineation contrast in order to compare these data sets. This can be accomplished as described below.

Figure 30 is a replot and combination of contrast threshold curves from Section II for various lighting conditions. As indicated on Fig. 30, visual contrast threshold can be expressed to a first-order approximation for visual range of interest, as a simple function of visual range:

$$\log C_T = \log C_{T_o} + c_1 x_V \qquad (16)$$

The parameter c_1 is the slope of the Fig. 30 data which is determined by target size, the type of lighting, and rain as illustrated. The parameter CT_o defines the vertical location as intercept of the threshold characteristics, and thus includes the effect of multiplying field factors applied to the Blackwell contrast threshold data as discussed in Section II.B. As described below, CT_o will have to be increased (i.e., larger thresholds) to gain correspondence between the simulator and field data.

Now Eqs. 14-16 can be combined to express performance as a function of contrast:

$$\sigma_y = b_1 + \frac{a_2 b_2 c_1}{\log C_T - \log C_{T_o}} \qquad (17)$$

By assuming that the field test visual range is equivalent to the range where the contrast threshold exceeds the measured delineation contrast, Eq. 17 can then be used to equate the field test results with the simulation results obtained as a function of visual range. An appropriate set of parameters for Eq. 17 was determined for each experiment as follows:

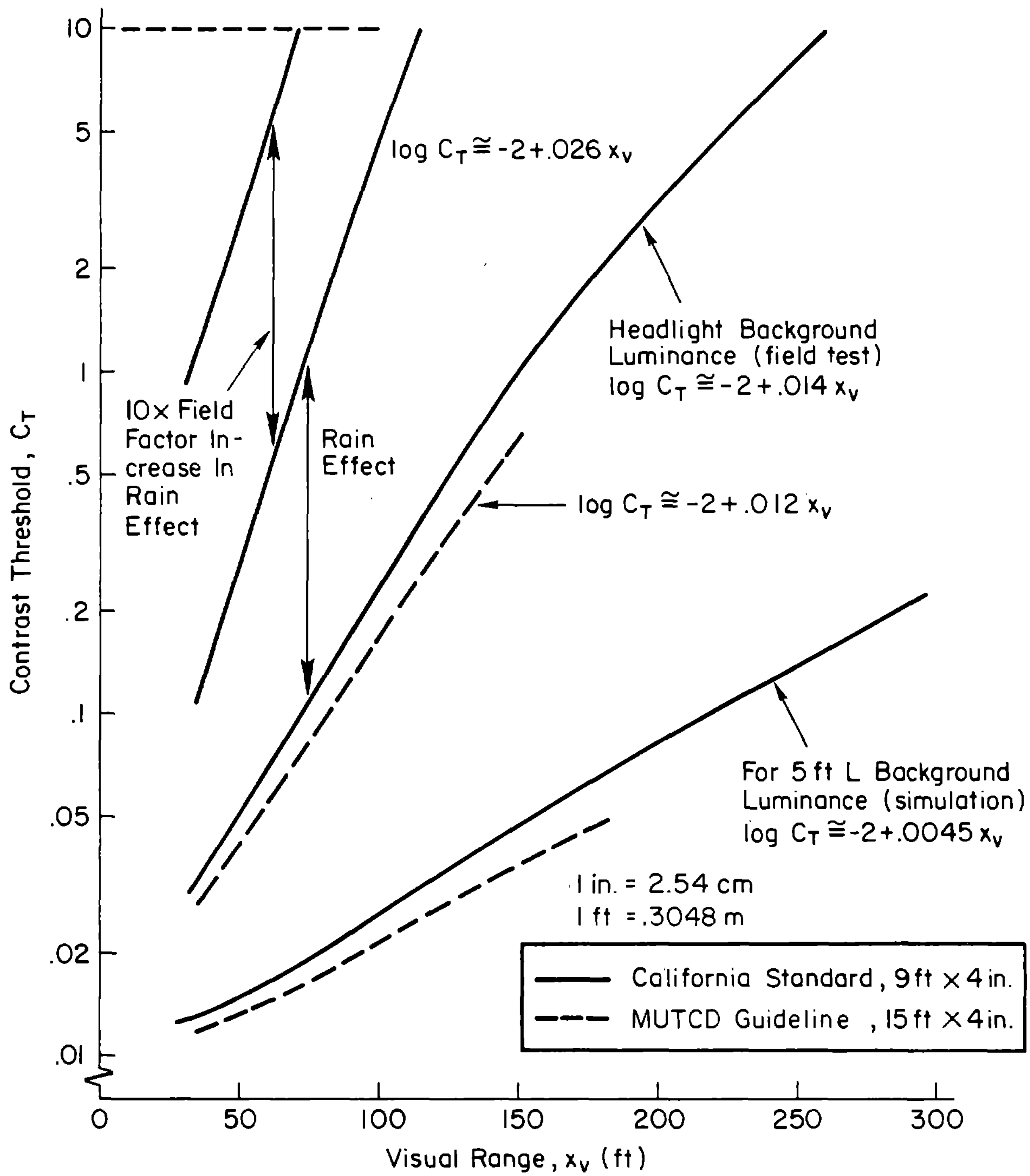


Figure 30. Contrast Thresholds for Delineation Targets Under Various Background Luminance Conditions

1. I-80 Delineation Contrast Study

The parameter b_1 defines the minimum value of σ_y for high contrast values (long visual ranges). Under daylight conditions previous investigators[38] have measured values of 0.3-0.4 ft (9-12 cm). On our I-80 test circuit under high contrast conditions drivers achieved average performance levels approaching 0.5 ft (15 cm) (see Appendix D). Therefore, we will assume here that $b_1 \doteq 0.5$. The parameter a_2 was measured in our simulation study as 0.72 for the curved road task which was basically the task on the I-80 test course (Fig. 22). b_2 is strictly a function of the delineation configuration [x_g = 15 ft (4.6 m), x_c = 24 ft (7.3 m)] and the vehicle forward visibility [x_o = 22 ft (6.7 m)] which results in a value of b_2 = 23.1 ft (7.0 m). c_1 is given by the slope of the appropriate Fig. 30 data (c_1 = 0.014 ft^{-1}; or 0.046 m^{-1}), and the intercept log C_{T_o} depends on what is assumed for a multiplying field factor. For the comparison here we will select a value for C_{T_o} that gives appropriate performance levels and observe whether other characteristics of the model are consistent with the observed field test results.

Using the above constants in Eq. 16 and setting log $C_{T_o} = -1$ (i.e., intercept contrast equals 0.10), we obtain the predicted performance curve as a function of contrast shown in Fig. 31. In comparison with the field test data the slope of the prediction curve looks appropriate in the contrast region above 0.5, approaching a lower bound at high contrast values as might be expected. At low contrasts the model curve accelerates rapidly, as the visual range predicted from the Blackwell data approaches zero. Of course, in the field other cues are present when delineation contrast approaches zero, which leads to a finite lower bound to visual range. This effect can be accounted for as follows.

Assume that at low delineation contrast values other road cues then come into play which can be accounted for as an equivalent lower bound on contrast. Equation 17 can then be modified as:

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[38]Soliday, "Lane Position Maintenance by Automobile Drivers."

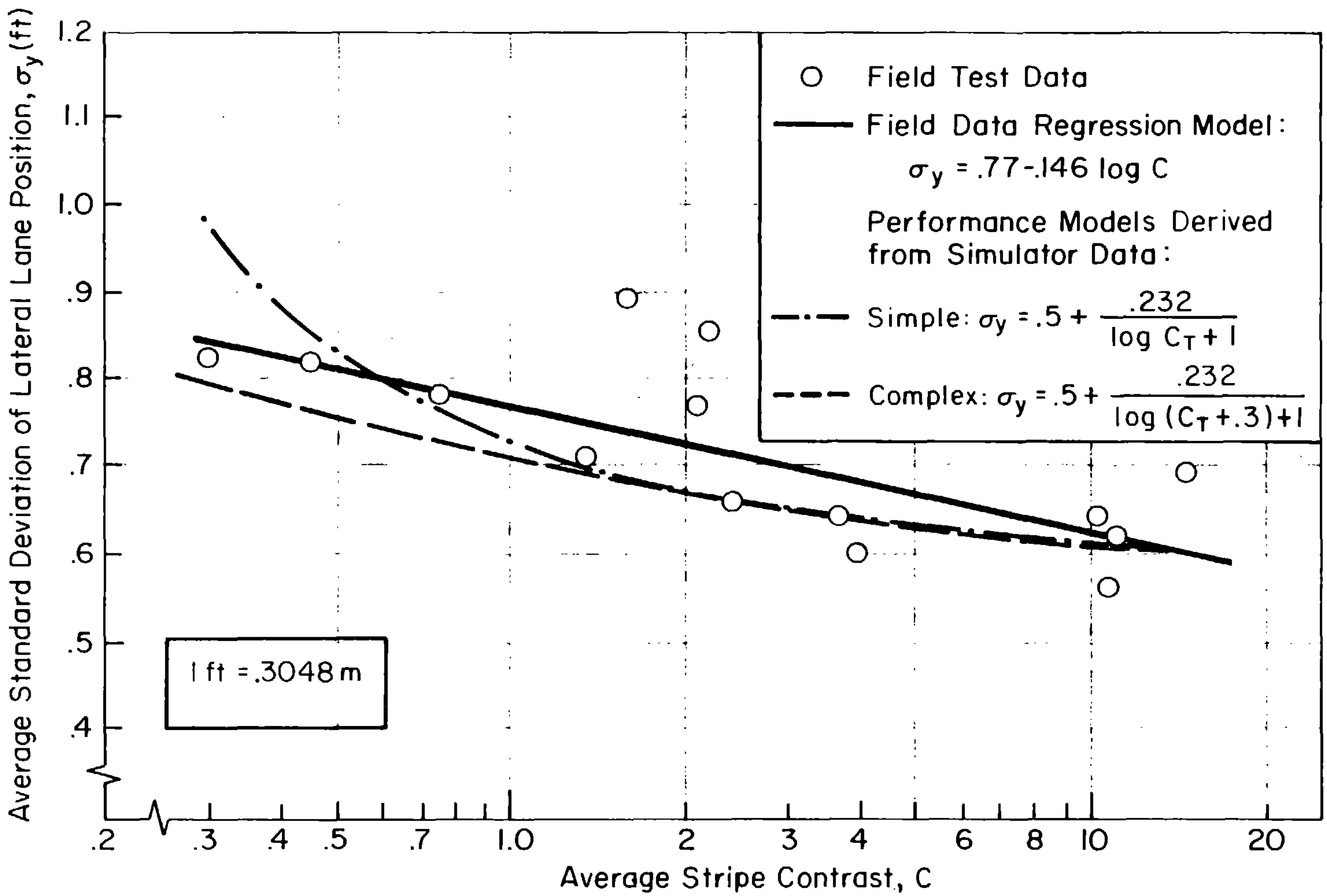

Figure 31. Comparison of Performance Prediction Equations with the I-80 Field Test Data

$$\sigma_y = b_1 + \frac{a_2 b_2 c_1}{\log(C_T + C') - \log C_{T_o}} \quad (18)$$

where C' is an equivalent lower bound on contrast. Assuming C' = 0.3, this results in the complex simulator performance model shown in Fig. 31, and also results in a lower bound on σ_y of about 1 ft (0.3 m).

2. I-5 Rain Study

Turn now to the I-5 rain data. As described in Section IV.F.2, the rain caused a differential effect with and without raised pavement markers of about 0.11 ft (33 cm) lane deviation (Fig. 26). Now assume a delineation contrast of 10, with rain and dry contrast threshold slopes of c_1 = 0.026 and 0.014, respectively, as derived from Fig. 31. Evaluating Eq. 17 gives a differential performance of about 0.10 ft (3 cm). As a further comparison raise the rain contrast threshold curve by the 10 times field factor assumed above for Eq. 17 as illustrated in Fig. 30. Now pick off the visual range associated with a delineation contrast of 10 and we get a value of 72 ft (21.9 m). Referring back to Table 7 in Section IV.D.3, this value is seen to be consistent with field-reported visual ranges in the rain.

The above analysis appears to give fairly good tie-in between simulator and field experiments, especially where trends (rather than absolute levels) are concerned. Before we draw conclusions about delineation contrast and configuration requirements, let us review the data and various assumptions used and their consequences. First, the minimum performance level b_1 in Eq. 17 was assumed to be consistent with levels measured in our experiment and past research, and thus is near the right magnitude. The parameters a_2 and b_2 were obtained from the simulator experiment and delineation configuration [9 ft (2.7 m) stripes, 25 ft (7.6 m) cycle length], respectively. These two parameters combine with the contrast threshold slope as a function of visual range, c_1, to form the numerator of the second term in Eq. 17. This numerator term essentially "scales" the amount of performance change as a function of contrast variation, and the above analysis has shown good correspondence in these covariations.

The weakest assumption in the above analysis was in setting the base contrast value C_{T_0}. The threshold curves in Fig. 30 had intercept values of 0.01 (i.e., $\log C_0 = -2$). This value was originally increased by a factor of 4 times over thresholds derived directly from Blackwell data (Fig. 2, Article II.B). Now to match performance we assumed a contrast intercept of 0.1 (i.e., $\log C_0 = -1$) which means a 40 times increase over the original Blackwell characteristics. Is that factor reasonable? As discussed in Articles II.B and II.C, field factors are commonly used to account for real-world observations, and order of magnitude field factors have been justified in past investigations.[8,19] Delineation detection is complicated, and the basic psychophysical study on this capability remains to be accomplished, as discussed in Article II.B. Such a study may show somewhat lower thresholds for pure detection than assumed here, but when combined with perception and control as studied here we suggest that "effective" thresholds of the order assumed here are probably in effect.

C. DELINEATION CONTRAST AND CONFIGURATION REQUIREMENTS

It is obvious from the simulation and field test results that steering performance improves with improved visibility in terms of delineation contrast and configuration. The question now is whether there are any obvious limits or inflections in these relationships that will suggest requirement boundaries, or whether cost/effectiveness analyses must be considered to determine tradeoffs between maintenance cost and derived benefits such as reduced accidents.

1. Contrast

Consider first delineation contrast. Take the field test regression relationship between delineation contrast and lane deviations (Eq. 13, Article IV.F) repeated here for reference:

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[8] Blackwell, et al., "Illumination Requirements for Roadway Visual Tasks."
[19] Duntley, et al., "Visibility."

$$\sigma_y = .77 - .146 \log C \qquad (19)$$

Assume on the average that the vehicle was centered in the lane. Given a 6 ft (1.8 m) wide vehicle and 12 ft (3.7 m) lane width, we can then calculate the probability of lane edge exceedance and relate this back to delineation contrast via Eq. 19 as illustrated in Fig. 32. Here we see a knee in the curve in the contrast range of 1-2. Although the probabilities are low in this region (approximately 0.004 to 0.01 percent), the simulator study showed that drivers attempt to keep lane deviations below 1.0 ft (0.3 m), and the field test lane deviations in the 1-2 contrast region were on the order of 0.7 to 0.9 ft (21-27 cm).

The knee of the Fig. 32 curve is also consistent with some ad hoc observations. First note that the demarcation point between the fresh and worn paint conditions on the I-80 study was in the region of a contrast value of 3 as indicated in Fig. 32. As reported to us, drivers on I-80 complain about worn paint conditions on the highway after the spring thaw and prior to restriping.[41] Secondly, drivers center themselves in the lane when delineation contrast degrades, presumably to minimize the probability of lane boundary exceedance. Thus, the above evidence suggests that delineation contrast should be maintained above the knee of the Fig. 32 curve, say contrast values of 2 and beyond.

The above contrast recommendation was established from data obtained under relatively good night driving conditions, i.e., a divided highway with low traffic volume during the test periods. Various conditions such as opposing traffic headlight glare and fog can lower the perceived road to delineation contrast, as discussed in Article II.C, and the question here is how much the minimum contrast recommendation should be elevated to account for these adverse visibility conditions. First of all, let us keep in mind how much latitude we have in achievable delineation contrast. In Article IV.C.3

[41]Personal communication with Perry Lowden, Senior Transportation Engineer for Signs and Delineation, Office of Traffic, California Department of Transportation.

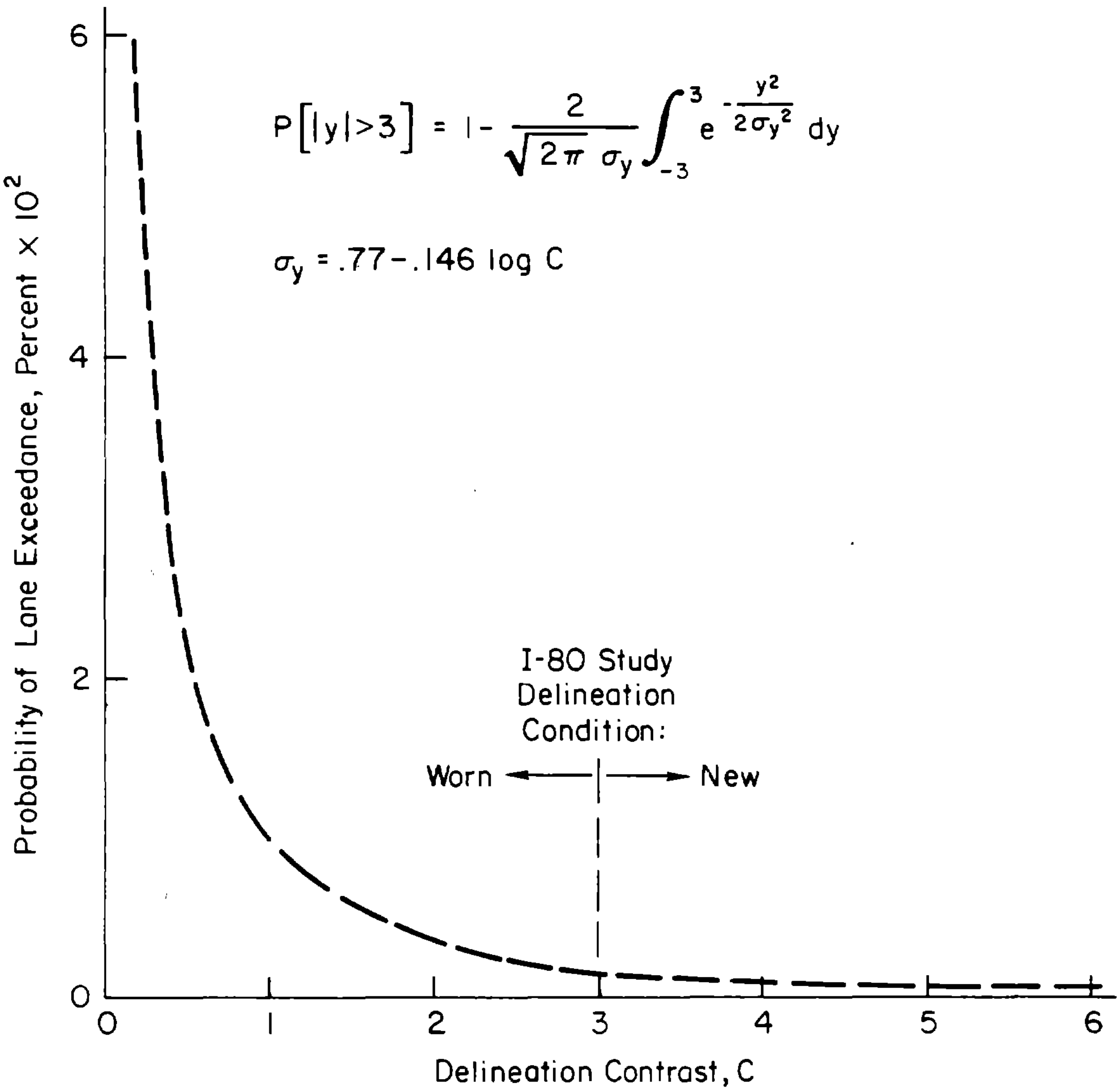

Figure 32. Effect of Delineation Contrast on the Probability of Lane Exceedance for the I-80 Field Test Experiment

we discussed the contrast measurements on our I-80 test site and concluded that average contrast levels much in excess of 10 are not practically achievable.

Let us say we have a contrast range of 2-12 to work within. If we were to double the minimum contrast requirement to 4, how much increased visibility would be gained? If we refer back to Fig. 5, Article II.C, we can graphically compute from the examples given that doubling minimum contrast from 2 to 4 gives only a 13 percent increase in delineation visual range. Now, if perceived contrasts are below the knee of the Fig. 32 curve, we see that contrast doubling should have a dramatic effect on lane exceedance probability, much above a perceived contrast of 0.5, however, and the gains do not appear to be very significant. Actually, a minimum road to delineation contrast of 2 does give some margin if perceived contrasts of 0.5 (i.e., an apparent contrast reduction of 4 times due to fog and/or glare) are considered to be adequate.

Actually, the bottom line on the above discussion is whether maintaining a given contrast level is cost-effective or not. How much does it cost to maintain a road to delineation contrast of 2 or 4? How much does this contribute to road safety? In regions of high fog incidence, high contrast levels would be more important. It is obvious that specific contrast recommendations beyond the qualitative considerations reviewed here will require additional sensitivity and cost analysis, which is beyond the scope of this effort. The minimum contrast level of 2 will allow us to make recommendations for field measurement devices, however, as discussed further below.

2. Configuration

Now consider configuration effects. In the previous article we illustrated how delineation configuration factors "scale" the effects of contrast on steering performance, specifically the parameters b_2 (Eq. 15), which relates to the configuration effect determined in the simulation study, and c_1, the contrast threshold slope which is related to delineation element size in Fig. 30.

In Table 12 we have computed values for the configuration parameter b_2 (Eq. 15) for three standard or proposed delineation configurations. We have also graphically determined visibility ranges as indicated in Table 12 under assumed fog and headlighting conditions, and assuming an inherent delineation to pavement contrast of 2. Several effects are apparent in Table 12. First, note that in going from the Caltrans standard configuration of 9 ft (2.7 m) segments and 15 ft (4.6 m) gaps to the old MUTCD guideline of 15 ft (4.6 m) segments and 25 ft (7.6 m) gaps, the configuration parameter b_2 increases by about 28 percent, while going to the new FHWA guideline b_2 increases by 71 percent. Performance deteriorates with increases in b_2

TABLE 12. CONFIGURATION CHANGE ANALYSIS

(1 ft = 0.3048 m)

CONFIGURATION			b_2 [d]	CLEAR NIGHT		DAY FOG		NIGHT FOG	
SOURCE	MARK/ CYCLE	MARK/ GAP		x_v [e] (ft)	C_v	x_v [f] (ft)	C_v	x_v [g] (ft)	C_v
Caltrans Standard[a]	9/24	9/15 3:5	21.9	178	.123	157	.139	82	.267
Old MUTCD Guideline[b]	15/40	15/25 3:5	28.1	200	.141	166	.169	86	.327
New FHWA Guideline[c]	10/40	10/30 1:3	37.5	178	.211	157	.239	82	.457

[a] Traffic Manual, State of California, Business and Transportation Agency, Department of Public Works, 1971.

[b] Manual on Uniform Traffic Control Devices for Streets and Highways, Federal Highway Administration, 1971.

[c] "Change in Recommended Segment to Gap Ratio for Pavement Markings, FHWA Bulletin, Office of Traffic Operations, 31 May 1977.

[d] $b_2 = \frac{(x_g + x_o)x_g}{x_c}$ (from Eq. 15), x_o assumed to be 20 ft

[e] x_v determined from Figs 5b or 30, $C_o = 2$

[f] x_v determined from Fig. 5a, $C_o = 2$

[g] x_v determined from Fig. 5b, $C_o = 2$

(Eqs. 17 and 18), so that the new FHWA recommendation represents some steering performance disadvantage over past practice.

Steering performance is also dependent on visibility range x_V as indicated in Eqs. 17 and 18, so to completely compare the example delineations in Table 12 assumed visibility conditions (night and/or fog) were used to graphically compute ranges. The visibility range can then be used to compute the configuration visibility parameter C_V (Eq. 15), which determines performance through Eq. 14. In Table 12 under clear night driving conditions C_V increases by 15 percent in going from the Caltrans standard to the old MUTCD guideline, while the configuration parameter b_2 had increased by 28 percent. The reduced configuration effect on C_V is because the longer segment length of the old MUTCD guideline represents a larger target size which yields a longer visibility range, x_V. Thus the increased x_V partially offsets the increased b_2, so that the total performance effect represented by C_V does not exhibit a significant change between the Caltrans standard and old MUTCD guidelines. It should be noted that both these configurations have the same 3:5 segment-to-gap ratios and even under day and night fog conditions the change in C_V is only about 22 percent. In going to the new FHWA guideline, however, we find for all visibility conditions that it has a 71-72 percent larger C_V value than the Caltrans standard, because although the target size for the two configurations is similar, the gap size changes by a factor of two.

Now, what can be concluded about configuration effects? First, from the above discussion it appears that changing the segment-to-gap ratio has the most significant effect on steering performance. Under relatively good visibility conditions (say clear night driving), the effect may not seriously affect steering performance. Under more adverse conditions (say night fog), the effect may be critical (e.g., note the high C_V value in the lower right-hand corner of Table 12). Thus, for some high fog regions, high segment-to-gap ratios are indicated.

Second, the previous discussions about the apparent sampling effect of striping under reduced visibility conditions should be recalled. In Article II.B it was brought out that contrast thresholds reduce under dynamic conditions and are a maximum in the frequency region of 2.5 Hz.[4] For the national standard cycle length of 40 ft (12.2 m), the 2.5 Hz frequency amounts to a speed of 100 ft/sec (68 mph) [30.5 m/sec (109 kph)], while for the California standard the optimum speed would be 40 ft/sec (27 mph) [12.2 m/sec (43 kph)]. Another sampling phenomenon was uncovered in the simulator tests which caused increased driver time delay at slow speeds under adverse visibility and a reported subjective desire to speed up (Article III.C.4). These two factors combine to suggest that delineation cycle lengths be kept as small as possible in order to avoid inducing inappropriately high speeds under adverse visibility conditions.

The configuration effects discussed above are somewhat qualitative, although they do expose the major variables affecting delineation visibility. Because of the potential cost savings associated with reduction in the delineation segment-to-gap ratio, it is recommended that a combination of further simulation research and cost/benefit analysis be conducted to determine potential tradeoffs between delineation configuration variations, driver steering performance and traffic safety, and delineation maintenance costs.

D. PHOTOMETRY REQUIREMENTS

Now that the order of magnitude of required contrast has been deduced from the experimental data we can address some of the photometry requirements for field measurements of delineation contrast that would be required to implement a delineation contrast specification.

Consider first the sensitivity of contrast to measurement errors. In order to determine contrast, two luminance values associated with the delineation target (L_T) and roadway background (L_B) must be measured. Then, it will be recalled that delineation contrast is defined as:

[4]Pantle, Research on the Recognition and Analysis of Complex and Dynamic Imagery.

$$C = \frac{L_T - L_B}{L_B} \qquad (20)$$

The sensitivity of contrast evaluations to errors in luminance measurements can be examined by considering the proportional total differential. The total differential is:

$$dC = \frac{dL_T}{L_B} - \frac{L_T}{L_B}\frac{dL_B}{L_B}$$

Then the proportional differential becomes:

$$\frac{dC}{C} = \frac{L_T}{L_T - L_B}\left[\frac{dL_T}{L_T} - \frac{dL_B}{L_B}\right]$$

$$= \left(\frac{C + 1}{C}\right)\left[\frac{dL_T}{L_T} - \frac{dL_B}{L_B}\right] \qquad (21)$$

For $C >> 1$, this becomes simply:

$$\frac{dC}{C} = \frac{dL_T}{L_T} - \frac{dL_B}{L_B} \qquad (22)$$

Presuming independence of the L_T and L_B measurements, the percentage errors in evaluation of contrast are the same order of magnitude as the measurement accuracies. On the other hand, if $C << 1$, the sensitivity factor $(C + 1)/C$ can become very large, thereby greatly magnifying the effect of luminance measurement errors on contrast assessments. Now if we attempt to measure contrasts on the order of 2, which is a recommended lower bound for adequate driver steering control, $(C + 1)/C \doteq 1.5$. Thus a 10 percent parameter measurement error in L_T or L_B results in an error in contrast of about 15 percent. Given this rather benign sensitivity to measurement errors, what methods can be used in the field to assess delineation contrast?

The most straightforward approach would be to meter delineation targets with a hand-held "spot" photometer. There are several commercially available inexpensive hand-held photographic light meters[42,43] with narrow acceptance angles (approximately 1 deg) that should be more than adequate for the measurement under consideration here. The measurement could be made during the day, since the marginal contrast level under consideration here probably represents fairly worn delineation with few if any beads to cause retro-reflection, which is important under headlighting conditions. To make field assessment even simpler we can restate Eq. 20 as

$$\frac{L_T}{L_B} = C + 1 \tag{23}$$

or

$$\log L_T - \log L_B = \log (C + 1) \tag{24}$$

Now if the meter is calibrated to read out in log units, the user merely takes the difference of two quantities in order to determine if the delineation contrast is up to specification. For a contrast of 2, Eq. 24 gives a differential of approximately 0.5 log to the base 10 ($\log_{10}$) units.

A more automatic procedure might be desirable using a device similar to the ERMA apparatus.[44] ERMA basically amounts to a photodiode and associated optics and electronics mounted in a light-tight box. The box is mounted on a vehicle and can be lowered to within a few inches of the pavement. A flexible "brush" like seal is provided to make a light-tight seal with the ground. ERMA uses its own light source which is mounted at a shallow angle with respect to the road to approximate headlighting.

With one sensor ERMA currently measures one luminance level. If we were to use a scanning photodiode array such as employed in the field test

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[42] Woltman, H. L., and W. P. Youngblood, "Evaluating Nighttime Sign Surrounds," presented at the 56th Annual Meeting of the Transportation Research Board, Washington, D. C., Jan. 1977.

[43] Walker, R. A., and J. K. Branch, "A New Photometer for Measuring Screen Brightness," Journal of the SMPTE, Vol. 83, Sept. 1974, pp. 737-740.

[44] Gillis, H. J., "ERMA, A Retro-Reflectivity Device," Minnesota Department of Highways, MN HW 5-180, 74-4, 1974.

lane tracking apparatus (Appendix C), then both road background and delineation target luminances could be obtained simultaneously. Special-purpose or microprocessor electronics could be used to scan the array, pick out high and low luminance levels, then compute contrast or the simpler luminance ratio given above. With this setup the device would not have to be aligned precisely with the delineation line since the scanning apparatus could be set up to determine the luminance levels wherever they might occur in the diode array field of view.

Other photometry factors discussed in Appendix E should be reiterated here. In general the measured contrast must be consistent with that perceived by the driver. This means first of all that the spectral response of the photometer should be similar to the eye. The degree of similarity depends on the spectral reflectance of the road and delineation, but in general the measurement should not include significant infrared or ultraviolet components.

A second photometry requirement is that the measurement procedure approximate the delineation illumination and viewing angles experienced by the driver. Drivers typically look down the road about 75 ft (22.9 m), and eye height in an automobile is on the order of 4 ft (1.2 m), thus giving a viewing angle with respect to the road of about 3 deg. Typical car headlight position would result in an illumination angle with respect to the road of about 2 deg (i.e., an incident angle of 88 deg). How critical are the angles? Not very. Drivers are not always looking down the road 75 ft (22.9 m), particularly when visibility range is restricted to a lesser value, and drivers of vans and trucks experience larger angles anyway. If an illumination source is used, then the source angle with respect to the road should be on the order of 2-4 deg and the measurement angle should be greater by a few degrees.

Is an illumination source important? It is most important when retroreflective material (i.e., beads) constitute a large portion of the delineation luminance. As the delineation wears and approaches an allowable minimum contrast value, much of the delineation retroreflective characteristic will have deteriorated and directed illumination becomes less important.

How much less? This is a question that needs to be answered with further delineation field research along the lines already carried out in California[40] and careful photometry should be included.

In the end we must bear in mind that we are seeking a practical, reliable, simple field contrast measurement capability, not a precision laboratory photometry procedure. If we can achieve a 5 percent accuracy in the differential log luminance expression of Eq. 24 when measuring a contrast on the order of 2, then the equivalent contrast will only be in error by about 10 percent, and this is certainly an acceptable accuracy for a field maintenance specification.

[40] Russell, G. L., Optimization of Traffic Lane Delineation.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

In this section conclusions and recommendations are given which relate to the original objectives stated in Section I and repeated again here:

- Develop dependent variables sensitive to roadway delineation treatments.
- Establish visibility requirements for roadway delineation.
- Determine luminance-contrast requirements for delineation treatments.
- Develop functional specifications for a practical test methodology suitable for assessing roadway marking contrast.

The conclusions are drawn from a combination of previous knowledge about visibility and perception as reviewed in Section II, and the current simulation and field tests discussed in Sections III through V. It is emphasized again that these results relate primarily to the driver's ability to laterally control his vehicle along a delineated pathway (steering control), as opposed to speed control and/or stopping which is primarily evoked by signing, signals, traffic and other obstacles on the roadway.

A. DEPENDENT VARIABLES SENSITIVE TO ROADWAY DELINEATION

In the simulator tests lane position variability, preferred speed, and driver rating were all found to be similarly sensitive to delineation configuration and visual range. In the field tests, lateral lane position variability was found to be sensitive to delineation contrast. Driver physiological response was also found to be sensitive to rain conditions which affect delineation visibility. Details of these various measures are given in Sections III and IV.

In addition to the above variables, various measures of the driver's dynamic response obtained in the simulation have given a great deal of insight into the manner in which adverse visibility restricts the driver's perception of automobile path and motion information required for steering control. These perceptual restrictions have been quantified in terms of the driver's dynamic steering behavior in response to random disturbances and path commands. Combinations of reduced visibility and delineation configuration (i.e., intermittent dashed or dotted lines) tend to induce increased time delay in the driver and impair his perception of road curvature. Reduced visibility also induces a reduction in equivalent dynamic look-ahead distance (the inverse of lateral position error gain) but does not appear to influence the weighting or gain the driver applies to heading errors.

The above effects appear to be related to the apparent intermittent or sampled nature of delineation under reduced visibility conditions. Driver time delay, τ_e, increases at slower speeds, due to decreased sampling frequency, even though vehicle dynamic lags decrease with speed. This effect induced a somewhat compelling urge in some subjects to speed up in order to increase their information rate, which is a rather insidious phenomenon if true for real-world driving, since it might encourage drivers to maintain speeds with associated stopping distances exceeding their visual range.

Changes in curve perception gain also appear to be related to information sampling, with the gain decreasing with decreased speed and/or reduction in the amount of perceptual information (i.e., increased C_V). In this case curvature perception is enhanced with speed, which may also be related to "streamer" theories of driver perception where the curved path motion of the car is indicated by the curved motion of visual field elements.

B. VISIBILITY REQUIREMENTS FOR ROADWAY DELINEATION

1. Conclusions

The driver's ability to steer his vehicle along a delineated pathway is dependent on the visual range and configuration of the delineation, vehicle speed, and road geometry. Delineation provides the visual perceptual input for driver steering control actions. Driver steering performance depends on the quality and extent of the perceptual input. Steering performance degrades with decreased visual range. Steering performance also degrades as the segment-to-gap ratio of delineation is reduced, and the cycle length is increased.

Under adverse visibility conditions of night and/or fog, steering performance can be improved by increasing delineation contrast to achieve a longer visual range, and by improving the quality of the delineation configuration by increasing segment-to-gap ratio and decreasing the segment cycle length. Adding a solid right edge line gives a rather dramatic improvement in performance under adverse visibility conditions.

Steering performance also is affected by roadway geometry. In some cases delineation visual range may be restricted simply by roadway curvature, and in these cases, combined with prevalent adverse visibility conditions, high quality delineation configuration (i.e., higher segment-to-gap ratios and shorter cycle lengths) is indicated.

Rain effectively obscures painted delineation, and raised pavement markers which penetrate the water surface provide the only effective countermeasure.

2. Recommendations

Cost/benefit analysis must be performed in order to determine the cost effectiveness of various delineation treatments and maintenance schedules. Frequent restriping and high segment-to-gap ratios will maximize driver steering performance but are costly. A compromise must be struck between cost and performance, and this tradeoff can be determined through cost/benefit analysis using the performance models developed in this report and maintenance and wear data provided in previous research.[40]

[40] Russell, G. L., Optimization of Traffic Lane Delineation.

Further simulator and field test research and visibility analysis should also be conducted to determine if improved delineation visibility under adverse visibility conditions might actually degrade traffic safety by inducing higher vehicle speeds. Optimum delineation, while improving steering performance, might induce vehicle speeds with associated stopping distances[14] which are in excess of typical obstacle detection ranges. This problem could be analyzed through a combination of simulator tests and visibility analysis, and verified with field measures of vehicle speeds under various visibility and delineation contrast and configuration conditions.

Further simulation research could be fruitfully conducted on variations of segment-to-gap ratios and delineation cycle lengths. Only certain selected cases were considered here, specifically the Caltrans standard[7] [9 ft (2.7 m) segments and 15 ft (4.8 m) gaps] and the old MUTCD guideline[5] [15 ft (4.8 m) segments and 25 ft (7.6 m) gaps]. Further research should include the new FHWA guideline[33] [10 ft (3.0 m) segments and 30 ft (9.1 m) gaps].

C. LUMINANCE-CONTRAST REQUIREMENTS FOR DELINEATION

1. Conclusions

Results of this study indicate that delineation contrast should be maintained above a value of 2 (dimensionless) for adequate steering performance under clear night driving conditions. For areas with more adverse visibility conditions (i.e., fog), delineation contrast should be maintained at even higher values. There is a tradeoff here between maintenance costs and improved driver performance, however, and a specific contrast increase cannot be stated without appropriate cost/benefit analysis. Practically achievable levels of road-to-delineation contrast are not much greater than 10, however, so the contrast range is somewhat limited.

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[14] A Policy on Geometric Design of Rural Highways — 1965.

[7] Traffic Manual, State of California.

[5] Manual on Uniform Traffic Control Devices.

[33] "Change in Recommended Segment to Gap Ratio for Pavement Markings."

2. Recommendations

A cost/benefit analysis should be conducted on the cost effectiveness of maintaining given levels of delineation contrast. The performance models developed in this study can be used as metrics of steering performance, and maintenance data and costs can be derived from previous research.[40] Also, as suggested above, further simulator and field research and visibility analysis should be conducted to determine whether improved visibility range due to higher contrast will induce higher vehicle speeds, which in fact could reduce traffic safety.

D. MEASURING ROADWAY MARKING CONTRAST

1. Conclusions

The above recommended lower bound on contrast of 2 implies a practical measurement problem that can probably be handled with a hand-held instrument. Another possibility involves a vehicle-mounted scanning diode array device. The details and qualifications on these measurements are discussed in Section V.D.

2. Recommendations

A study should be conducted to compare the contrast measurements of various practical field photometers with the precision spectra photometer used in this study. Various commercially available hand-held spot photometers[42] and possibly a prototype of the diode scanning device suggested in Section V.D should be compared under actual field conditions with a laboratory photometer used as the standard of comparison. The study should consider a range of road surfaces and markings in various stages

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[40] Russell, Optimization of Traffic Lane Delineation.

[42] Woltman and Youngblood, "Evaluating Nighttime Sign Surrounds."

of wear. The measurements should be made with and without artificial illumination sources and include variations in source and measurement angle in order to evolve the simplest acceptable technique for conducting a field maintenance test. Finally, it might be possible to develop a crude observational technique under night conditions with a headlight illumination source. This approach would involve simply counting visible delineation segments and using a criterion based on the configuration visibility parameter C_V reviewed in Section V.B to determine when repainting is required (e.g., $C_V < 0.123$, Table 12, Section V.C.2).

APPENDIX A

SIMULATOR MECHANIZATION

APPROACH

In setting up the simulation for this study the visual field was of primary concern. A moving base was ruled out from a cost/benefit point of view for the research topics of primary interest. There are a variety of possible display approaches, as summarized in Table 13, which have been ranked in order of increasing capability for presenting image complexity, from the relatively simple technique of electronically generating lines on CRT's to actual real-world views.

CRT line drawings are probably the simplest solution for providing an interactive roadway display. They can be generated rapidly with electronic circuits (including hybrid computers) and intensity control can be used to obtain desired image brightness. An unlimited number of electronic computations can be set up to operate in parallel so that high image frame rates can be maintained (within the bandwidths of the circuits) to produce displays with excellent dynamic characteristics.[45] Projection systems can be used to present large-size displays, and a notable example of this approach is given by Donges.[46]

The approach described here involves a computer-controlled electronically generated roadway with a video projector display. The current configuration was developed through modifications to an extant simulation,[47] including additional delineation complexity and more sophisticated control of intensity to properly simulate adverse visibility effects.

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[45] Lincke, W., B. Richter, and R. Schmidt, "Simulation and Measurement of Driver Vehicle Handling Performance," SAE Paper 730489, May 1973.

[46] Donges, Edmund, "Experimental Investigation of Human Steering Behavior in a Simulated Road Driving Task," ATZ Automobiltechnische Zeitschrift, Vol. 77, Nr. 5/6/1975, pp. 141-146.

[47] Allen, R. W., J. R. Hogge, and S. H. Schwartz, "An Interactive Driving Simulation for Driver Control and Decision-Making Research," Proceeding of 11th Annual Conference on Manual Control, NASA TM X-62,464, May 1975, pp. 396-407.

TABLE 13. DRIVING SIMULATOR DISPLAY APPROACHES

TYPE	TYPICAL EXAMPLES	ADVANTAGES	DISADVANTAGES
Electronically Generated Imagery	MIT Man-Machine Lab. Calspan UC/Berkeley STI Saab Volkswagen	High repetition rates for dynamic displays Continuous intensity control No time penalties for computational complexity (parallel processing) Natural for dynamic, interactive display (high rates of motion) Sharp resolution of far field	Complex scenes impractical Basic contrast and brightness limitations of CRTs
Digital Computer Generated Imagery	General Electric Evans and Sutherland McDonnell-Douglas Electronics Marconi	Easily programmable Complex scenes with solid objects	Time penalties for increasing scene complexity (serial computational processing) Intensity gradations difficult Quantization of far fields
Point Light Source	Liberty Mutual Virginia Polytechnic	Simple setup Relatively complex visual field	Difficult to achieve desired luminance and contrast condition
Movie Film	UCLA-ITTE Aetna Insurance Co. Allstate Insurance Co. GM Design Staff	Real visual scenes can be easily set up and changed	"Canned" program, dynamic interaction limited due to fixed perspective Difficult to achieve desired luminance and contrast conditions.
Scale Models	UCLA-ITTE Ohio State MIT Man-Machine Lab. Redifon	Allows geometric and photometric complexity Realistic visual fields	Limited distance range Correct scale lighting difficult (e.g., night scenarios) Difficult to scale photometric properties of surfaces, textures Difficult to simulate environmental effects (fog, rain) Depth of field/focus problems Dynamic interaction difficult (moving belts, servoed TV cameras, etc.)
Full Scale (On-the-road vehicles)	Volkswagen STI HFR Auto industry	Unlimited reality: textures, geometry, perspective correct Motion effects included Validation of simpler simulation	Expensive field testing Limited control over environment Safety problems Many peripheral variables need to be controlled Night scenarios difficult to duplicate

FUNCTIONAL LAYOUT

A block diagram of the major simulation elements used in this study is shown in Fig. 33. Good face validity is maintained by use of an actual car cab with operational instruments and controls (Fig. 10, Section III) providing interaction with a projected electronic line-drawn roadway. Additional information is provided by a variety of auditory cues (speed, lane marker bumps, crashes).

Figure 34 shows the driver/vehicle control interactions. The car steering and speed equations are programmed on an analog computer. The driver can control forward speed with his accelerator and brake. Speed is displayed on the car cab speedometer, by dashed lane markers which move proportional to speed, and as an auditory cue with frequency proportional to speed. The driver's steering control produces car-roadway relative translation and heading motions through speed-variable two-degree-of-freedom dynamic equations. Driver dynamic behavior and driver/vehicle performance can be measured by interjecting wind/road disturbances and/or road curvature command inputs into the equations of motion as discussed in Appendix B.

The lateral steering dynamics are basically linear two-degree-of-freedom equations (no roll axis), derived from tire and wind forces and moments acting on the car.[48] Small angle approximations are used (e.g., $\sin \psi \doteq \psi$), and speed variations are assumed to be slow compared to relevant lateral car motions. The equations are speed variable in that the lateral response (e.g., steering gain and time constants) changes correctly with speed, and also a hold circuit is provided so that the car can be brought to a complete stop.

The speed dynamics are given by a nonlinear first-order equation with a feedback term to account for wind resistance, tire friction, etc. The acceleration/deceleration capability for throttle inputs has finite limits to correspond to real car characteristics. In order to simplify the longitudinal kinematics, braking is set up to give a constant deceleration level

[48] Weir, D. H., C. P. Shortwell, and W. A. Johnson, "Dynamics of the Automobile Related to Driver Control," SAE Paper 680194, Feb. 1967.

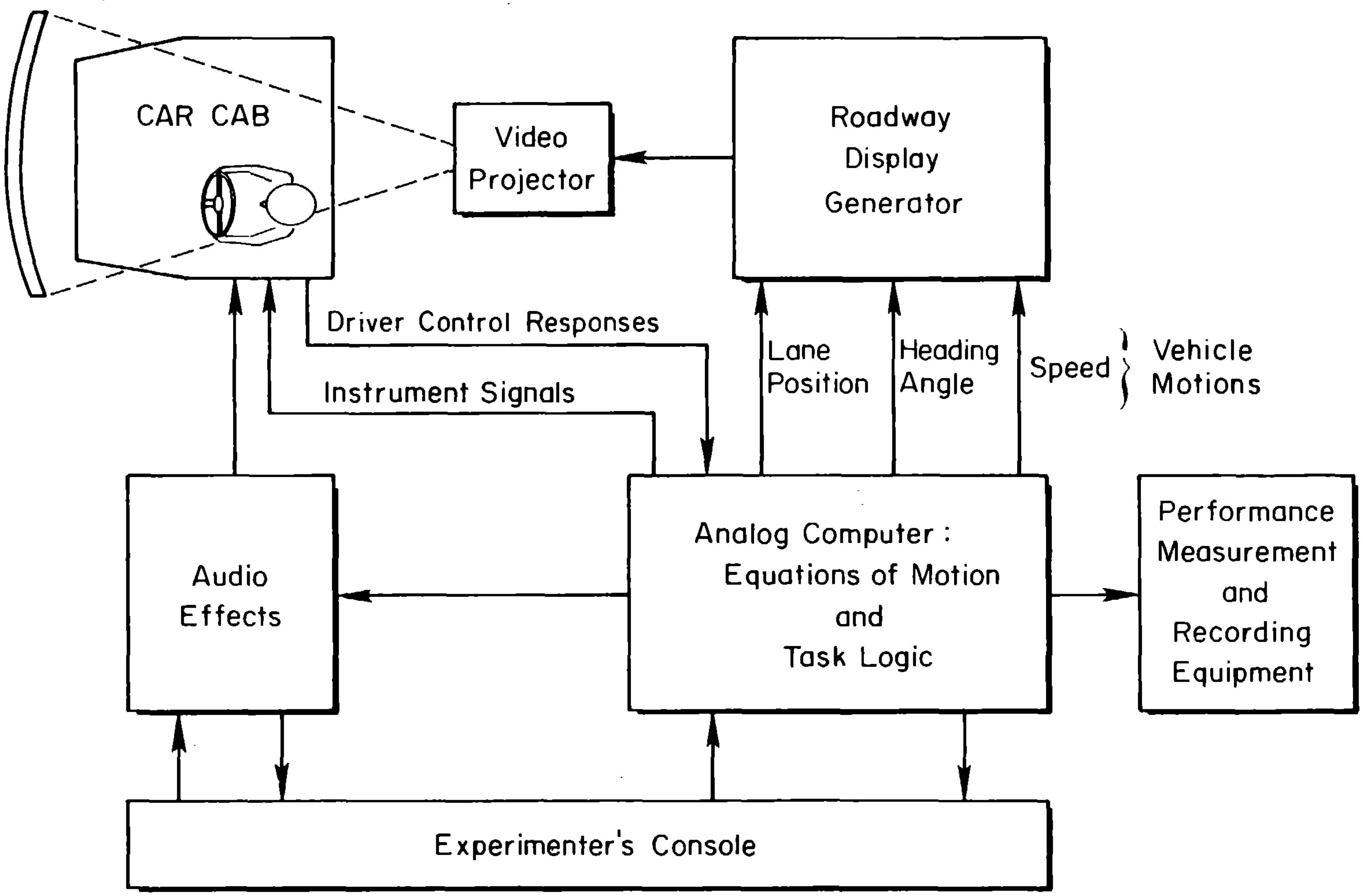

Figure 33. Block Diagram of Major Simulation Elements

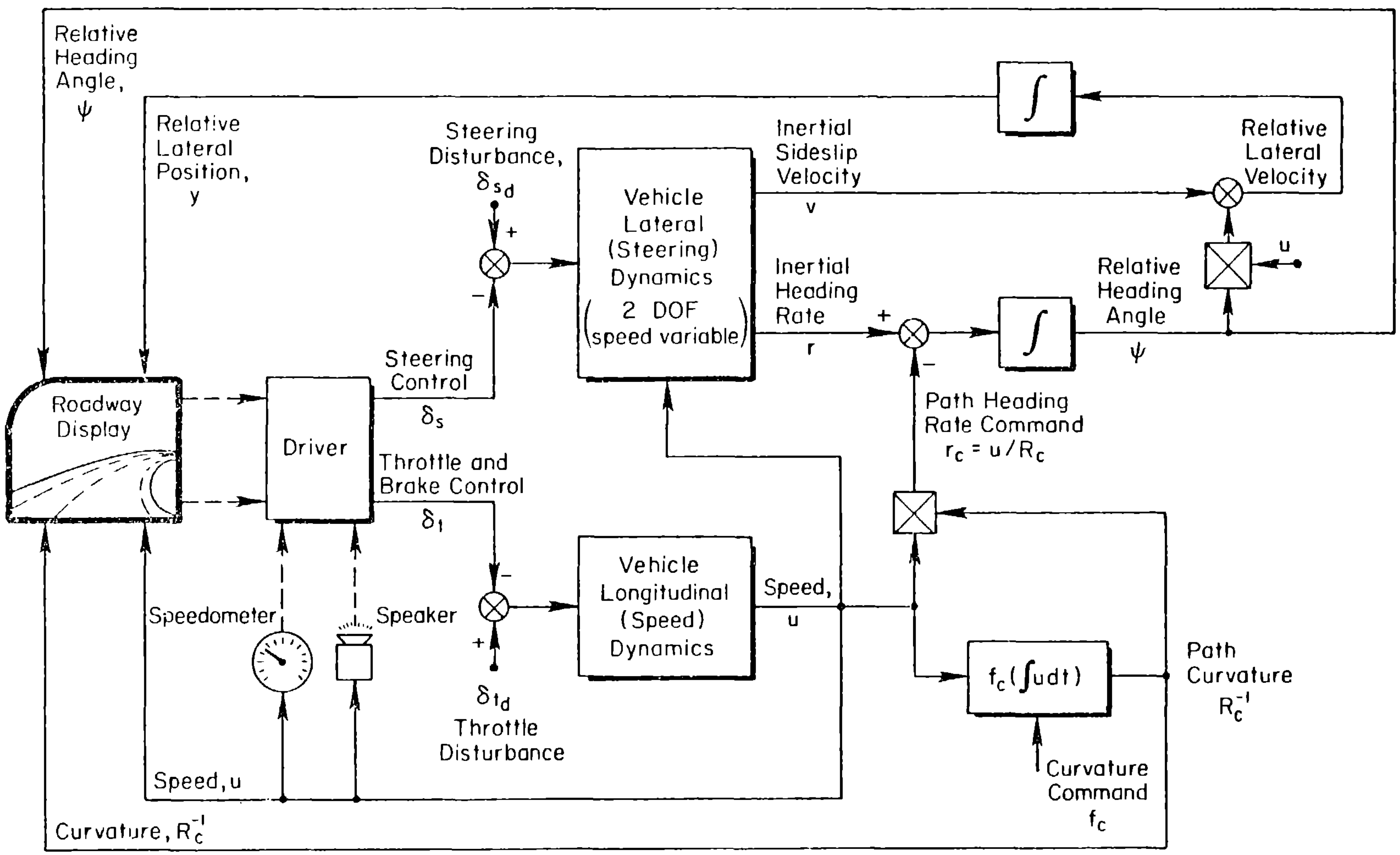

Figure 34. Simulator Steering and Speed Control Dynamics

corresponding to a maximum braking capability under ideal conditions (i.e., approximately 0.6 g). Subjects have reported the speed dynamics to be quite realistic and are typically not aware of the idealized braking characteristics.

The road curvature kinematics shown in Fig. 34 are an approximation which assumes that the rate of change of road curvature with respect to distance traveled is small. The path curvature develops as a function of distance down the road ($s = \int u \, dt$), and the curvature command is used both as an input for the visually displayed curvature (which is unidirectional only) and the path heading rate command. The curvature command can be generated by an event programmer actuated circuit that generates a left, right or "S" curve command, or by a continuous command function. The circuitry is such that the driver can come to a complete stop on a curve with the display correctly showing no roadway motion.

The car motion variables provide inputs to the roadway display generator which consists of special-purpose electronic circuits that draw smooth flicker-free oscilloscope line images at a 100 Hz repetition rate. The combined scene is then raster scan converted by a video camera and the TV image projected on a large screen in front of the driver as discussed below.

The experimenter's console shown in Fig. 35 was arranged to allow for simple setup of the various display configurations discussed below. The console also allowed for the setup and control of the various simulation tasks, as well as providing the experimenter with immediate feedback on subject performance.

ROADWAY DISPLAY

Display computations are initially done in the ground plane as shown in Fig. 36 where lines are straight and parallel and all points appear to move at the same speed. All symbols are then multiplexed and the correct geometric transformation applied to give proper perspective in the display plane consistent with the driver's viewing distance from the screen and eye height above the road. A simple provision is also made for display roadway curvature in the final stage of line generation as shown in Fig. 36.

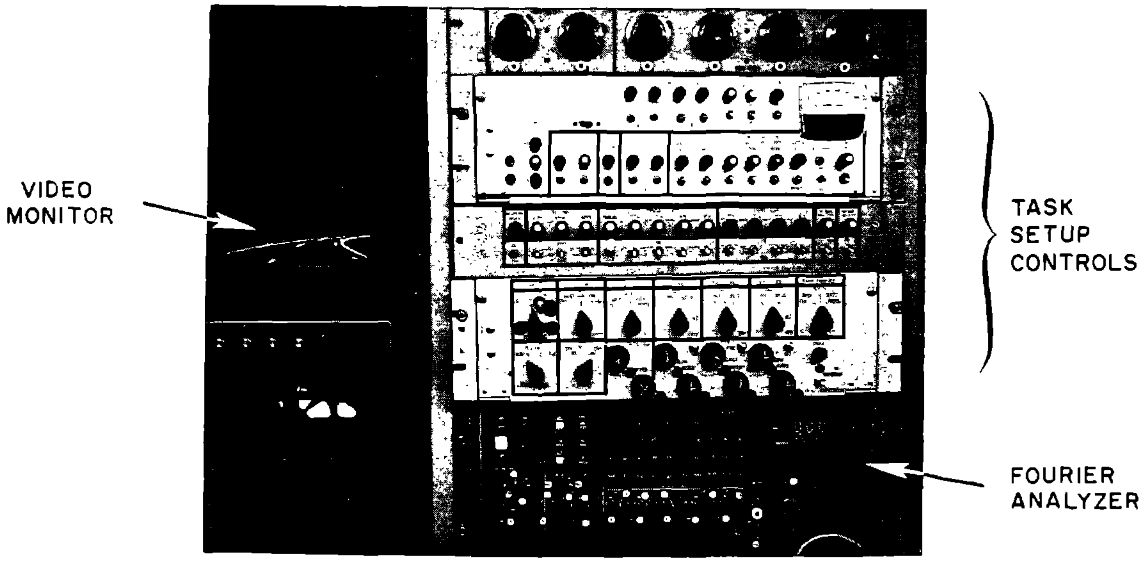

Figure 35. Experimenter's Console

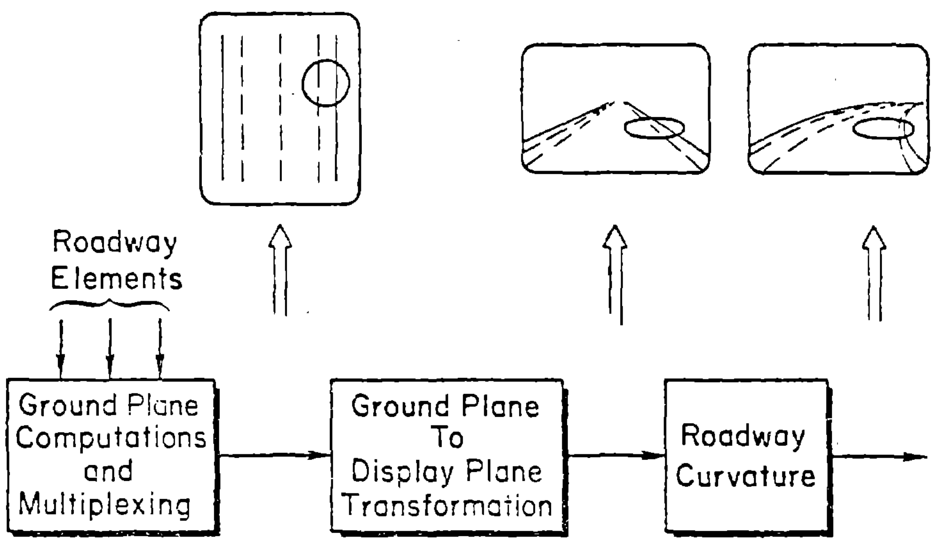

Figure 36. Road Display Generation

A modified Advent Videobeam 1000A projection system[49] is used to display the roadway to the driver. As shown in Fig. 10 (Section II), the projector is mounted upside down, above and directly behind the driver. The 7 ft (2.1 m) diagonal curved screen is also inverted and centered in front of the driver. Viewing distance is 6 ft (1.8 m), with a screen/projector distance of 8 ft (2.4 m) as specified by Advent.[49]

The Advent monitor-grade electronics provide wide bandwidth and good DC (black level) restoration. This results in resolution and contrast limited only by the Federal Communications Commission (FCC) standard video bandwidth and 525 line raster scan format. The Advent's sealed fixed-focus Schmidt optics projection tubes are very efficient and produce maximum luminances of 20 ft-L on a highly reflective screen surface. The 3 in. (7.6 cm) projector tube targets require only small scan deflections which combine with high quality circuitry to produce very linear imagery.

The line-drawn CRT image is converted to raster scan by a RCA TC1005/N01 vidicon camera as shown in Fig. 37. This monochrome 2 to 1 interlace camera uses a 1 in. (2.54 cm) Nuvocon vidicon tube featuring high resolution without bloom, lag, or burn-in problems. Since the camera electronics have 12 MHz bandwidth, again the FCC bandwidth and format are the limiting factors. The oscilloscope is a linear deflection high resolution Tektronix 5103N featuring linear intensity modulation capability. The display generator itself uses instrument-grade electronic circuitry which produces a highly linear roadway representation.

Roadway detail appears quite sharp when viewing as close as 4 ft from the Advent screen, and an objective analysis can be made of the resolution limitations of the roadway display. An upper limit for video system resolution of roughly 400 lines vertically and 300 lines horizontally may be assumed,[50] although more than one line may be required for detection.[51]

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[49] Videobeam 1000A Installation and Service Manual, Cambridge, Mass., Advent Corp., 1975.

[50] Semple, C. A., Jr., R. J. Heavy, E. J. Conway, Jr., and K. T. Burnette, Analysis of Human Factors Data for Electronic Flight Display Systems, Air Force Flight Dynamics Lab, Rept. AFFDL-TR-70-174, Apr. 1971.

[51] Biberman, L. M., ed., Perception of Displayed Information, New York, Plenum Press, 1973.

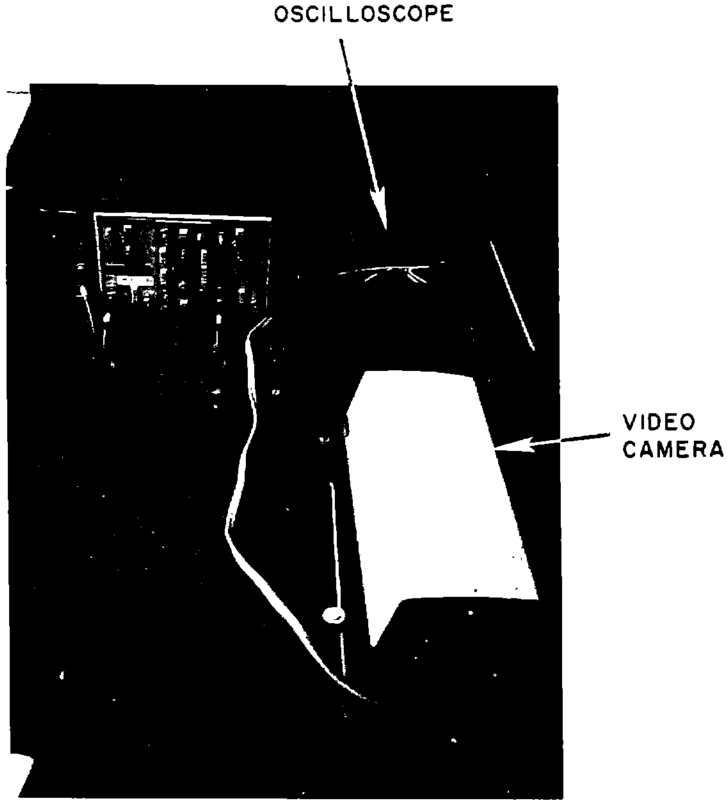


Figure 37. Optical Combiner and CRT to Video Converter

Given the 52 × 69 in. (1.3 × 1.8 m) video screen, Table 14 lists projected visual angular resolution achieved at various viewing distances for the assumed resolution. This may be compared to Table 15 which gives the visual angle subtended by a common road delineation element, a 4 in. wide by 15 ft long (10 cm × 4.5 m) stripe, at various down-the-road distances. As an example comparison, the display angular resolution at a 6 ft (1.8 m) viewing distance allows accurate representations of elements larger than 6.2 min of arc vertically. This is closely equivalent to the 5.2 min of vertical arc size of the delineation element which the driver sees at 200 ft (61 m) distance.

By comparing Tables 14 and 15 we can derive Table 16 which expresses equivalent resolution distance down the road as a function of display viewing distance. The tradeoff between field of view and distance resolution is apparent in Table 16.

TABLE 14. PROJECTED DISPLAY ANGULAR RESOLUTION LIMITS AT VARIOUS VIEWING DISTANCES (1 ft = 0.3048 m)

AXIS	ANGULAR RESOLUTION AT VARIOUS VIEWING DISTANCES			
	4 ft	6 ft	8 ft	16 ft
Vertical (400 lines) — 0.13 in. Absolute Resolution	9.3 min	6.2 min	4.7 min	2.3 min
Horizontal (300 lines) — 0.23 in. Absolute Resolution	16 min	11 min	8.2 min	4.1 min

TABLE 15. ANGULAR SIZE OF A LANE STRIPE (4" × 15') AT VARIOUS ROAD DISTANCES (1 ft = 0.3048 m; 1 in. = 2.54 cm)

AXIS	DOWN-THE-ROAD DISTANCE (ft)				
	50	100	200	300	400
Vertical — θ_v	82 min	21 min	5.2 min	2.3 min	1.3 min
Horizontal — ψ_v	23 min	11 min	5.7 min	3.8 min	2.9 min

Apparent angular size:

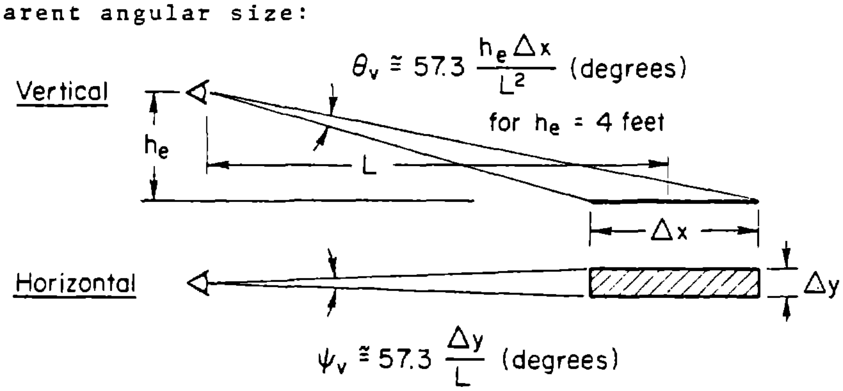


TABLE 16. FIELD OF VIEW AND EQUIVALENT DISTANCE RESOLUTION OF A 4" × 15' STRIPE AT VARIOUS DISPLAY SCREEN VIEWING DISTANCES (1 ft = 0.3048 m)

VIEWING DISTANCE	HORIZONTAL FIELD OF VIEW	EQUIVALENT DISTANCE RESOLUTION
4 ft	71 deg	100 ft
6 ft	51 deg	150 ft
8 ft	39 deg	200 ft
16 ft	21 deg	300 ft

As illustrated in Fig. 38, the road perspective is determined within the first few hundred feet down the road. Past research on observed driver sight distances also shows 100-200 ft (30-60 m) to be adequate.[52] Although it may be difficult to accurately resolve individual stripes beyond the distances given in Table 16, there is some lane delineation apparent (though "smeared") and some streaming of the stripe elements due to forward speed. Thus, heading, lateral position, and speed information in this area is still available to aid in car control.

Based on actual observations of the complete installation, a viewing distance of 6 ft (1.8 m) was selected. This gives an adequate field of view to allow for streaming effects which contribute to speed perception in the driver's parafoveal vision. Also, the delineation distance resolution is more than adequate for providing lateral (steering) control cues.

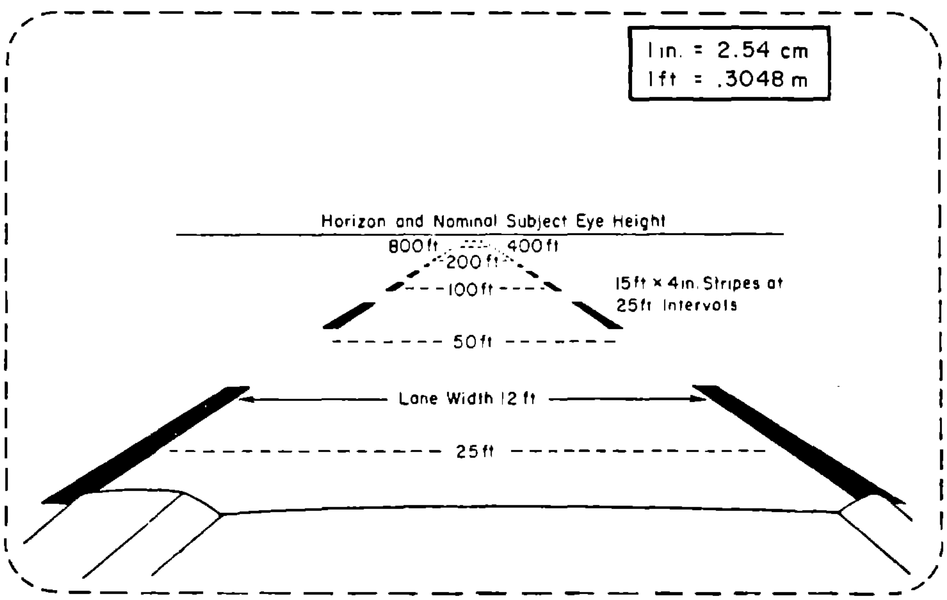


Figure 38. Displayed Roadway Perspective

[52]McLean, J. R., and E. R. Hoffmann, "The Effects of Restricted Preview on Driver Steering Control and Performance," Human Factors, Vol. 15, No. 4, Aug. 1973, pp. 421-430.

DELINEATION CONFIGURATION AND CONTRAST

Intensity modulation is used to realize an assortment of delineation configurations and to simulate the effects of adverse visibility conditions (e.g., rain, fog). The lines can be solid or dashed and the dash and gap lengths varied. In all cases the broken delineation elements move in correct perspective as a function of forward speed.

Line intensity was modulated as a function of distance down the road to simulate the effects of atmospheric attenuation. Atmospheric scattering caused by rain and fog tend to exponentially decrease delineation contrast as a function of viewing range as discussed in Section II, and function generators were used to approximate this effect in the display electronics.

Typical examples of visibility and configuration conditions are illustrated in Figs. 39 and 40. In Fig. 39 it is apparent how reduced visual range effects lateral position, heading, and curvature cues. In Fig. 40, the effects of the various delineation configurations under reduced visual range are apparent; the decreased directional cues with shorter delineation elements, and the vast improvement with a solid edge can also be seen.

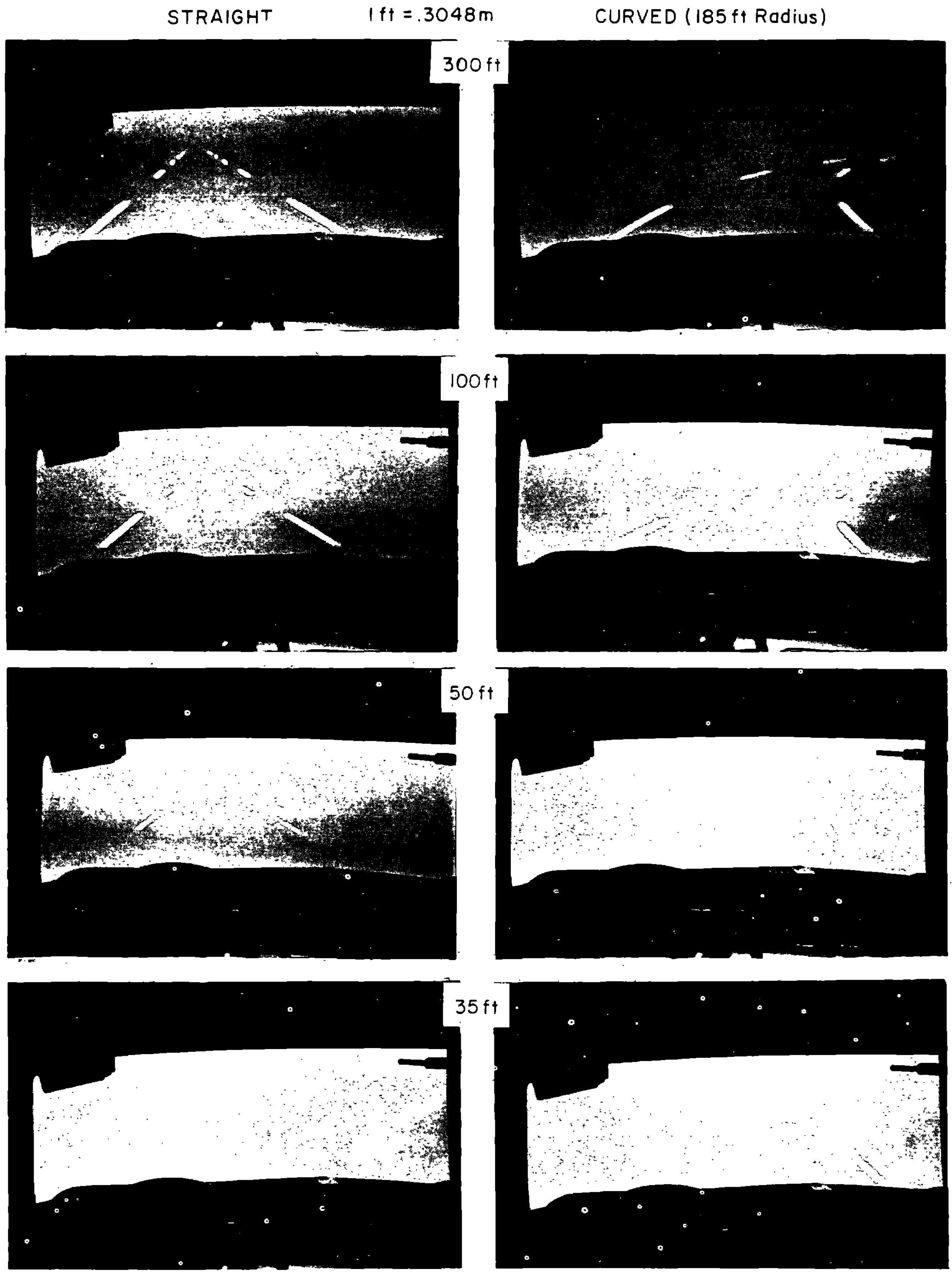


Figure 39. Federal Standard Delineation Striping
Under Various Levels of Reduced Visibility

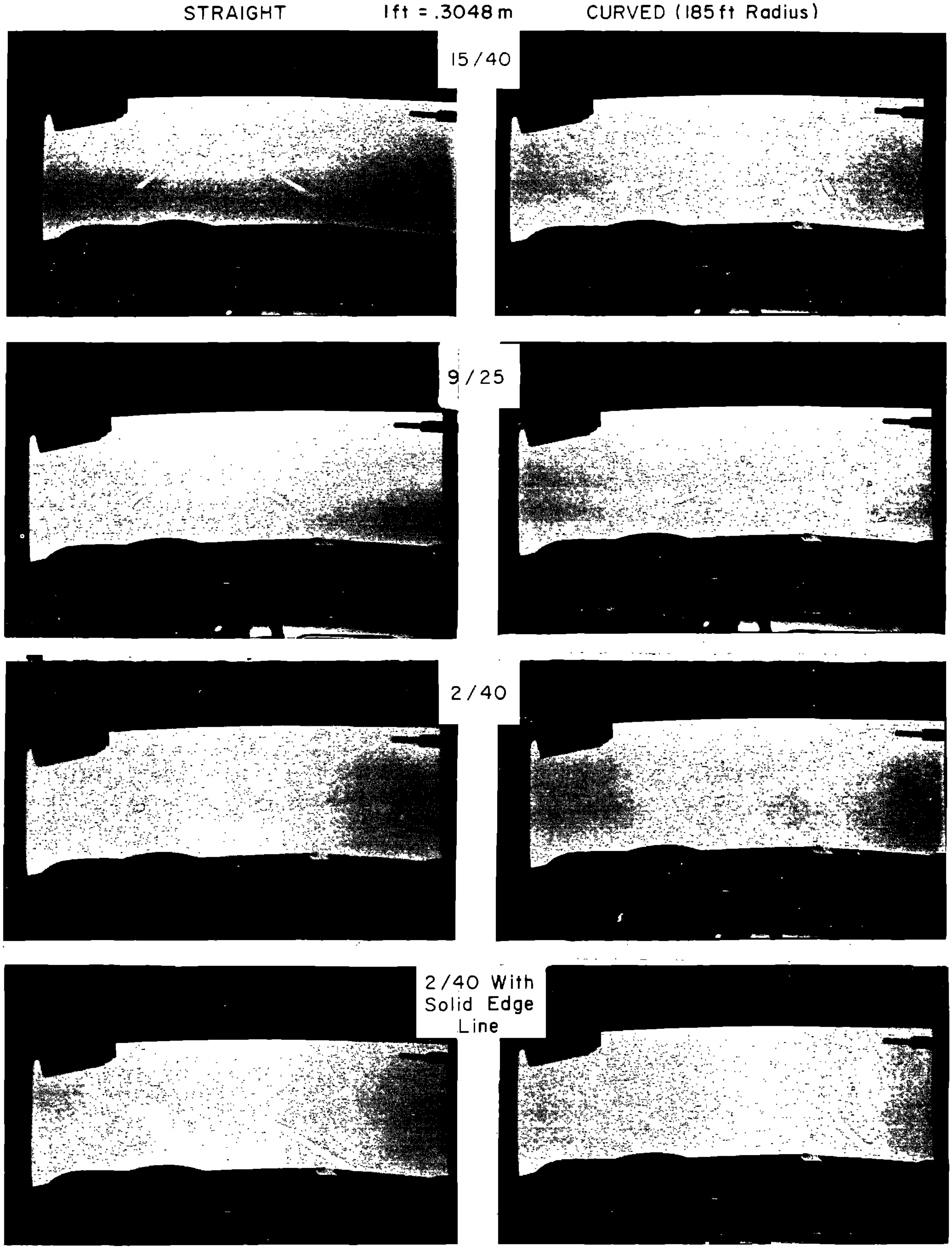


Figure 40. Delineation Configuration Variations Under 50 ft Visual Range

APPENDIX B

DRIVER DYNAMIC RESPONSE MEASUREMENTS

BACKGROUND

Automobile steering control is a dynamic task that is performed by the driver in order to establish and/or maintain the vehicle on a specified pathway in the presence of disturbances such as crosswinds and roadway fluctuations. The motions of an automobile in response to steering actions and aerodynamic disturbances can be described in terms of differential equations, transfer functions, etc.,[53,54] and it is logical to attempt to describe the driver in similar terms

As discussed in Sections II and III the motivation for this description and measurement of the driver is twofold: 1) to determine and quantify the effect of adverse visibility on driver perception of the cues required for steering control; and 2) to determine those changes in driver behavior that contribute to degraded performance under conditions of reduced visibility. Understanding the basic effects of adverse visibility on driver behavior should then allow us to predict effects for conditions not tested and/or suggest general countermeasures to the problems encountered.

Dynamic models and measurements of the driver for automobile steering control are fairly well established.[55,56] The basic structure of the

[53]Segel, L., "Theoretical Prediction and Experimental Substantiation of the Response of the Automobile to Steering Control," in Research in Automobile Stability and Control and in Tyre Performance, London, Institute of Mechanical Engineers, 1957.

[54]McRuer, D. T., "Simplified Automobile Steering Dynamics for Driver Control," presented to the SAE Aerospace Control and Guidance Systems Committee Meeting No. 35, Palo Alto, Calif., 19-21 Mar. 1975.

[55]McRuer, D. T., D. H. Weir, H. R. Jex, et al., "Measurement of Driver/Vehicle Multiloop Response Properties with a Single Disturbance Input," IEEE Trans., Vol. SMC-5, No. 5, Sept. 1975, pp. 490-497.

[56]McRuer, D. T., R. W. Allen, D. H. Weir, and R. H. Klein, "New Results in Driver Steering Control Models," Human Factors, Vol. 19, No. 4, Aug. 1977, pp. 381-397.

driver/vehicle steering control model was discussed in Section II (Fig. 9), so our objective here is briefly to describe the measurement technique and results.

As illustrated in Fig. 9, inputs to the steering task were applied as either an equivalent wind disturbance (added in as a front wheel steering disturbance in series with and isolated from the driver) or as a heading or yaw rate command with corresponding road curvature displayed to the driver. In both cases appropriate driver behavior is apparent — to produce steering wheel actions that will effectively follow the input and counteract the disturbance in order to maintain reasonable lateral position within a delineated lane.

In the case of the wind disturbance the driver has no perception or preview of the disturbance and must wait for the disturbance to affect the vehicle's motion before responding. This mode of control is termed compensatory in that the driver is "compensating" for disturbance-caused errors.

When following a curving road (a path command) with sufficient visual range, the driver has the opportunity to preview or anticipate the desired path. With a visual segment large enough to permit adequate perception of the road's curvature, the driver can achieve a pursuit mode of control behavior and very nearly duplicate the commanded path. This is simply accomplished by the driver because the curved path followed by a car is nearly directly proportional to front wheel angle,[54] and the vehicle lags are well-learned and can be anticipated. Thus, the driver merely steers with actions directly proportional to perceived road curvature, sufficiently advanced in time to offset vehicle lag. Disruption of the curvature cue will degrade pursuit performance, however, which is a possibility with various combinations of adverse visibility and delineation as discussed in Section II.

[54]McRuer, "Simplified Automobile Steering Dynamics for Driver Control."

PURSUIT BEHAVIOR ANALYSIS

Consider now the control and performance implications of compensatory and pursuit behavior. Given the model structure of Fig. 9 (Section II) and nominal driver parameters obtained in this study under good visibility at 30 mph (48.3 kph), we have analyzed the dynamic implications of curvature perception. Referring to Fig. 9, consider the driver/vehicle system response due to a command path input. The commanded path causes an equivalent heading rate input, r_c, to be applied to the system. Driver steering action should then create vehicle yaw rates, r, which are nearly equal to the commanded heading rate so as to give a small heading rate error, r_e, which is the difference between the command input and the vehicle's motion.

To illustrate the potential improvement in performance between pursuit and compensatory driving we can consider the describing function relating heading rate error, r_e, to heading rate input command, r_c. Figure 41 shows Bode plots of this driver/vehicle system ratio as the curvature perception parameter (driver's "pursuit gain"), K_{R_C}, is increased. The compensatory baseline curve ($K_{R_C} = 0$) is based on a representative set of driver/vehicle data, and the other curves simply indicate the effect on $|r_e/r_c|$ when the additional driver control pathway represented by K_{R_C} is added. At low frequencies the describing function amplitude shows that errors are less than the original input, while at very high frequencies they may be somewhat greater. Note in particular that for an optimum value* of $K_{R_C}/\ell \doteq 1$, errors in the frequency region of 0.3-1.0 rad/sec give a reduction in error of about 15 dB or a factor of greater than 5 times! At any given frequency, lane dispersions are directly proportional to heading rate

*For the essentially neutral steer car of this study the steady-state turn radius is equal to the wheelbase divided by the front wheel angle, so the curvature perception gain should be equal to the car's wheelbase, in this case 9.25 ft (2.8 m).

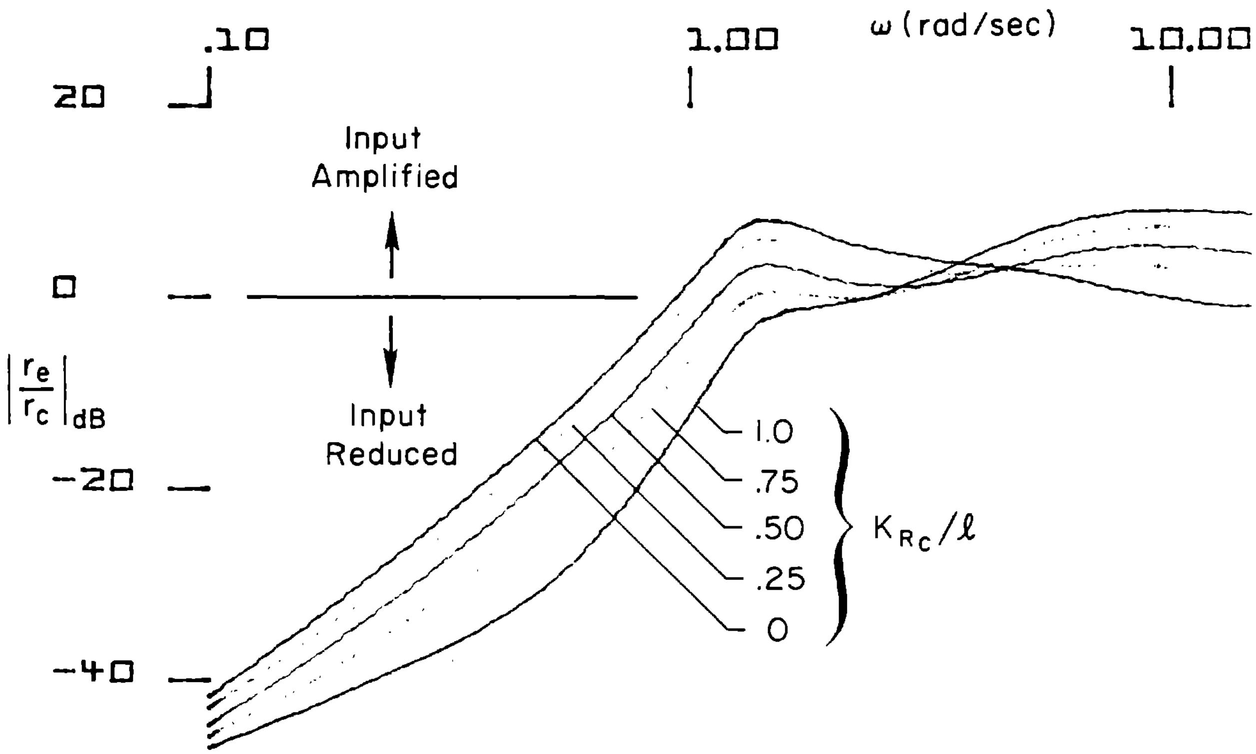


Figure 41. Effects of Variations in the Curvature Perception Gain on the Heading Error Rate to Heading Rate Input Transfer Function

errors and thus the curvature perception in the above frequency region would reduce lane dispersions by more than a factor of 5.*

In our data analysis procedures we actually work with the describing function between the system error and the system output. This is derived from the error-to-input describing function by the equation

$$\frac{r}{r_e} = \frac{1 - (r_e/r_c)}{r_e/r_c} \tag{25}$$

*To put this frequency range dimension in context, at 30 mph (48.3 kph) the 0.3-1.0 rad/sec frequency region (0.05-0.16 Hz or 6-21 sec/cycle) implies a curvature inflection (zero curvature) about every 3-10 sec or 133-461 ft (40.5-140.5 m), which is realistic for a winding real-world task.

and is illustrated in Fig. 42. At the low frequencies where r_e/r_c is small, r/r_e is approximately equal to the inverse of r_e/r_c, which is evident in comparing Figs. 41 and 42.

For $K_{R_c} = 0$ the system becomes effectively compensatory, and the r/r_e describing function can be described simply by crossover model parameters[57] which give useful summary information about driver behavior.

For the pursuit cases ($K_{R_c} > 0$), the low-frequency $|r/r_e|$ is larger than for the compensatory baseline, indicating that pursuit following of the input is superior. This is the same point made in connection with Fig. 41. This superior dynamic performance is also indicated by the increase in apparent crossover frequency as K_{R_c} increases.

MEASUREMENT TECHNIQUE

The method for obtaining driver describing function* data is shown in Fig. 43. A Fourier analyzer generates a sum of sine waves input (Table 17) that is injected into the system as either a command or a disturbance, and receives back another system quantity which is subsequently Fourier analyzed at each of the input frequencies ω_i.

As noted in Fig. 43 the actual quantities used to compute the equivalent driver/vehicle open-loop describing function depend on the circumstances. For the winding road command input case, where pursuit behavior is possible, the error (r_e) to input (r_c) describing function is computed and then transformed by Eq. 25 to give an equivalent open-loop transfer function r/r_e. For the compensatory, wind gust disturbance input the

*In the context of the research reported here describing functions are defined as statistical estimates of the driver's transfer characteristics over a given time interval. The describing function gives an estimate of the system response linearly correlated with the input. The remaining response is termed remnant, and in this study is attributed to driver noise or stochastic variations as presented in Section III.

[57]McRuer, D., D. Graham, E. Krendel, and W. Reisener, Jr., Human Pilot Dynamics in Compensatory Systems — Theory, Models, and Experiments with Controlled Element and Forcing Function Variables, Air Force Flight Dynamics Lab, Rept. AFFDL-TR-65-15, July 1965.

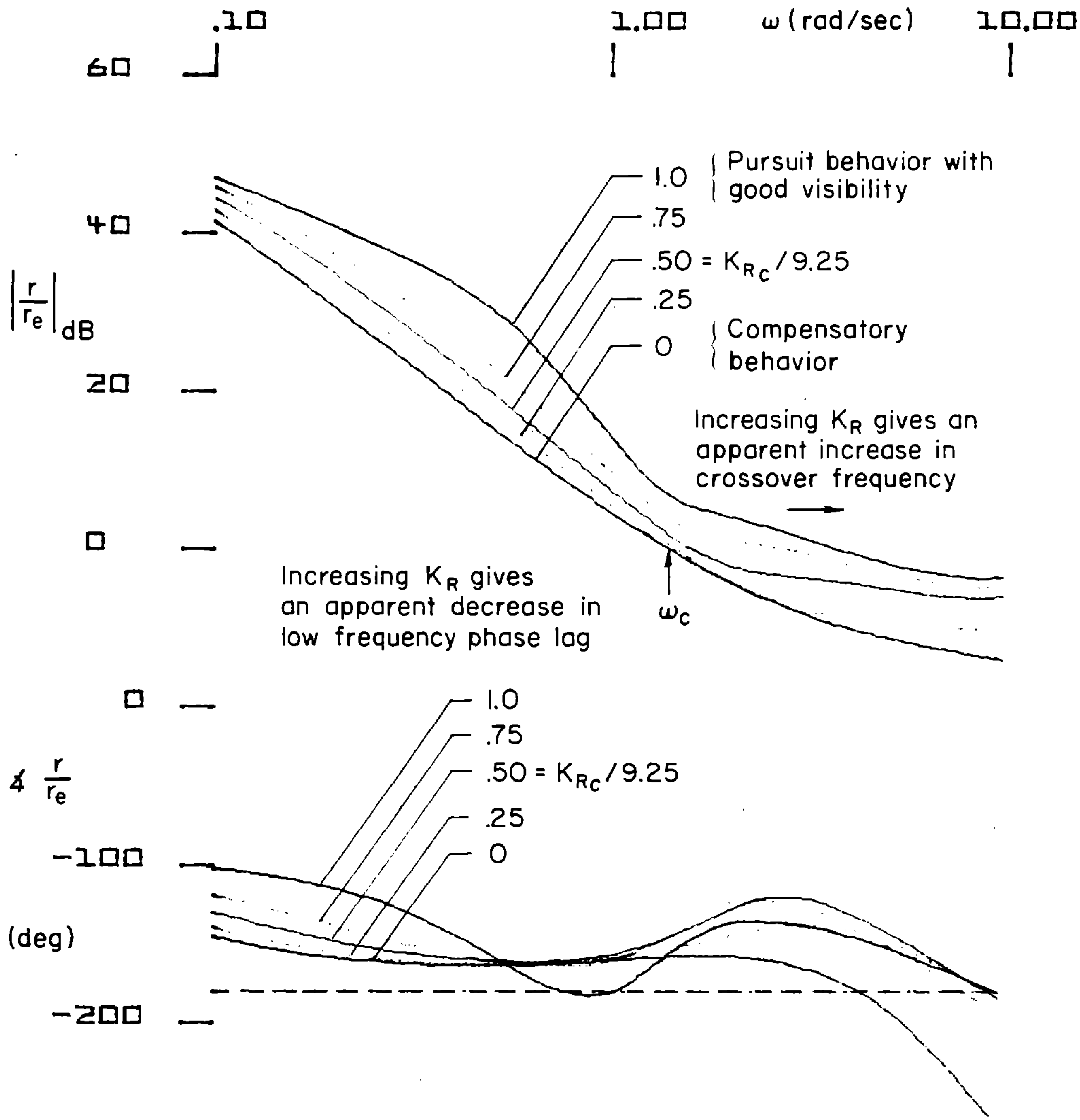
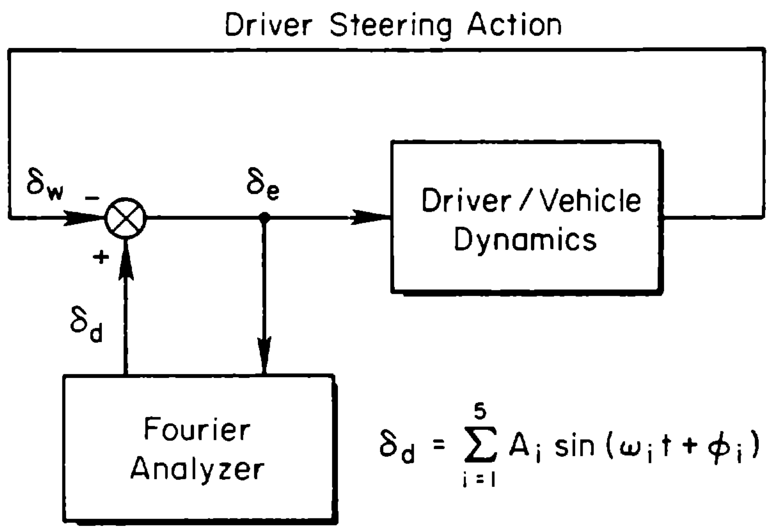
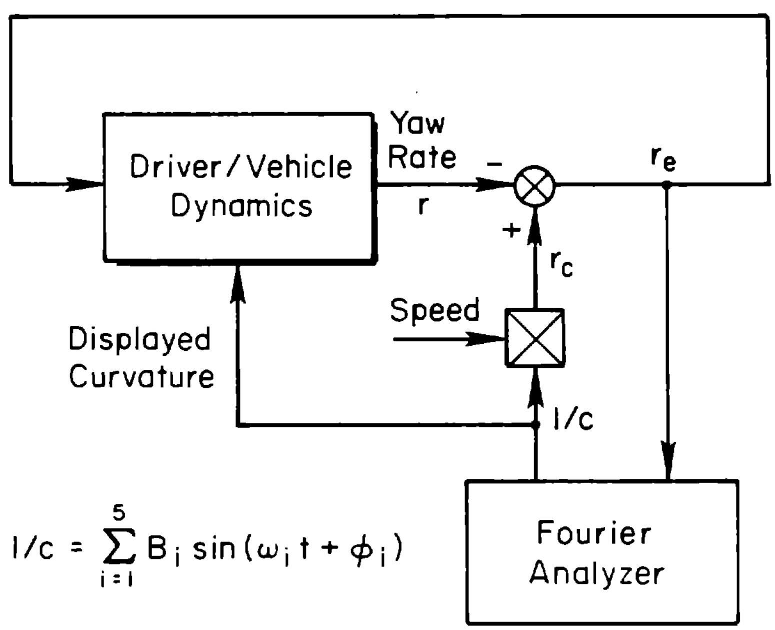


Figure 42. Equivalent Open-Loop Transfer Function for Gain



a) Wind Gust Disturbance Input



b) Winding Road Command Input

Figure 43. Driver Describing Function Measurement Technique

TABLE 17. INPUT AMPLITUDES AND FREQUENCIES
(1 ft = 0.3048 meters)

FREQUENCY (rad/sec)	WIND GUST AMPLITUDES (EQUIVALENT FRONT WHEEL ANGLE, deg)	ROAD CURVATURE AMPLITUDES (INVERSE RADIUS OF CURVATURE, ft^{-1})
0.188	0.172	2.07×10^{-3}
0.503	0.172	2.07×10^{-3}
1.25	0.172	1.98×10^{-3}
3.	0.172	1.66×10^{-3}
6.28	0.086	0.56×10^{-3}
rms	0.251	2.79×10^{-3}

equivalent open-loop transfer function is found from operations on the δ_e/δ_d ratio, as described by McRuer, et al.[58]

After the describing function data are developed, an optimal identification routine is used to find driver parameters for the Fig. 9 system model that will give a good match to the measured describing function data.

As an example, consider the data illustrated in Fig. 44 for the two baseline visibility conditions. The measured describing functions were averaged across six subjects, and the describing function fits match the data rather well. The characteristic effect of the curve perception parameter K_{R_c} is apparent in both cases in comparing the compensatory (wind gust disturbance) and pursuit (winding road command) tasks.

MODEL PARAMETER DATA

Model parameters for both steering tasks over a number of visibility and delineation configuration conditions are compared in Table 18. The most apparent consistent effect in the complete model parameters seems to

[58] Allen, R. W., and H. R. Jex, "A Simple Fourier Analysis Technique for Measuring the Dynamic Response of Manual Control Systems," IEEE Trans., Vol. SMC-2, No. 5, Nov. 1972, pp. 638-643.

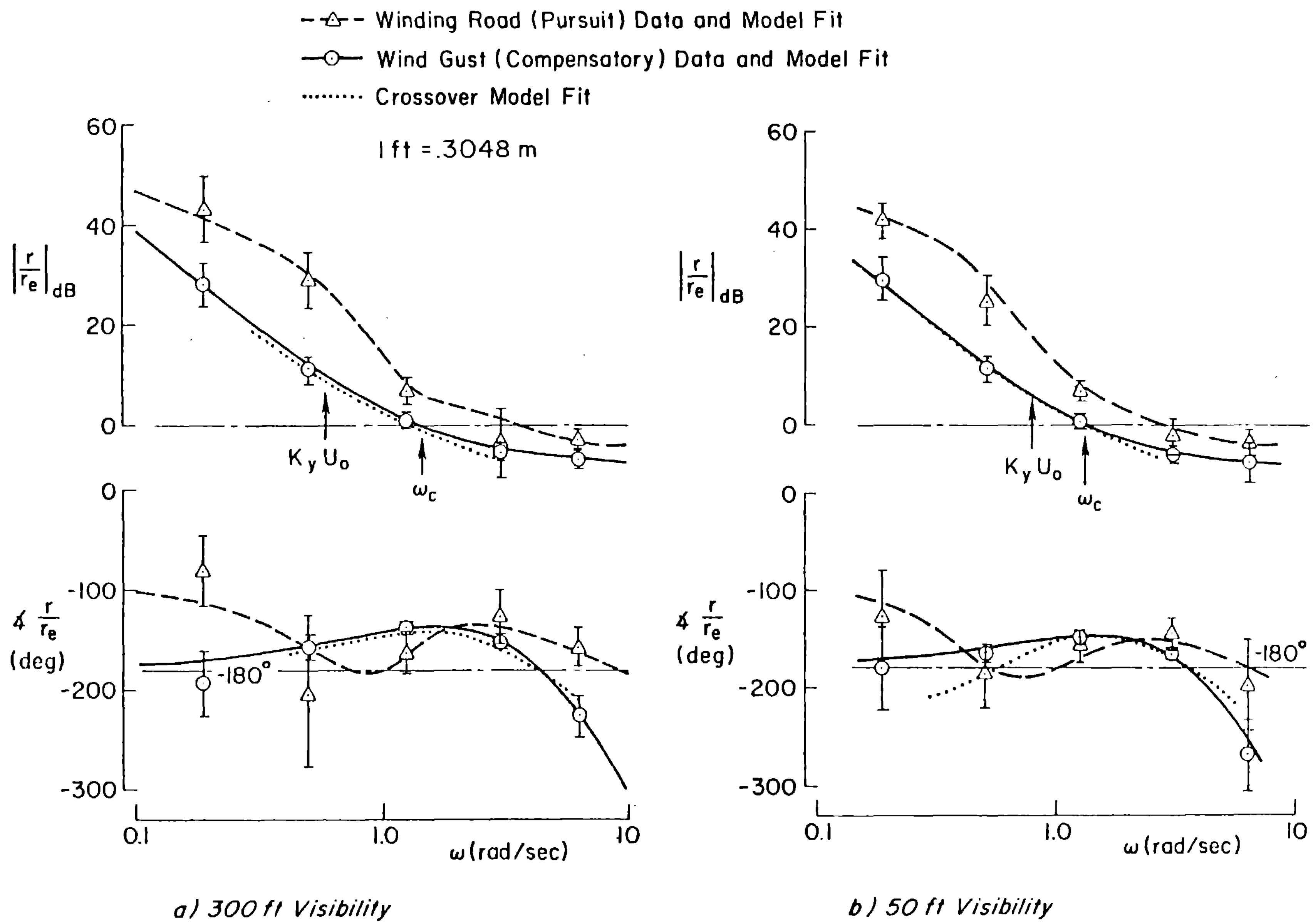


Figure 44. Baseline Condition Driver/Vehicle Describing Functions and Transfer Function Model Fits

TABLE 18. DYNAMIC RESPONSE PARAMETERS

EXPERIMENTAL CONDITION				PURSUIT (WINDING ROAD COMMAND)					COMPENSATORY (WIND GUST DISTURBANCE)						
				MODEL FIT PARAMETERS					COMPLETE MODEL FIT PARAMETERS					CROSSOVER CHARACTERISTICS	
VISIBILITY RANGE (ft)	MARK/CYCLE LENGTH (ft)	CONFIGURATION VISIBILITY PARAMETER, C_v	SPEED, U_o (mph)	$\frac{K_{RC}}{\ell}$	K_y (ft^{-1})	K_ψ	T_L (sec)	τ (sec)	K_y (ft^{-1})	K_ψ	T_L (sec)	τ (sec)	$\frac{1}{K_y U_o}$ (sec)	ω_c (rad/sec)	φ_m
300	15/40	0.09	30	0.837	0.0387	0.174	0.247	0.422	0.022	0.195	0.471	0.526	1.03	1.46	39.02
100	2/40	0.54	30	0.903	0.0286	0.136	0.164	0.450	0.0355	0.105	0.652	0.600	0.64	1.15	28.23
50	9/25	0.44	15	0.795	0.159	0.220	0.276	0.490	0.0130	0.274	0.342	0.691	3.5	0.835	45.02
50	9/25	0.44	30	0.959	0.0114	0.260	0.152	0.551	0.0319	0.141	0.563	0.628	0.71	1.38	26.44
50	9/25	0.44	55	1.005	0.0098	0.224	0.154	0.377	0.0258	0.132	0.477	0.471	0.48	2.21	13.76
50	15/40	0.55	15	0.772	0.0436	0.156	0.310	0.518	0.0113	0.315	0.109	0.541	4.0	0.785	42.86
50	15/40	0.55	30	0.856	0.0218	0.244	0.241	0.540	0.0251	0.169	0.483	0.620	0.91	1.30	27.58
50	15/40	0.55	55	0.979	0.0033	0.0769	0.769	0.604	0.0231	0.133	0.530	0.552	0.54	2.20	13.33
50	2/40	1.08	30	0.571	0.0819	0.0854	0.453	0.58	0.0301	0.154	0.389	0.652	0.76	1.12	16.29
35	15/40	0.79	15	0.141	0.0605	0.355	0.447	0.387	0.0116	0.223	0	0.328	3.92	0.687	28.38
35	15/40	0.79	30	0.825	0.0143	0.26	0.115	0.529	0.0176	0.206	0.332	0.672	1.29	1.36	24.64

1 ft = 0.3048 m; 1 mi = 1.6 km

be the reduction in curvature perception (K_{R_c}) with increased configuration visibility parameter, C_V.

Aside from the curve perception parameter, K_{R_c}, the large number of parameters which comprise the complete model data in Table 18 exhibit covariations that make it difficult to focus the effects of adverse visibility on any one particular parameter.

To permit more generalization we need a simpler summary of the driver's dynamic response that would nonetheless have properties pertinent to closed-loop driver/vehicle performance. For this purpose an "extended" crossover model is appropriate. For the equivalent compensatory open-loop transfer function of Fig. 44 this has the form:

$$\frac{\delta}{\delta_e} = \frac{s + (1/U_o K_y)}{s} \frac{\omega_c e^{-\tau_e s}}{s} \qquad (26)$$

This relationship is based on the equivalent driver/vehicle transfer function developed by McRuer, et al.[55] The equivalent time delay τ_e combines the high-frequency phase properties of the driver (lead, neuromuscular lags, transport delay) and vehicle (basically the heading response dynamics). The crossover frequency, ω_c, combines the driver and vehicle heading gains which can be expressed by the useful approximation[56]

$$\omega_c = \frac{K_\psi K_s U_o}{\ell} \qquad (27)$$

where K_ψ is the driver's heading gain from the complete model, K_s is the steering ratio (which has arbitrarily been set to unity for all the K_ψ parameters reported herein), and ℓ is the vehicle wheelbase. One free s in the denominator of Eq. 26 approximates the wheel input to car heading angle

[55]McRuer, et al., "Measurement of Driver/Vehicle Multiloop...Properties."
[54]McRuer, "Simplified Automobile Steering Dynamics for Driver Control."

dynamics. The phase lags of the additional high-frequency lag properties are accounted for in τ_e, and typical crossover frequencies are low enough that the high-frequency amplitude properties are not important. Finally, the combined numerator zero at $(U_oK_y)^{-1}$ and second denominator free s account for the driver's operations on lane position. U_oK_y can be interpreted as an equivalent look-ahead time constant (T_a in Eq. 7, Section II) and K_y^{-1} is the corresponding look-ahead distance.

A simple approximation can be used to compute the parameters of Eq. 26 From moderately low to high frequencies, the phase angle of the numerator zero at $(U_oK_y)^{-1}$ can be approximated by an exponential[57]

$$\measuredangle \frac{[s + (U_oK_y)^{-1}]}{s} \doteq e^{-\alpha/s} \tag{28}$$

where $\alpha \doteq (U_oK_y)^{-1}$. Using this approximation, the phase of Eq. 26 then can be written as

$$\measuredangle \frac{\delta}{\delta_e} = -\tau_e\omega - \frac{\alpha}{\omega} - \frac{\pi}{2} \tag{29}$$

This equation can now be evaluated at the gain and phase crossover frequencies of the driver/vehicle describing function in order to solve for τ_e and α. At gain crossover frequency ω_c (the frequency at unity amplitude) the phase angle is equal to π radians less the phase margin φ_m, and the phase crossover frequency ω_u is defined as the frequency at which the phase angle is equal to π radians. Therefore, τ_e and α can be computed from the equation:

$$\begin{bmatrix} \omega_c & 1/\omega_c \\ \omega_u & 1/\omega_u \end{bmatrix} \begin{bmatrix} \tau_e \\ \alpha \end{bmatrix} = \begin{bmatrix} (\pi/2) - \varphi_m \\ \pi/2 \end{bmatrix} \tag{30}$$

[57] McRuer, et al., Human Pilot Dynamics in Compensatory Systems.

Using this relationship a few key dynamic response parameters can be calculated for the driver/vehicle system that are appropriate to the basic closed-loop properties and performance.

Using the above relationships, values of τ_e and α were computed for all the wind gust (compensatory) runs as given in Table 19. The extended crossover model fit of Eq. 26 to the baseline data is illustrated in Fig. 44. Table 19 also presents derived values for the look-ahead distance, x_a, given by:

$$x_a = K_y^{-1} = U_o\alpha \qquad (31)$$

It is apparent in Table 19 that x_a gets smaller as C_V increases, suggesting that the effective dynamic look-ahead parameter decreases with visual range. This corresponds to an increase in path control gain, K_y, and indicates increased attention to lateral deviation control as visibility degrades. Also, effective time delay increases with C_V, suggesting that perceptual load increases with the reduction in visual segment. These results are discussed further in Section III.

TABLE 19. EXTENDED CROSSOVER MODEL PARAMETERS

EXPERIMENTAL CONDITION										
VISIBILITY RANGE (ft)	MARK/CYCLE LENGTH (ft)	CONFIGURATION VISIBILITY PARAMETER, C_v	SPEED, U_o (mph)	ω_c (rad/sec)	ω_u	φ_m	τ_e (sec)	$\alpha \doteq U_oK_y$ (rad/sec)	$\frac{1}{U_oK_y}$ (sec)	K_y^{-1} (ft)
300	15/40	0.09	30	1.462	4.290	39.02	0.334	0.587	1.70	75
100	15/40	0.28	30	1.295	3.758	35.56	0.375	0.601	1.66	73.2
100	15/40	0.28	55	2.167	4.385	22.48	0.298	1.153	0.867	70
100	2/40	0.54	30	1.147	3.672	28.23	0.372	0.747	1.34	59
100	2/40	0.54	55	2.060	3.800	13.76	0.317	1.398	0.715	58
50	9/25	0.44	15	0.835	3.367	45.02	0.436	0.352	2.84	62
50	9/25	0.44	30	1.377	3.528	26.44	0.381	0.806	1.24	55
50	9/25	0.44	55	2.21	3.565	13.96	0.341	1.269	0.788	64
50	15/40	0.55	15	0.785	3.312	42.86	0.440	0.375	2.67	59
50	15/40	0.55	30	1.302	3.607	27.58	0.375	0.782	1.28	56
50	15/40	0.55	55	2.205	3.295	13.33	0.371	1.146	0.87	70
50	2/40	1.08	15	0.595	2.687	24.78	0.516	0.495	2.02	44
50	2/40	1.08	15	0.762	3.240	37.71	0.443	0.438	2.28	50
50	2/40	1.08	15	0.643	3.395	26.2	0.416	0.544	1.84	40
50	2/40	1.08	30	1.117	2.895	16.29	0.436	0.893	1.12	49
50	2/40	1.08	30	1.347	3.210	15.44	0.388	1.05	0.952	42
50	2/40	1.08	30	1.253	3.705	26.70	0.365	0.812	1.23	54
35	15/40	0.79	15	0.687	2.918	28.38	0.478	0.516	1.93	43
35	15/40	0.79	30	1.355	2.897	24.64	0.458	0.704	1.42	62

1 ft = 0.3048 m; 1 mi = 1.6 km

APPENDIX C

FIELD TEST VEHICLE AND INSTRUMENTATION

OVERVIEW

The field test vehicle was a modified 1971 Dodge 3/4-ton van. Basic structural modifications include a 20-gallon auxiliary gasoline tank, a 2.5 KVA electricity generator mounted on a platform behind the rear doors, alternate hydraulic steering and brake systems with foot pedal controls (aircraft type), and an alternate ignition switch. The latter safety features are located at the onboard experimenter's station centered in the Driving Research Vehicle (DRV) behind the driver's seat as illustrated in Fig. 45. This basic setup has been used on several previous research projects (e.g., O'Hanlon,[59] Mackie[60]).

The vehicle contained apparatus for measuring the following driver/vehicle variables:

- Steering wheel position — from a gear-driven potentiometer on the steering column.
- Vehicle speed — from an electronic tachometer driven by the speedometer cable.
- Vehicle lateral position — from an externally mounted electro-optical sensor.
- Driver physiological variables — ECG (electrocardiogram) and EEG (electroencephalogram) via body mounted biopotential electrodes and high gain amplifiers.
- Experimenter responses — lane drifts, traffic and road events indicated via panel mounted switches.

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[59] O'Hanlon, J. F., and G. R. Kelley, A Psychophysiological Evaluation of Devices for Preventing Lane Drift and Run-Off-Road Accidents, Human Factors Research, Inc., Tech. Rept. 1736-F, 1974.

[60] Mackie, R. R., J. F. O'Hanlon, and M. E. McCauley, A Study of Heat, Noise, and Vibration in Relation to Driver Performance and Psychophysiological Status, Human Factors Research, Inc., Tech. Rept. 1735, 1974.

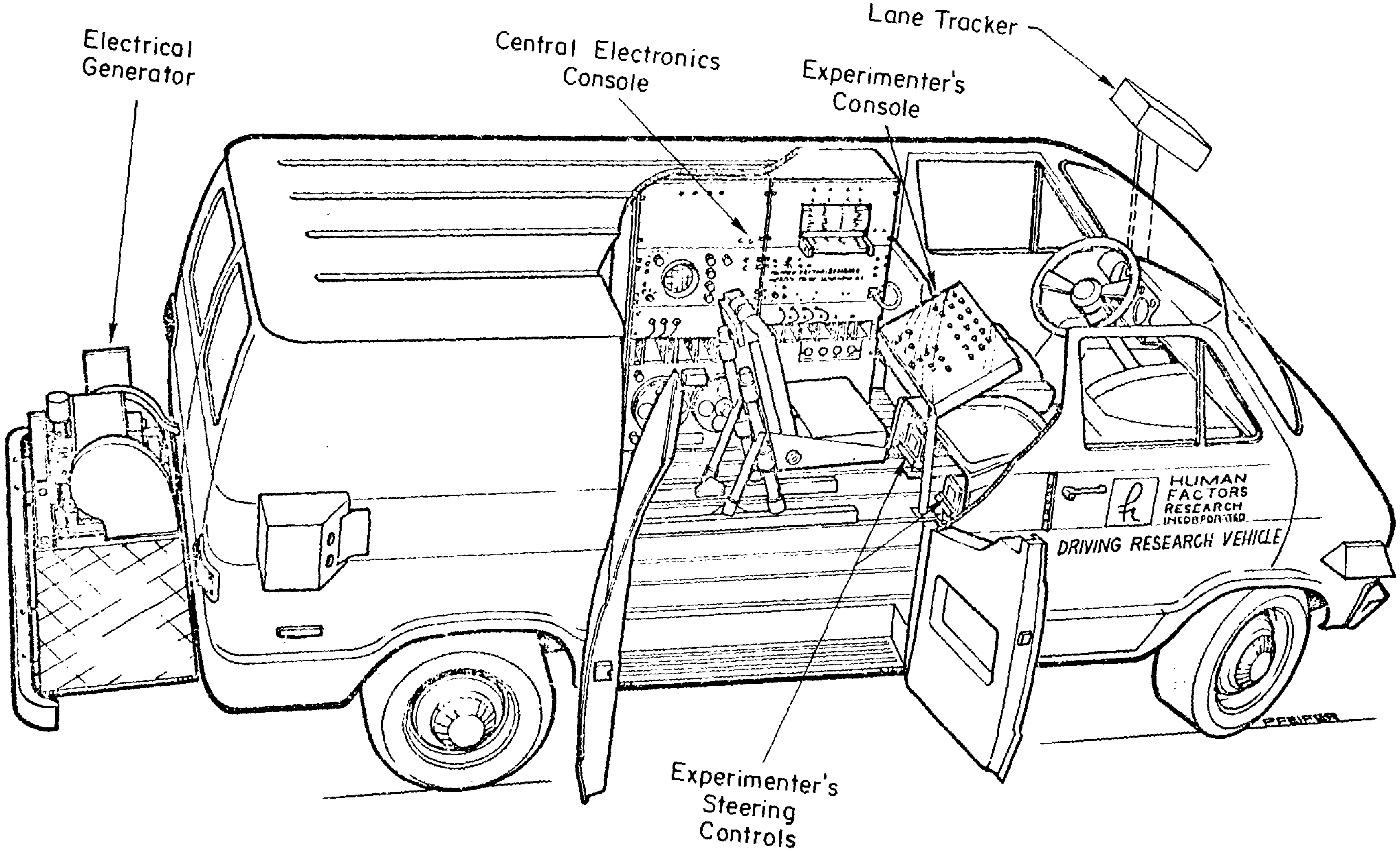

Figure 45. Instrumented Field Test Research Vehicle

A central electronics console provided for signal conditioning and tape recording. Continuous analog voltage inputs are amplified and filtered, when appropriate, to reduce noise levels. Each of these signals is encoded by pulse width modulation and recorded on a separate track of 1/4 in. electromagnetic tape, played from reel to reel (10 in. diameter) on an Ampex 8-track recorder, running at 7 ips. The digital output of an internal electronic clock is similarly recorded on another track. Each different discrete voltage input, such as from a switch on the experimenter's console, is used to trigger a specific 6-bit pulse code. Separate pulse codes are sequentially recorded on the same tape track at rates of up to 1-2 codes per second. In addition, the central electronic system contains an oscilloscope and a 4-track stripchart recorder for monitoring the various input signals. A voice channel was also provided for the experimenter to record noteworthy data not otherwise logged by the above system.

Details of the various sensors and measures are given below.

Speed and Steering Sensors

Steering wheel position was continuously recorded on a separate tape channel from a 10-turn potentiometer linked by a gear-chain drive to the steering column. The system was accurate to within ±0.5 deg of steering wheel rotation.

Vehicle speed was measured by an electronic tachometer attached to the speedometer cable. The calibrated analog voltage was pulse coded and recorded on the "digital information" tape channel at 5 sec intervals with a single measurement accuracy to within ±0.5 ft/sec (±0.15 m/sec).

Lane Position Sensor

Externally, the vehicle mounted an electro-optical lateral lane position sensor or "Lane Tracker" mounted in a protective housing ($7 \times 7 \times 13$ in.; $17.8 \times 17.8 \times 33$ cm) 8 ft (2.44 m) from the ground. In earlier experimental runs, the Lane Tracker was mounted above the right front wheel for measuring the lateral distance to the lane/shoulder interface (first experiment) or edge line (second experiment). However, for approximately the last half of the runs the Lane Tracker's position was shifted to over the left front wheel for measuring the lateral distance to the broken lane line. The change was made after it was determined that the latter delineation feature provided a more reliable signal for road tracking. Because the separation between lane line and either the road/shoulder interface or the edge line was known and nearly constant in all cases, appropriate conversion of the right side measurements was made to the scale of reference for left side measurement, with appropriate adjustment for the distance separating the two mounting configurations.

Additionally, a set of 2-4 floodlights was mounted externally at the height of the vehicle's front bumper to provide road surface illumination in the Lane Tracker's field of view. The range of this illumination extended for approximately 20 ft (6.1 m) in front of the vehicle and constituted no hazard to other vehicles in the judgment of the California State Highway Patrol.

The Lane Tracker is a solid-state electro-optical device comprised of a line-scan camera with associated electronics for automatically adjusting its sensitivity to varying light levels (range: 2-256 ft-L with camera f-stop setting of 2.0), for noise rejection, and for tracking either solid or broken linear road features (striping or road/shoulder interface) having a visual contrast above 0.2. Its line-scan camera focuses the image of the road surface, perpendicular to the direction of travel, on a linear photodiode array. Road position is determined, from rapid successive readings of the array, by determining the diode sensing the greater reflected light from road delineation, then transforming the information into an analog voltage, proportional to calibrated lateral distance from a vehicle reference point to the delineation. Positional information is accurate to within ±0.5 percent of the viewing angle of the camera lens. In this research an 8.5 mm, F = 1.9 Cosmicar lens was used, providing a 10 ft (3 m) road scan with positional resolution to within ±0.5 in. (±1.27 cm).

The Lane Tracker's voltage analog of vehicular lateral position was continuously recorded, after pulse width modulation, on one of the tape channels.

Driver Physiological Variables

EEG was recorded using a bipolar lead configuration, with Grass cup-type active electrodes over the subject's occipital-parietal cortex (O1-P3 positions of the International 10-20 System,[61]) and the reference electrode over the ipsilateral mastoid bone. Electrodes were affixed with collodion adhesive. The EEG signal was amplified and filtered in a specially built preamplifier (gain, 10^5) placed on a headset worn by the driver.* The EEG system had an essentially flat spectral response between 1.0 and 30.0 Hz, down 3 dB at 0.5 and 40.0 Hz, and dropping by 18 dB per octave beyond. The preamplifier's output was passed through a second-stage isolation amplifier (gain, 10^1) and, after pulse width modulation, onto tape channel.

ECG was recorded from standard Beckman electrodes in a bipolar lead configuration with the active electrodes in the clinical CR4 positions on the subject's chest and the reference electrode displaced to the right abdomen. These leads were connected to a specially built differential preamplifier (gain, 10^3) with an essentially flat spectral response between 1.0 and 50.0 Hz (3 dB down points at 0.5 and 60 Hz, and dropping by 18 dB per octave beyond). From these the ECG signal was passed through a unity-gain isolation amplifier and a Schmidt Trigger with an automatically adjusting threshold, set to trigger at 80 percent of the preceding ECG QRS-wave. Each trigger pulse was used to generate a pulse code which was also recorded on the digital information channel of the tape.

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*This arrangement was shown to be critical in earlier over-the-road studies by Human Factors Research, Inc. Remote preamplifier location and longer, unshielded lead length resulted in an unacceptably high noise level in the EEG recordings. We suspect that the usual employment of the latter technique has been responsible for commonly reported difficulties in obtaining valid EEG recordings in previous research on drivers.

[61] Jasper, H. H., "The Ten-Twenty Electrode System of the International Federation," Electroencephalography and Clinical Neurophysiology, Vol. 10, 1958, pp. 371-375.

Experimenter Responses

The occurrence of temporal/geographic events, such as the beginning and end of delineation treatment sections traversed by the subject during the course of each run, was recorded by the onboard experimenter who engaged corresponding switches on a response console (Fig. 46) at appropriate times. In addition, the experimenter similarly recorded noteworthy discrete events arising during the subject's continuous vehicle operation. These included apparently inadvertent lane drifts to the left and right which caused the vehicle to enter the adjacent traffic lane or the road shoulder. Finally, the experimenter engaged his "log entry" switch and made simultaneous voice recordings in order to describe important road, traffic, or climatic conditions. All console switch closures generated respective 4-bit pulse codes which were recorded on the tape digital information channel in quadruplicate. Two types of switches were present on the console: the first, instantaneous-contact type, was for recording transient events; the second, on-off type, for recording situations having appreciable duration. The latter switch closure caused successive recording of the particular event at 1-second intervals for as long as the switch was on.

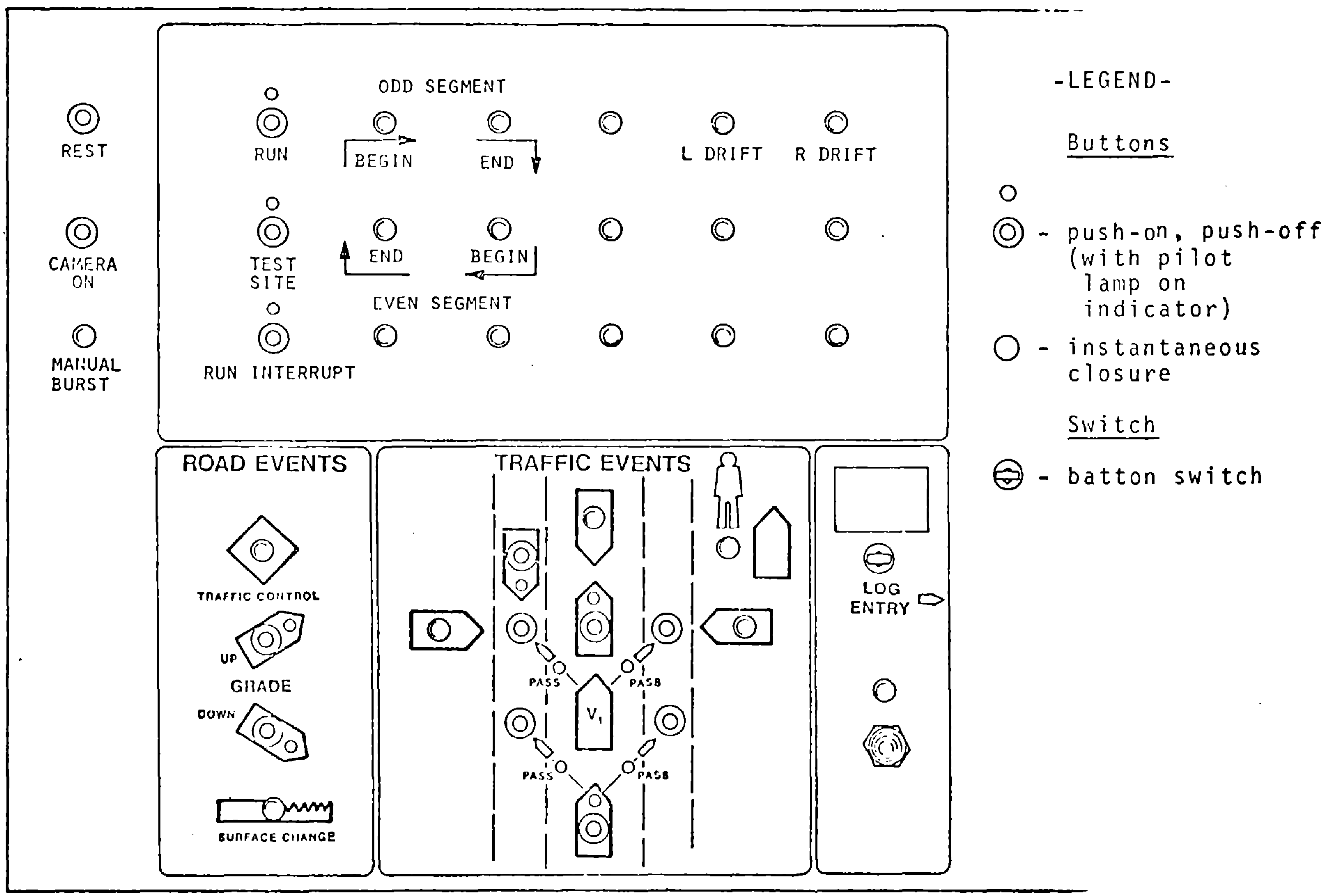

Figure 46. Experimenter's Response Console

APPENDIX D

FIELD TEST DATA STATISTICAL ANALYSIS

FIRST EXPERIMENT (I-80 DELINEATION CONTRAST VARIATIONS)

Analyses of the data from the first experiment consisted of the following:

1. ANOV of vehicular control and physiological variables from all subjects who yielded data in all (or nearly all) experimental conditions.

2. Regression analysis of all appropriate data to define the functional relationship between striping contrast and lateral lane position variability.

ANOV Results

Complete, or nearly complete, data were obtained from five of six subjects in Group 1 (special treatment — worn treatment) and from four subjects in Group 2 (worn treatment — standard treatment). These data comprised the base for the ANOV of each dependent variable, except those arising from ECG recordings. In the latter case, data for two more subjects in the second group were lost because of equipment malfunctions. For ECG measures, no meaningful group comparison was possible, so all of the remaining seven subjects were treated as comprising a single group in respective ANOVs of the mean heart rate, standard deviation of heart rate, and coefficient of variation of heart rate ($SD_{HR}/\overline{HR}$) variables.

The results from all ANOVs are summarized in Table 20. Between-subject interactions were always used as error terms for the F ratios. Due to the extent and complexity of those results, it was not feasible to discuss them all, or even isolated results indicating statistically significant effects. Rather, the major consistent results are described as these pertain to the objectives of the research.

Vehicular control variables. The first group's vehicular control performance was generally superior to that of the second. This difference was significant for the standard deviation of lateral lane position. Overall, the first group showed less lateral position variability than the second (0.69 ft versus 0.89 ft; .21 m versus .27 m).

TABLE 20. F-RATIOS AND SIGNIFICANCE OF RESULTS FROM ANOV OF I-80 DATA, WHERE INDEPENDENT VARIABLES INCLUDE GROUPS (G), TREATMENT SEGMENTS (T), DIRECTION OF TRAVEL (D), CIRCUITS (C), AND PAINT CONDITION (P)

		G	T	TxG	D	DxG	TxD	TxDxG	C	CxG	TxC
1.	MEAN LATERAL POSITION	3.46	17.76 **	.38	5.92 *	.89	5.90 **	1.15	.00	2.02	.69
2.	SD LATERAL POSITION	12.91 **	5.39 **	2.48	2.68	1.55	6.66 **	1.45	4.67	.04	.10
3.	MEAN SPEED	.11	11.04 **	2.04	24.38 **	.09	3.97 *	1.65	3.31	3.56	1.06
4.	SD SPEED	2.40	2.47	1.58	1.12	.54	5.08 **	2.36	.97	3.83	.98
5.	EEG DELTA %	.24	2.46	.05	.53	5.76 *	.91	2.00	.00	1.93	.94
6.	EEG LOW THETA %	4.00	1.64	1.60	.06	.55	.46	.50	3.18	3.69	.39
7.	EEG MID THETA %	5.37	1.21	.71	1.55	.02	2.58	1.67	4.75	.05	.15
8.	EEG HIGH THETA %	5.45	.42	1.14	.06	.46	.82	.23	1.88	1.99	.64
9.	EEG ALPHA %	1.37	1.88	1.24	2.31	.69	1.37	.25	1.54	1.40	.25
10.	EEG SIGMA %	2.04	1.89	.39	.00	1.66	1.15	.52	.37	2.49	.65
11.	EEG BETA %	3.48	2.67	.90	1.22	4.68	.77	.77	.59	2.61	.64
12.	MEAN HEART RATE		7.22 **		8.84 *		1.69		7.59 *		1.15
13.	SD HEART RATE		2.32		.15		4.28 **		12.82 *		.98
14.	SD/M HEART RATE		2.47		.01		4.42 **		22.62 **		1.11
Rows 1-4:	df =	1,7	4,28	4,28	1,7	1,7	4,28	4,28	1,7	1,7	4,28
Rows 12-14:	df =		4,24		1,6		4,24		1,6		4,24

Significance - * p < .05; ** p < .01

TABLE 20 (CONTINUED)

		TxCxG	DxC	DxCxG	TxDxC	TxDxCxG	P	PxG	TxP	TxPxG	DxP
1.	MEAN LATERAL POSITION	1.72	.09	.22	.57	.20	18.47**	32.21**	11.37**	.40	1.20
2.	SD LATERAL POSITION	.71	.18	2.55	1.23	.85	5.41	1.18	3.04*	.48	15.59**
3.	MEAN SPEED	.42	5.30	1.02	2.69	.53	2.67	1.05	2.16	1.30	3.40
4.	SD SPEED	.92	.54	.34	2.57	1.09	.01	.64	1.15	2.21	6.22*
5.	EEG DELTA %	1.35	.09	.89	.25	.48	.23	.38	.31	1.53	.02
6.	EEG LOW THETA %	.22	.01	.08	1.83	.62	.01	1.31	1.14	1.46	.22
7.	EEG MID THETA %	1.07	1.70	2.92	1.25	.70	.00	.00	.31	.33	1.03
8.	EEG HIGH THETA %	1.25	.04	.16	.82	1.03	.05	.02	.59	.81	2.95
9.	EEG ALPHA %	1.62	.11	1.18	.40	.33	.03	.88	.61	.45	.54
10.	EEG SIGMA %	.83	.04	.37	1.35	3.01	.29	.83	.68	.82	2.36
11.	EEG BETA %	.65	.63	1.79	.63	.95	.22	.39	.30	.36	.43
12.	MEAN HEART RATE		2.60		.80		.27		.89		2.59
13.	SD HEART RATE		.02		.62		.01		8.30**		.08
14.	SD/M HEART RATE		.21		.83		.01		7.54**		.02
Rows 1-4:	df =	4,28	1,7	1,7	4,28	4,28	1,7	1,7	4,28	4,28	1,7
Rows 12-14:	df =		1,6		4,24		1,6		4,24		1,6

Significance - * p < .05; ** p < .01

TABLE 20 (CONCLUDED)

		DxPxG	TxDxP	TxDxPxG	CxP	CxPxG	TxCxP	TxCx PxG	DxCxP	DxCx PxG	TxDx CxP	TxDx PxG
1.	MEAN LATERAL POSITION	* 9.17	** 12.69	.48	1.04	5.35	.84	1.15	.32	.32	1.34	.91
2.	SD LATERAL POSITION	.17	2.65	.54	3.41	.49	2.43	1.21	* 9.88	.03	.23	1.63
3.	MEAN SPEED	1.16	2.04	1.27	.16	.68	.38	1.75	.19	2.60	.16	.83
4.	SD SPEED	3.04	1.13	.23	.49	.00	1.37	.88	1.61	4.28	.08	.80
5.	EEG DELTA %	4.41	.89	.39	.09	.12	1.22	2.68	1.60	.46	* 4.54 (2,22)	.92
6.	EEG LOW THETA %	.02	.19	.87	1.14	.61	.47	.89	** 13.17	.53	.84	2.38
7.	EEG MID THETA %	.90	.66	1.59	.04	.23	* 3.31	1.09	.00	.15	1.33	.80
8.	EEG HIGH THETA %	** 14.68	1.26	1.93	.50	1.76	1.24	.93	2.59	.22	.45	1.52
9.	EEG ALPHA %	1.26	2.35	.55	.44	.02	1.71	4.88	4.93	1.31	* 4.61 (2,22)	.44
10.	EEG SIGMA %	2.61	.24	.68	.30	.03	.13	1.39	4.88	.89	2.63	2.47
11.	EEG BETA %	.47	.09	.31	.38	.01	.58	.46	* 6.09	.14	1.03	1.91
12.	MEAN HEART RATE		** 7.47		.27		1.25		.09		.45	
13.	SD HEART RATE		.81		.25		1.47		.00		.80	
14.	SD/M HEART RATE		1.01		.42		1.49		.06		1.19	
Rows 1-4:	df =	1,7	4,28	4,28	1,7	1,7	4,28	4,28	1,7	1,7		
Rows 12-14:	df =		4,24		1,6		4,24		1,6		4,24	

Significance - * p < .05; ** p < .01

Vehicular control measures (with the exception of speed variability) varied significantly among treatment segments. This effect is difficult to interpret, however, due to the natural confounding of highway geometry and delineation, and because the treatment factor was different for the two groups. That is not to say that it is impossible to isolate the delineation effect in the results. (This has been done in Section IV.) However, it does indicate that the significant treatment effects should merely be interpreted as showing that the subjects as a whole drove differently on different treatment segments.

The direction of travel, or more specifically the road grade, had several significant effects. Mean lane position was affected showing greater separation between the lane-line and the vehicle's left front wheel in the upgrade, eastbound direction than in the downgrade, westbound direction [2.79 ft (0.85 m) versus 2.69 ft (0.82 m)]. Mean speed was less on the upgrade [47.01 mph (75.2 kph)] than on the downgrade [50.45 mph (80.7 kph)].

There was no significant difference between the results obtained on the first and second I-80 circuits for any vehicular control measure. With one exception there was no significant interaction effect of circuits with any other factor or combination of factors in 124 separate tests. The one interaction significant at a $p < 0.05$ level (SD lateral position; $D \times C \times P$) would be expected on the basis of chance alone, given the number of tests.

The condition of the painted striping had a highly significant effect upon mean lateral lane position. Overall, the subjects tended to position their vehicles with the left front wheel at a distance of 2.57 ft (0.78 m) from the lane line when the paint was good (i.e., after the application of either special or standard striping). That distance increased to 2.91 ft (0.88 m) when the paint was bad (i.e., after being degraded by snow removal and tire chains). [It should be noted that a 3 ft (0.9 m) separation between lane line and left front wheel would place the vehicle in an exact center-lane position.]

The significant interaction effects of Treatments (T), Directions (D), and Paint Conditions (P) upon mean lateral lane position and lateral position

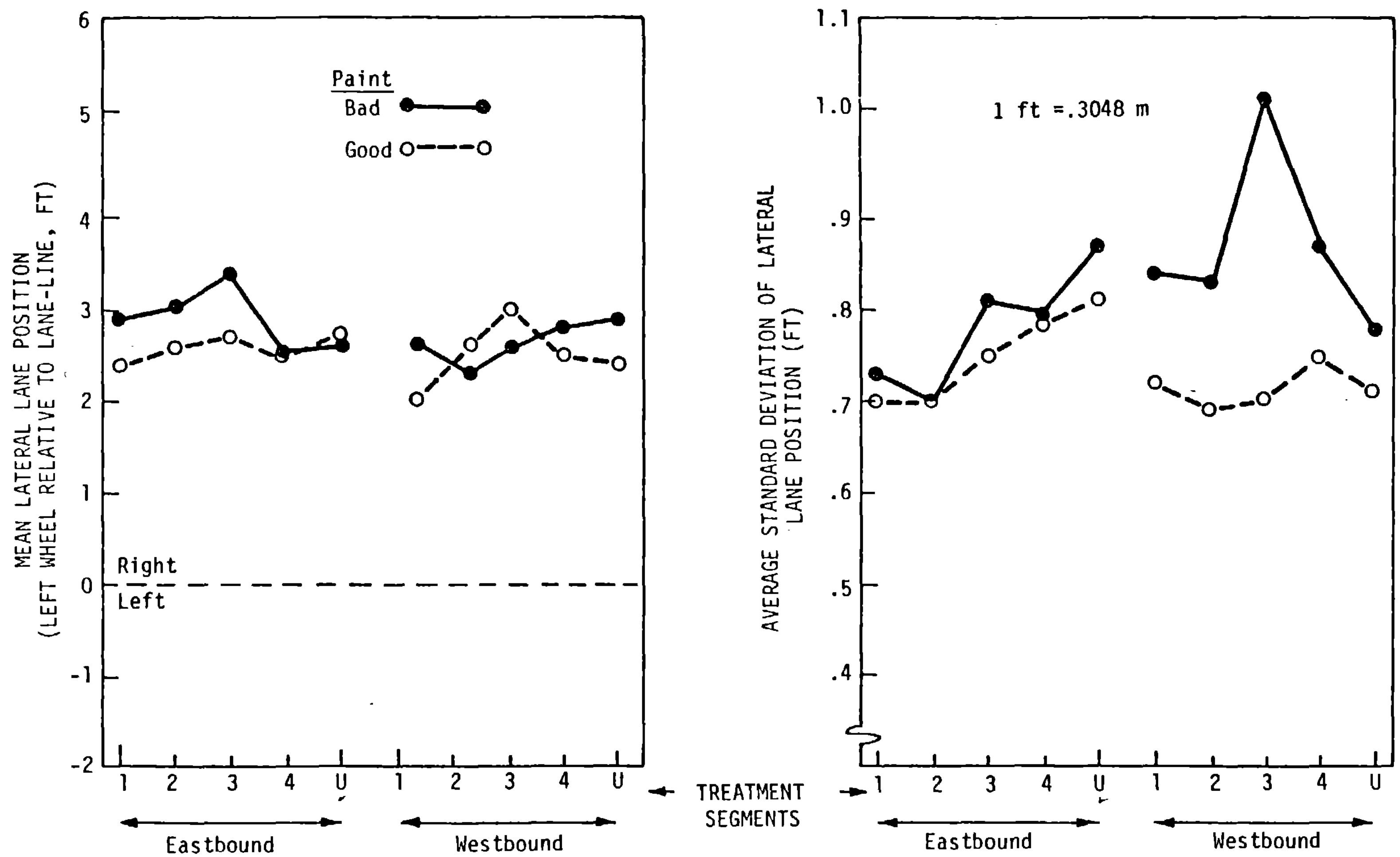

Figure 47. Mean Lateral Lane Position (Left) and Average Standard Deviation of Lane Position (Right) for All Subjects in Both Directions Under Good and Bad Delineation Paint Conditions on Treatment Segments of the I-80 Circuit

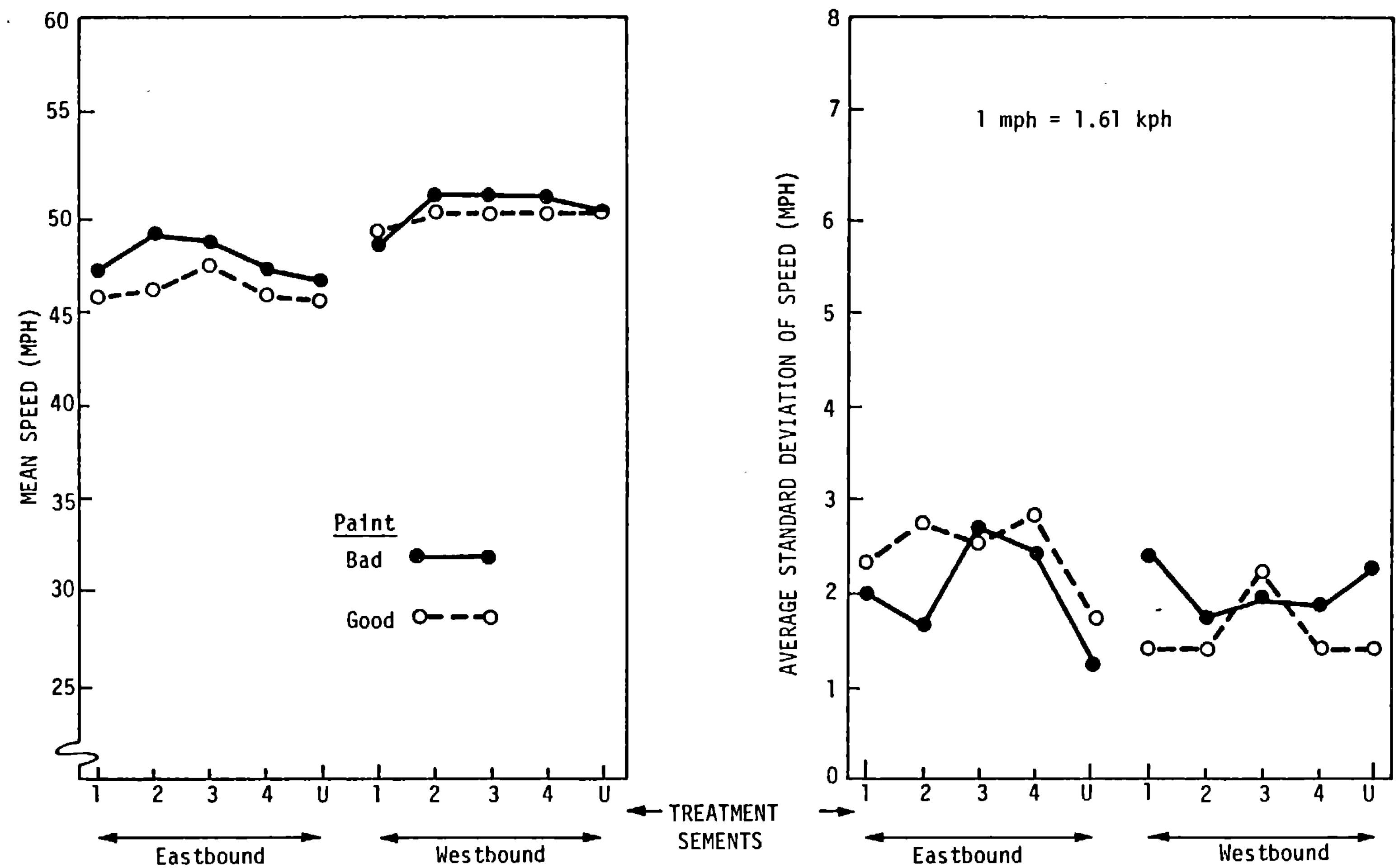

Figure 48. Mean Speed (Left) and Average Standard Deviation of Speed (Right) for All Subjects in Both Directions Under Good and Bad Delineation Paint Conditions on Treatment Segments of the I-80 Circuit

variability may be interpreted using Fig. 47 , and their effects upon mean speed and speed variability using Fig. 48.

Mean lateral position indicated greater lane-line/vehicle separation with bad paint over Segments 1-3 on the eastbound upgrade but no consistent pattern on the westbound downgrade. On the other hand, the standard deviation of lateral lane position was not differentially affected by paint condition on the upgrade section, but was strikingly greater on the downgrade section when the paint was bad.

Mean speed was generally a little greater when the paint was bad; and the differential effect of the paint conditions was greater on the upgrade than on the downgrade. Speed variability was generally greater with good paint on the upgrade but the opposite was true on the downgrade.

Higher order interaction effects, involving all of the above factors, plus circuits, upon vehicular control measures, may be interpreted using Figures 49 through 52. The results depicted in these figures represent the most detailed level of analysis for the groups of subjects. They are included here mainly for the sake of completeness. However, a few points can be made from these results.

Figure 49 shows again that the differential effect of paint conditions on mean lateral position was confined principally to Group 1, and that this effect was variable across treatment segments. In no condition did either group's lane-line/vehicle separation rise far above 3.0 ft (0.9 m).

Figure 50 similarly shows that the differential effect of paint condition was most consistent upon Group 1's lateral position variability. But, in certain combinations of treatment segment and direction, the effect was also present for Group 2. In particular, when the paint was bad, Group 2 showed exceedingly high lateral position variability in treatment Segment 3 on the westbound downgrade. This was true for both circuits. However, no such rise in Group 2's lateral position variability was seen on the same segment when the paint was good.

Figures 51 and 52 impart little additional information, except to indicate that the differential effect of paint condition on mean speed was

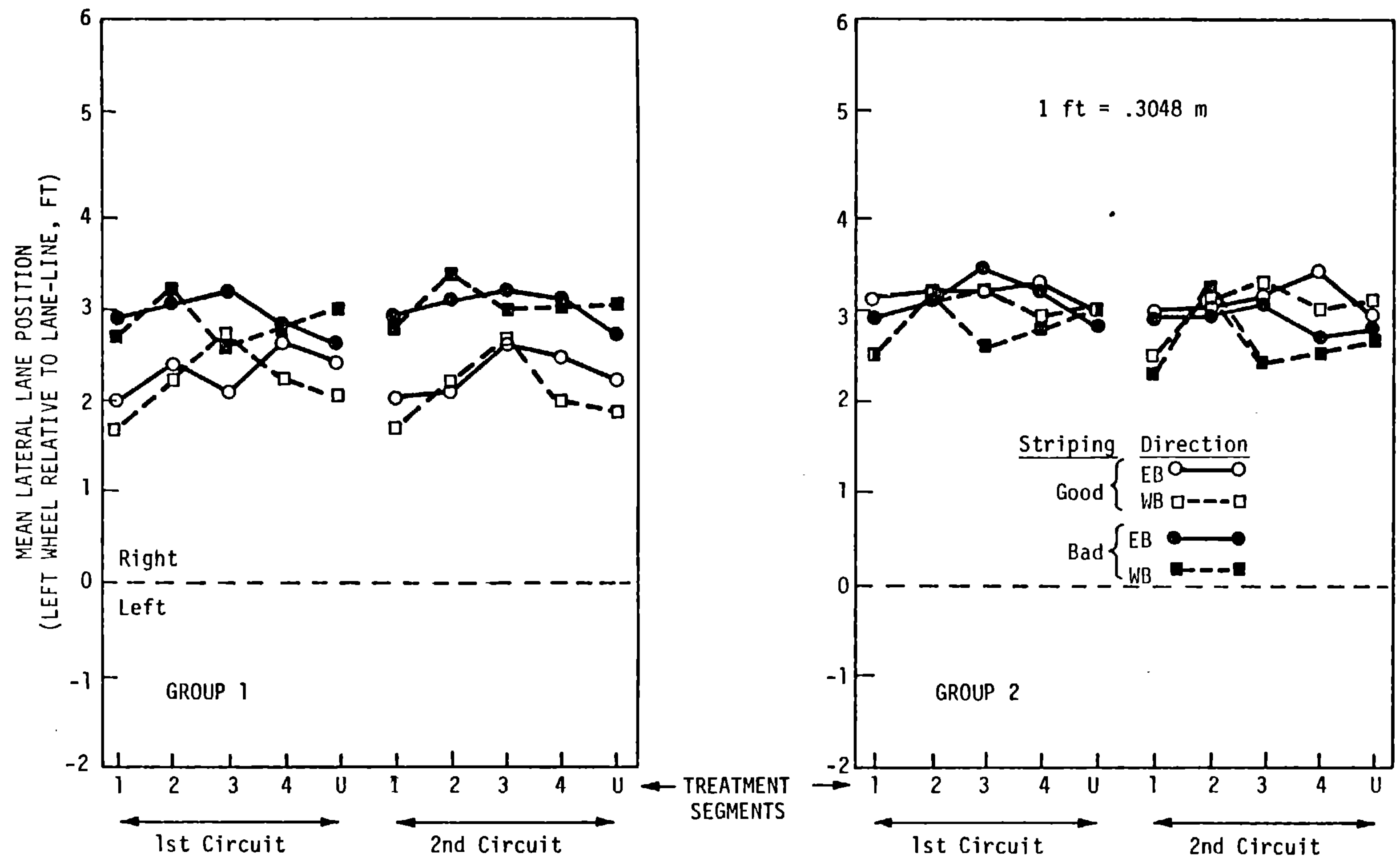

Figure 49. Mean Lateral Lane Position for Group 1 (Left) and Group 2 (Right) Under All Conditions on Treatment Segments of the I-80 Circuit

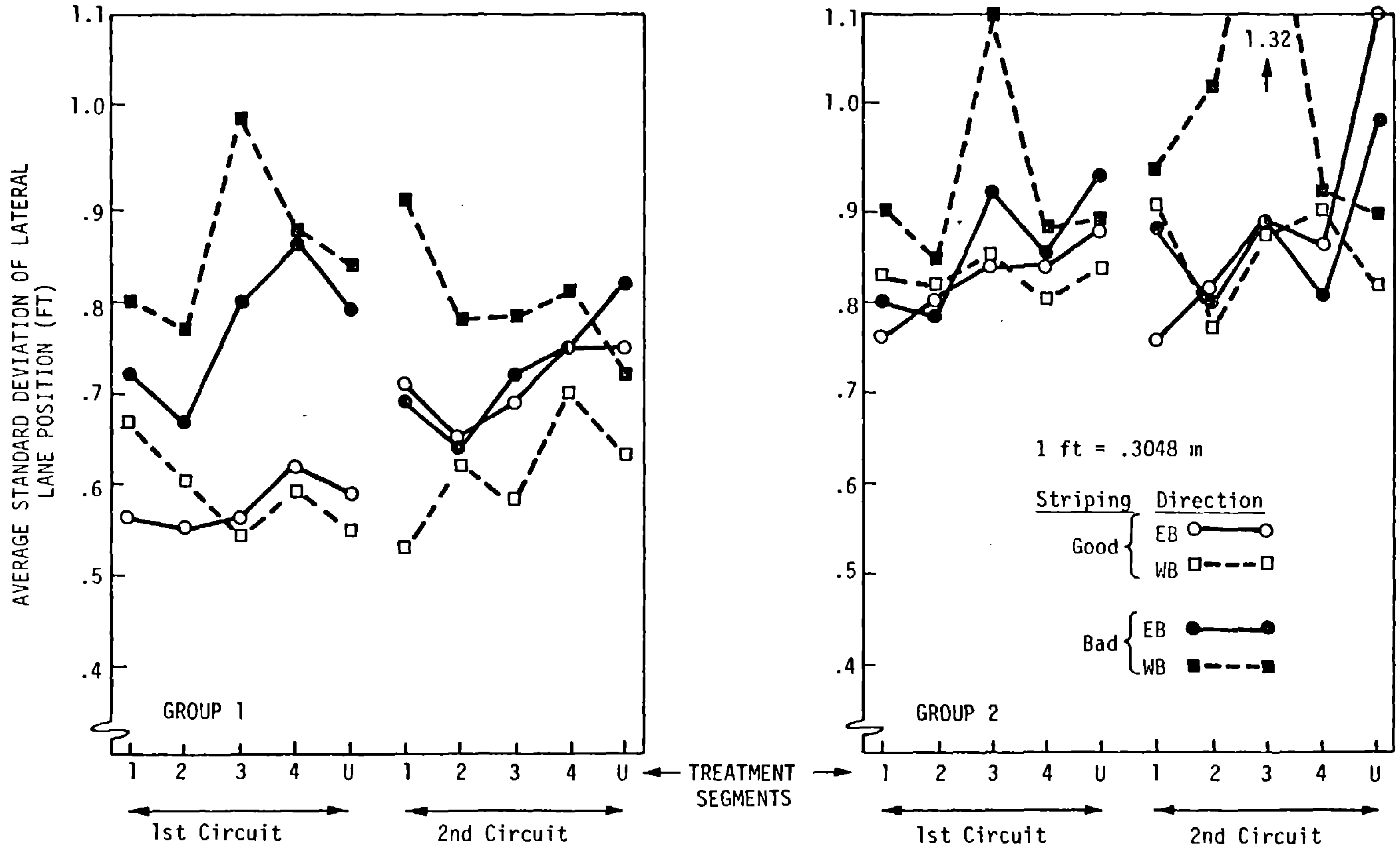

Figure 50. Average Standard Deviation of Lateral Lane Position for Group 1 (Left) and Group 2 (Right) Under All Conditions on Treatment Segments of the I-80 Circuit

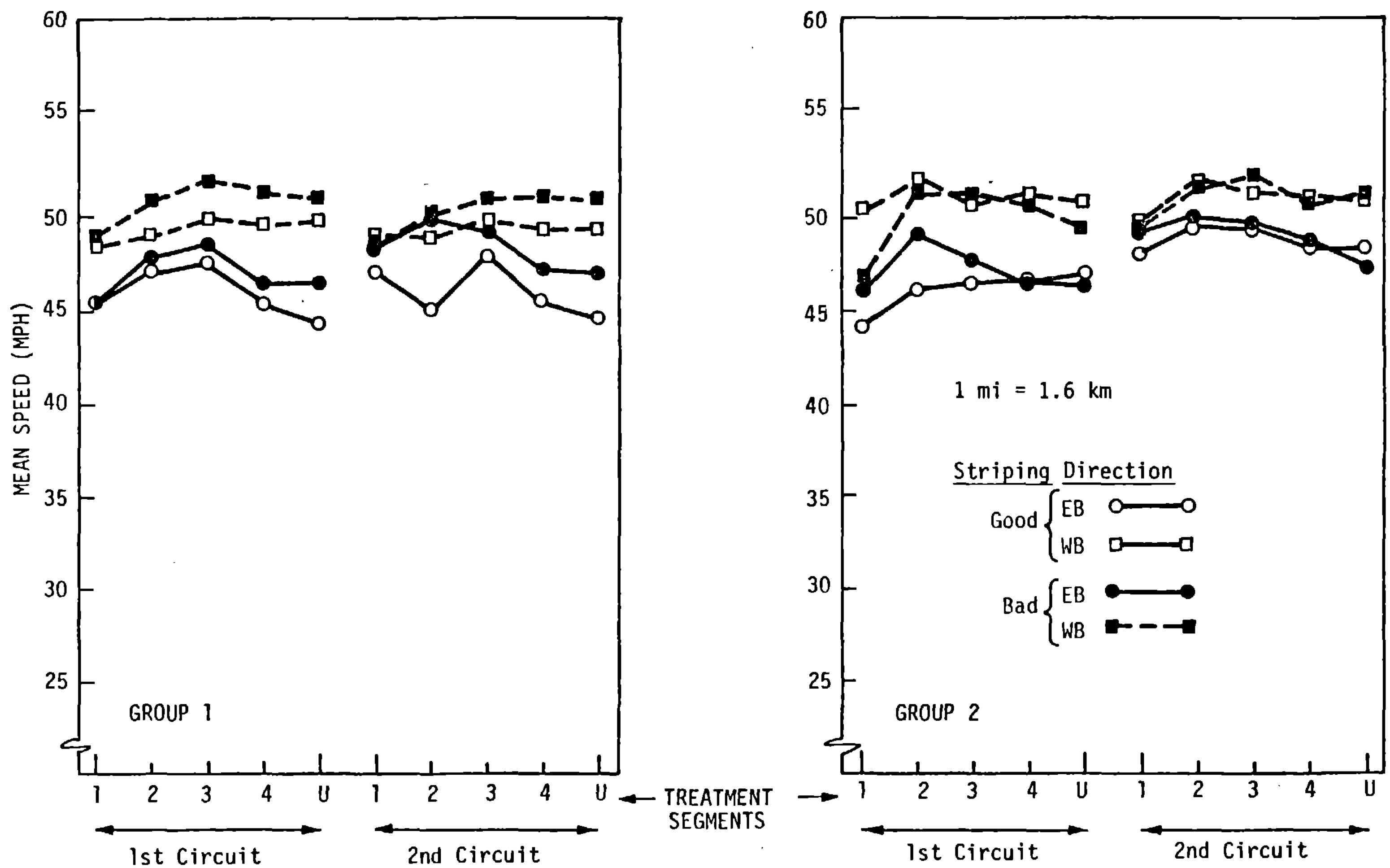

Figure 51. Mean Speed and Group 1 (Left) and Group 2 (Right) Under All Conditions on Treatment Segments of the I-80 Circuit

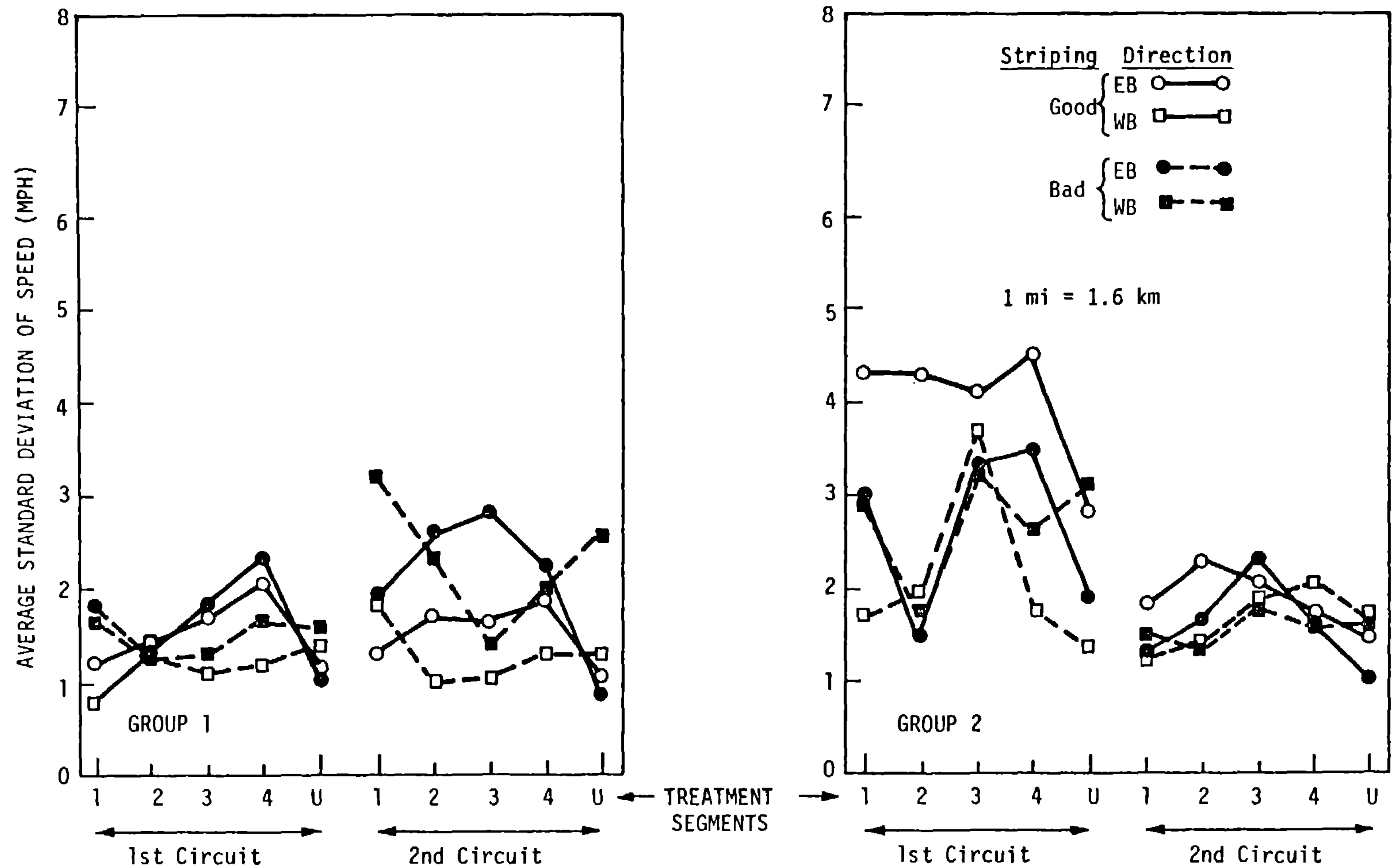

Figure 52. Average Standard Deviation of Speed for Group 1 (Left) and Group 2 (Right) Under All Conditions on Treatment Segments of the I-80 Circuit

almost entirely confined to Group 1. For them, however, the effect was quite consistent in both directions and over both circuits.

Physiological variables. As shown in Table 20, the EEG variables were generally insensitive to changes in all independent variables. The EEG variables alone showed some effect of repeated circuits. Moreover, mean heart rate was also significantly affected by treatments and directions. However, all differences among conditions were relatively small, never exceeding 9 bpm for the standard deviation of heart rate.

SECOND EXPERIMENT (I-5 RAIN EFFECTS)

Analyses of the data from the second experiment consisted of the following:

1. ANOV of vehicular control and certain physiological variables for six subjects under wet and dry weather conditions.

2. ANOV of vehicular control and physiological variables for 10 subjects under dry weather conditions only.

ANOV: Wet Versus Dry Conditions

The results from all ANOVs of dependent variables recorded under wet and dry driving conditions over the I-5 circuit are summarized in Table 21. It may be noticed that reference to the factor for quarters of segments was omitted from the table. Little unique information was obtained from tests of differences in measured reactions on successive quarters of treatment segments, either alone or in interaction with other factors. Thus, the exclusion of the Quarters factor simplified the table but did not detract significantly from the description of results. The grouping of the data by quarters of treatment segments did aid, however, in the evaluation of thermoplastic effects as discussed in Section IV of this report.

Vehicular control variables. The effect of Delineation Treatment (T) on the standard deviation of lateral lane position was highly significant. When pavement delineation consisted of striping plus raised pavement markers, the subjects' average standard deviation of lateral lane position was 0.50 ft (0.15 m). With striping alone it was 0.78 ft (0.24 m). However, the natural

TABLE 21. F-RATIOS, df, AND SIGNIFICANCE OF RESULTS FROM ANOV 1 (I-5) WHERE INDEPENDENT VARIABLES INCLUDE DELINEATION TREATMENT (T), DIRECTION OF TRAVEL (D), CIRCUITS (C), AND WEATHER (W)

	T	D	TxD	C	TxC	DxC	TxDxC	W	TxW	DxW	TxDxW	CxW	TxCxW	DxCxW	TxDxCxW
1. MEAN LATERAL POSITION	4.30	1.54	.85	37.69**	1.05	9.16*	6.89*	31.49**	1.50	.00	.05	13.27*	.45	1.32	4.14
2. SD LATERAL POSITION	49.77**	.52	.44	.08	.78	.92	.11	35.28**	4.72	.50	.07	.02	15.39*	1.00	1.50
3. MEAN SPEED	12.04*	.27	7.53*	1.81	.13	.65	2.12	.72	12.12*	8.01*	.07	1.05	1.22	.20	6.32
4. SD SPEED	.05	.46	1.49	.01	.07	.66	1.03	1.64	.83	.01	.03	.00	.67	.74	.74
5. EEG DELTA %	3.27	1.50	6.44	1.53	3.43	.12	2.04	.06	3.38	.01	11.94*	2.56	2.74	.11	.72
6. EEG LOW THETA %	2.33	.28	.72	7.50	1.69	.47	.05	.15	5.97	11.24*	3.42	8.73*	9.69*	.37	2.25
7. EEG MID THETA %	5.65	.80	.00	7.80*	.05	2.56	4.54	.60	4.20	.00	.14	14.96*	1.69	.22	1.80
8. EEG HIGH THETA %	2.42	.93	1.75	8.01*	4.15	.93	.68	.16	.08	.29	14.44*	.04	.07	.68	1.33
9. EEG ALPHA %	.90	.00	6.49	.15	11.56*	.42	.01	.06	14.94*	3.27	1.43	2.94	4.46	.11	2.67
10. EEG SIGMA %	.66	.15	2.54	.16	.20	2.04	.48	.03	9.19*	1.05	.04	.25	.02	.68	.74
11. EEG BETA %	8.57*	2.35	.41	.95	2.51	.50	.11	.09	7.36	.26	.13	1.72	32.57**	1.27	2.34
Rows 1-4: df =	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Rows 5-11: df =	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4

Significance - * $p < .05$; ** $p < .01$

confounding between delineation treatments and road geometry on the I-5 circuit should be recalled. Striping alone occurred where the road curvature was generally greater. Likewise, the significant effect of Delineation Treatment on mean speed [respectively, 51.8 mph (82.9 kph) versus 49.9 mph (79.8 kph)] should be interpreted with caution for the same reason.

There was no overall effect of Direction (D) on any variable. Generally, the subjects tended to react similarly while traveling in both directions over the I-5 circuit.

There was a significant overall effect of Circuits (C) on mean lateral lane position. During the first circuit its average value was 2.7 ft (0.8 m) and during the second, 2.5 ft (0.76 m). This result indicates a progressively decreasing lane-line/vehicle separation over time on the road.

Weather (W) had highly significant effects upon both mean lateral position and lateral position variability. These effects are discussed in Section IV-E. The overall shift in mean lateral position from dry to wet driving conditions was from 2.2 ft (0.67 m) to 3.0 ft (0.9 m). The latter value indicates that the drivers maintained the vehicle's average lateral placement in the exact center of the traffic lane during the wet condition. The overall standard deviation of lateral lane position increased from dry to wet conditions from 0.53 ft (0.15 m) to 0.74 ft (0.23 m).

Some interaction effects of the factors upon vehicular control variables were striking. Foremost was the Treatment by Circuit by Weather ($T \times C \times W$) effect upon standard deviation of lateral lane position. Although lateral position variability was generally greater in wet weather, it was more so on the treatment segments having striping alone, and greater still on the second circuit as compared to the first.

Mean lateral lane position was affected significantly by the interaction of Circuit and Weather ($C \times W$). Subjects tended to move closer over time toward the lane-line in wet weather, but not as noticeably in dry weather as discussed in Section IV-E.

Mean speed and speed variability were not significantly affected by the weather, but both changed in the expected direction as shown in Fig. 53. Mean speed was affected significantly by several interactions of factors T, D, and W. In general, differences in mean speed between the two types of treatment were greater in wet weather (T × W) than dry, and for the southbound direction than northbound (D × W).

ANOV: Dry Condition Only

Complete data with respect to vehicular control and EEG variables were obtained over three circuits under dry weather conditions from 10 subjects, including the 6 yielding data for the above analyses. These data were used in another ANOV for determining whether differences in delineation treatments would affect any dependent variables over a longer period of continuous exposure without the additional effect of adverse weather. The results are summarized in Table 22 and vehicular control reactions are illustrated in Figs. 54 and 55. However, little differential treatment effect over time was found. The only significant T × C interaction effect was for mean lane position. That variable was virtually constant over successive circuits at a value of about 2.0 ft (0.6 m) on the treatment segments with markers plus striping delineation. However, it declined slightly from the first to the later circuits [i.e., 2.2-2.0 ft (0.7-0.6 m)] on the segments with striping alone.

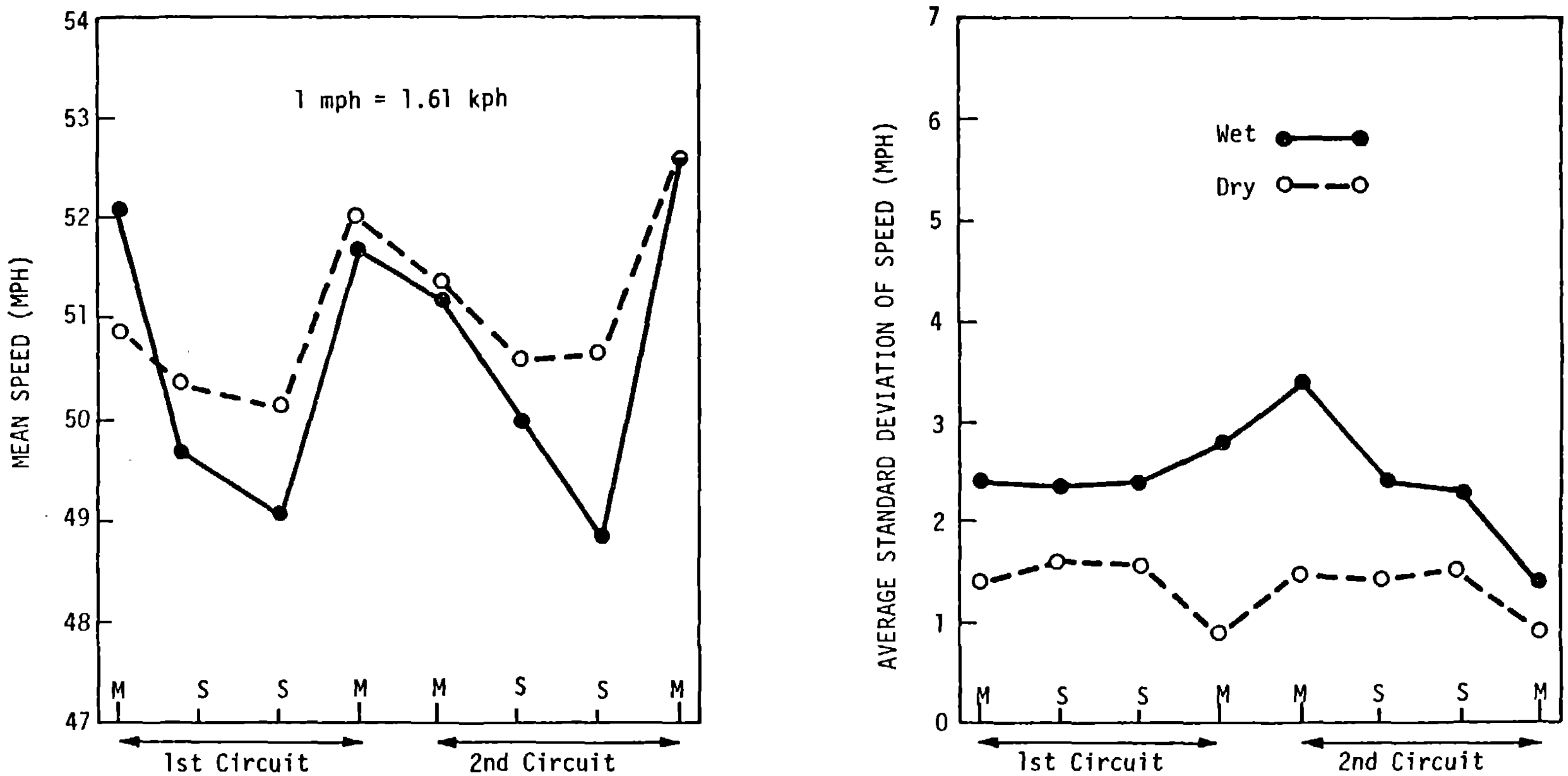

Figure 53. Mean Speed (Left) and Average Standard Deviation of Lateral Lane Position (Right) Under Best Wet and Dry Weather Conditions, Over Treatment Segments Where Pavement Delineation Consisted of Either Raised Pavement Markers Plus Striping (M) or Striping Alone (S), on Two Successive I-5 Circuits

TABLE 22
F-RATIOS, df, AND SIGNIFICANCE OF RESULTS FROM ANOV 2 (I-5) WHERE INDEPENDENT VARIABLES INCLUDE DELINEATION TREATMENT (T), DIRECTION OF TRAVEL (D), AND CIRCUITS (C)

		T	D	TxD	C	TxC	DxC	TxDxC
1.	MEAN LATERAL POSITION	8.17*	.20	1.99	6.78**	4.20*	.44	.86
2.	SD LATERAL POSITION	33.53**	.04	9.70*	.54	1.41	9.09**	1.61
3.	MEAN SPEED	18.26**	.70	8.17*	1.19	.74	2.11	1.11
4.	SD SPEED	2.89	.14	.03	1.00	.53	1.60	1.66
5.	EEG DELTA %	2.70	.69	.41	1.99	.43	.62	.76
6.	EEG LOW THETA %	1.76	1.62	4.03	.46	.57	1.10	.91
7.	EEG MID THETA %	9.96*	.03	.91	1.15	.60	2.39	.05
8.	EEG HIGH THETA %	14.04**	.62	5.41*	.52	4.82*	.66	.28
9.	EEG ALPHA %	.01	3.36	.45	2.23	.18	.49	.13
10.	EEG SIGMA %	.00	.01	2.58	.59	.07	.21	.38
11.	EEG BETA %	5.35*	1.06	8.56*	1.36	.46	.17	1.15
12.	MEAN HEART RATE	1.58	.65	.82	1.78	.38	.73	3.50
13.	SD HEART RATE	1.60	1.15	.14	.26	.16	.64	.25
14.	SD/M HEART RATE	1.32	1.76	.13	1.37	.23	.43	.02
Rows 1-11: df =		1,9	1,9	1,9	2,18	2,18	2,18	2,18
Rows 12-14: df =		1,5	1,5	1,5	2,10	2,10	2,10	2,10

Significance - * p < .05; ** p < .01

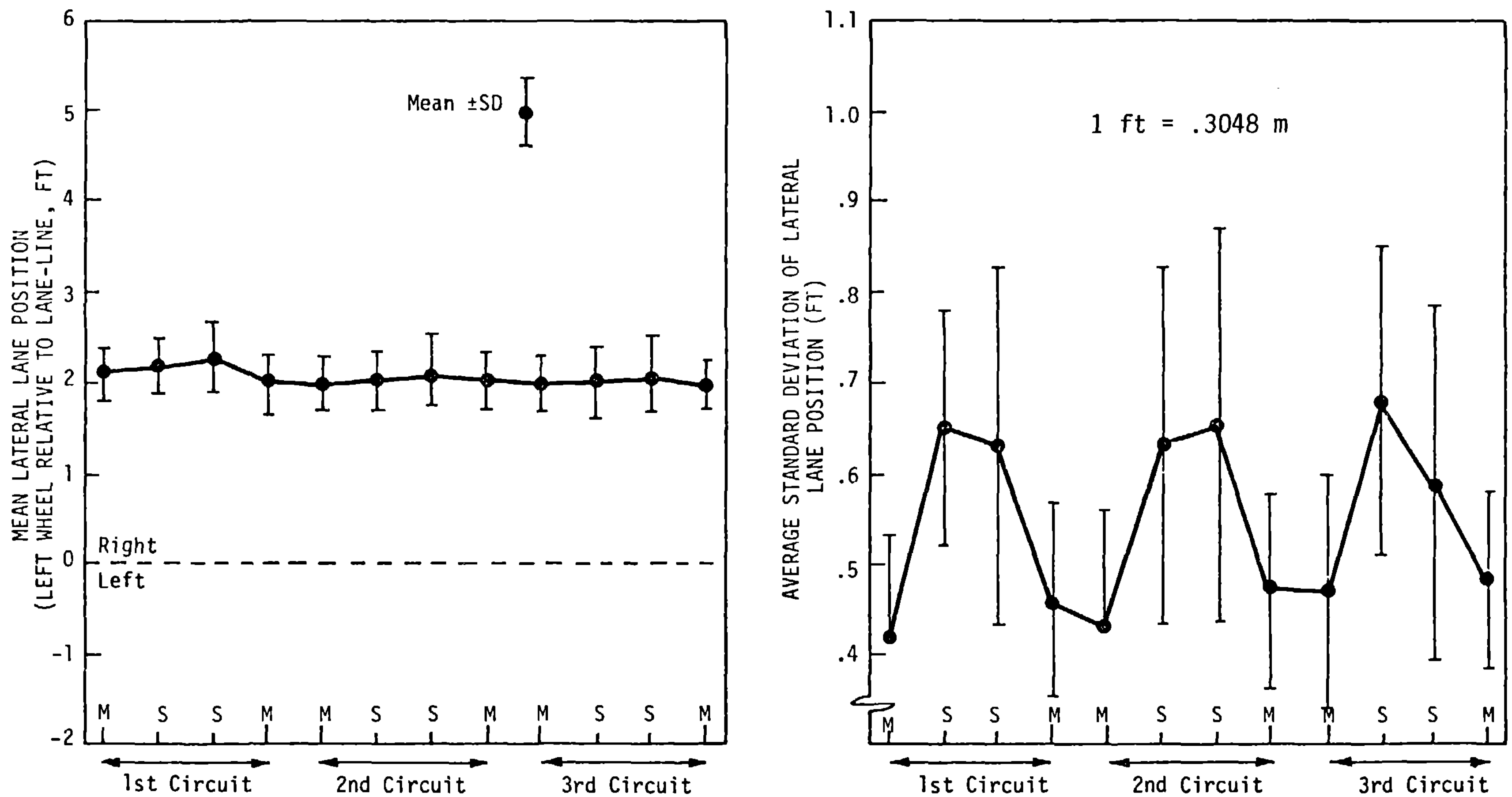

Figure 54. Mean Lateral Lane Position (Left) and Average Standard Deviation of Lateral Lane Position (Right) Under Dry Weather Conditions Only, Over Treatment Segments Where Pavement Delineation Consisted Either of Raised Pavement Markers Plus Striping (M) or Striping Alone (S) on Three Successive I-5 Circuits. Vertical Bars Indicate Standard Deviations of Individual Scores.

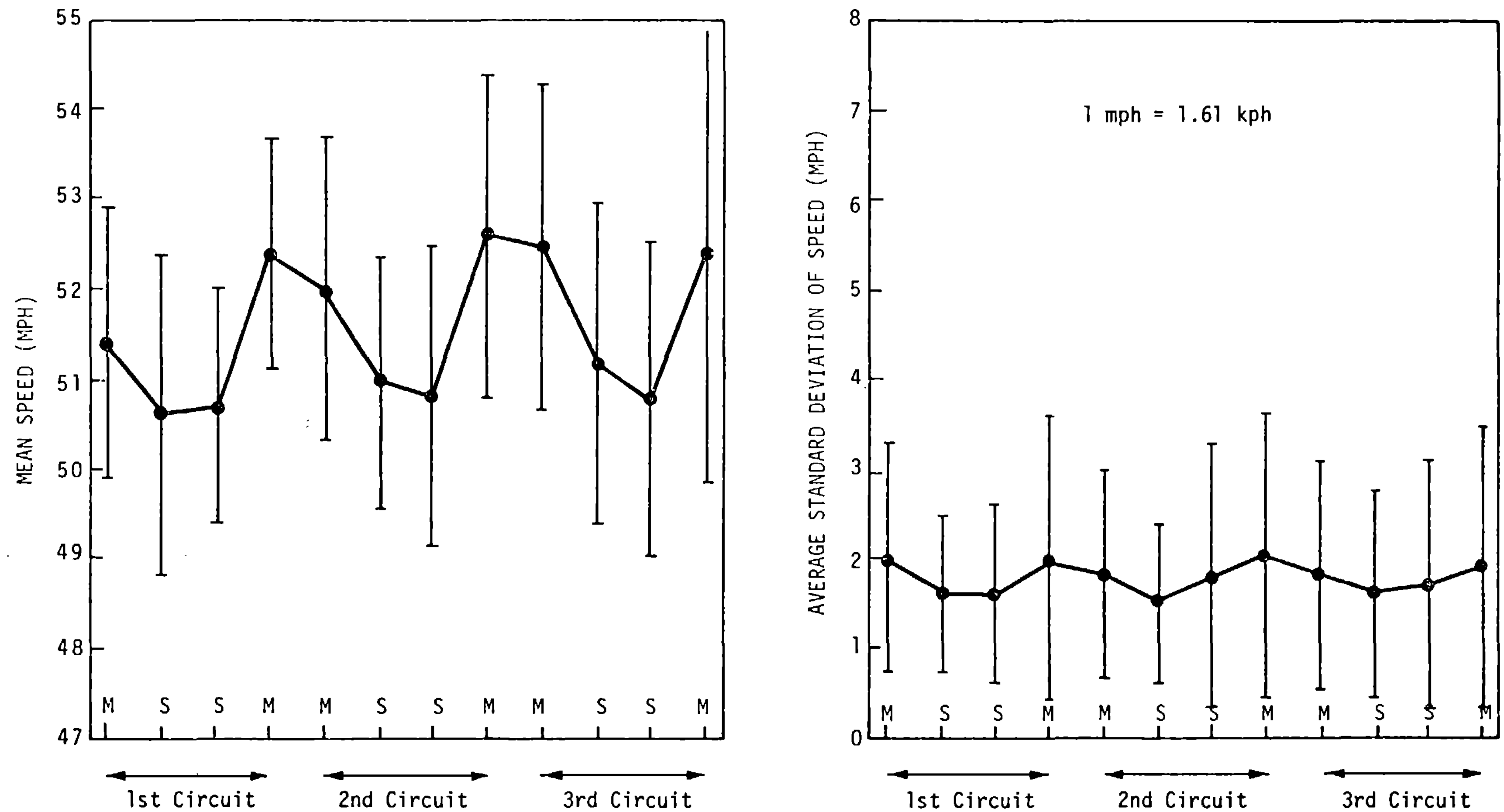

Figure 55. Mean Speed (Left) and Average Standard Deviation of Speed (Right) Under Dry Weather Conditions Only, Over Treatment Segments Where Pavement Delineation Consisted Either of Raised Pavement Markers Plus Striping (M) or Striping Alone (S) on Three Successive I-5 Circuits. Vertical Bars Indicate Standard Deviations of Individual Scores.

APPENDIX E

PHOTOMETRY

INTRODUCTION

Photometric measurements were made of the roadway and delineation markings on the I-80 sites. These measures were subsequently used to determine the contrast of the delineation to the roadway and the shoulders to the roadways as seen by the driver. Additionally, measurements of the luminance distribution of low-beam headlights from the test vehicle were made on a new black asphalt test strip. The following is a description of the photometric measurement methods and a presentation of the obtained data.

APPARATUS

All photometric measures were made using a Spectra Pritchard Photometer, Model 1980, with the standard 7 in. focal length f/3.5 lens. For all measurements, the photometer lens was located inside one of two carryall vans at the driver's eye position. The usual vehicle was a 1971 Dodge 3/4 ton van which was used for the driving tests. A replacement vehicle used for making some of the photometric measures at the I-80 sites was a 1972 Ford Econoline van. Both vehicles were equipped with the standard two-lamp headlight system. On both vehicles the headlights were located 2 ft 10-1/2 inc. (0.88 m) above the roadway, and the photometer lens was positioned at the driver's eye position, 5 ft 9 in. (1.7 m) above the roadway. Prior to each series of measurements, the headlights were aligned by a California licensed headlamp adjustment station.

HEADLIGHT PATTERN

The headlight luminance distribution of the research vehicle used in the driving portion of this study was measured with the vehicle parked on a newly constructed asphalt test strip. This strip was not subject to vehicular traffic and was uniform in appearance. The data obtained on the headlight luminance distribution are shown in Table 23 and Fig. 56. The

TABLE 23

LUMINANCE (ft-L) OF UNIFORM BLACK ASPHALT UNDER LOW-BEAM ILLUMINATION FROM 1971 DODGE VAN USED IN ON-THE-ROAD PORTION OF STUDY (NUMBERS IN PARENTHESES ARE LUMINANCE VALUES AT LATERAL DISTANCES INTERMEDIATE TO DISTANCES INDICATED FOR COLUMNS)

(1 ft = 0.3048 m)

DISTANCE FROM FRONT OF VAN, ft	LATERAL DISTANCE, ft									
	LEFT					RIGHT				
	19	15	10	5	0	5	10	15	20	25
300					.00075	.00105				
200	.0010				.0014	.0014				
150	(.0016)	(.002)	(.0021)	(.00245)	(.0051)	(.01145)	(0.262)	(.0152)	(.0029)	
100	.00256	.0028	.0034	.00475	.0086	.0236	.0506	.01744	.0046	.0054
90	.0033	.00317	.00445	.0052	.0104	.0422	.0678	.0234	.00608	.004
80	.0045	.00465	.0063	.0059	.0116	.054	.0908	.0115	.00593	.00365
70	.0053	.0048	.0065	.0093	.0155	.0722	.1033	.0255	.0065	.0045
60	.0037	.0056	.0037	.0025	.018	.093	.110	.015	.06	.0023
50	.004	.007	.013	.015	.036	.131	.123	.0250	.0156	.008
40	.001	.0044	.0156	.030	.066	.162	.119	.039	.022	.0115
30	.00064		.0122	.0328	.0845	.18	.152	.0566	.0241	.0049
20					.0155					

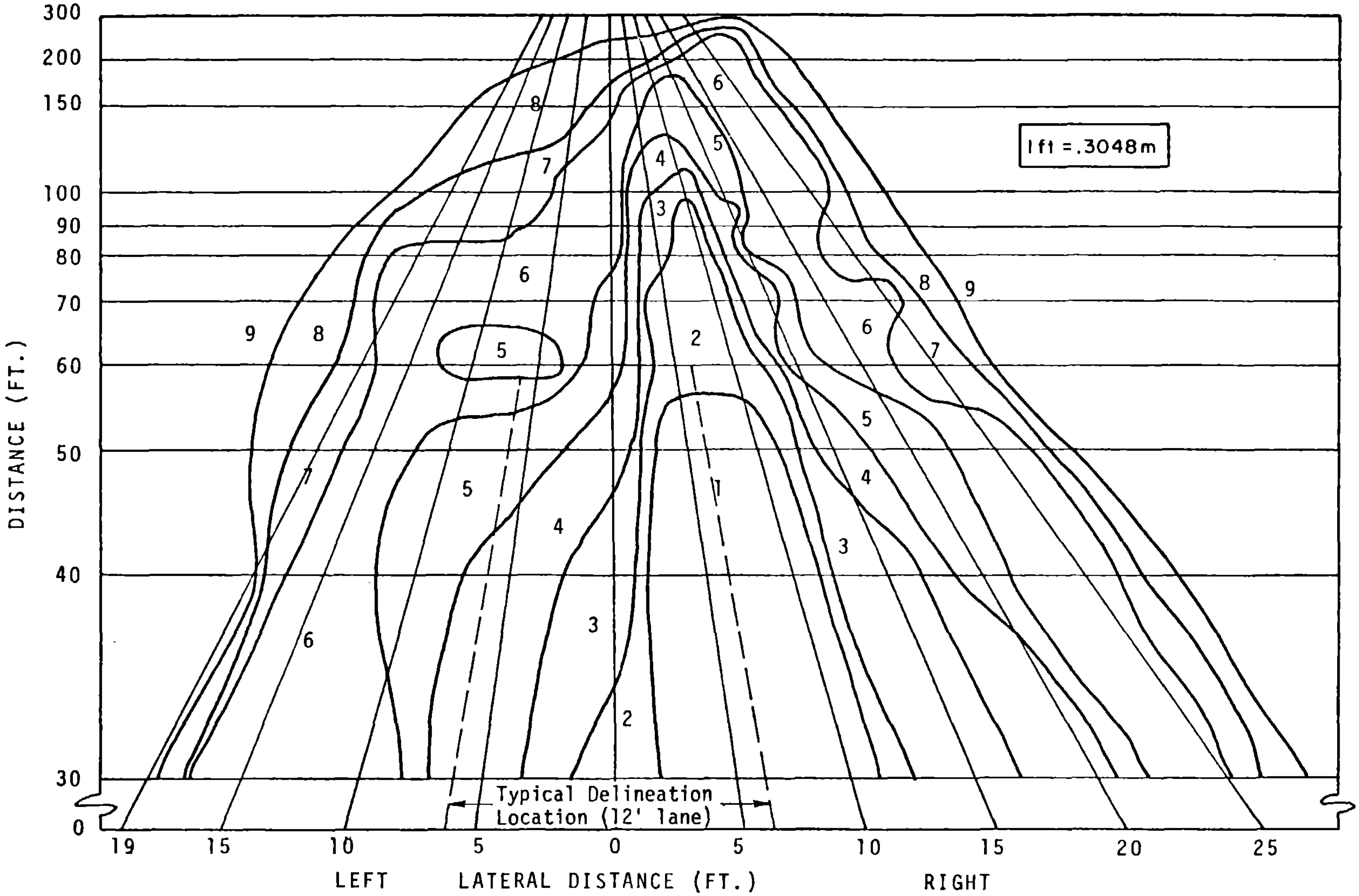

Figure 56. Perspective Drawing of Luminance of Uniform Black Asphalt Under Low-Beam Illumination from the 1971 Dodge Van Used in On-the-Road Portion of Study. Isoluminance contours fitted by hand Each line is difference of 0.2443 log units. Area 1 is luminance of 0.1025 ft-L or greater; Area 9 is luminance less than 0.002 ft-L.

figure is a perspective drawing of the test strip as seen from the driver's eye position in the van, the location of the photometer when the measurements were taken. The drawing was constructed by taking the logarithm of the luminance values multiplied by 1000, log (ft-L × 1000), and divided into 10 bins differing by 0.2443 log units. The isoluminance lines in the figure were plotted by hand. It was not possible to make more than one measurement closer than 30 ft (9.2 m) from the front of the vehicle due to obstruction by the vehicle frame and instrument panel.

In general, it can be seen that the region of highest luminance extends from the center of the van approximately 10 ft (9.2 m) to the right and out to a distance of approximately 50 to 55 ft (15.2-16.8 m). Luminance generally diminishes with distance and eccentricity to the right and left with the region of maximum luminance at all distances biased slightly to the right. These data are reasonably consistent with the pattern of light expected from conventionally mounted and aligned dual headlight systems operating on low beam.

In the main text, nighttime visibility conditions are analyzed in terms of a simple headlight luminance distribution depending only on range down the road (Articles II.C and V.B). This headlight characteristic was obtained as follows. First, luminance values from the asphalt measurements of Table 23 were averaged over the 5 columns between 10 ft left and 10 ft right lateral distance and are illustrated in Fig. 57. These data should give a good average luminance for the headlight pattern in the region the delineation is likely to occur. Second, differences between asphalt and concrete retroreflectivity were taken into account. In general, these include a generally lower retroreflectivity of concrete versus asphalt at lower incidence angles (short ranges) plus a relative increase in retroreflectivity of concrete with increasing incidence angle, i.e., increasing range.[62] These characteristics were combined with an overall general higher reflectivity expected of the older worn concrete surfaces on our field test

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[62]Farber, E., and V. Bhise, "Development of a Headlight Evaluation Model," in Driver Visual Needs in Night Driving, Transportation Research Board, Special Report No. 156, 1975, pp. 23-39.

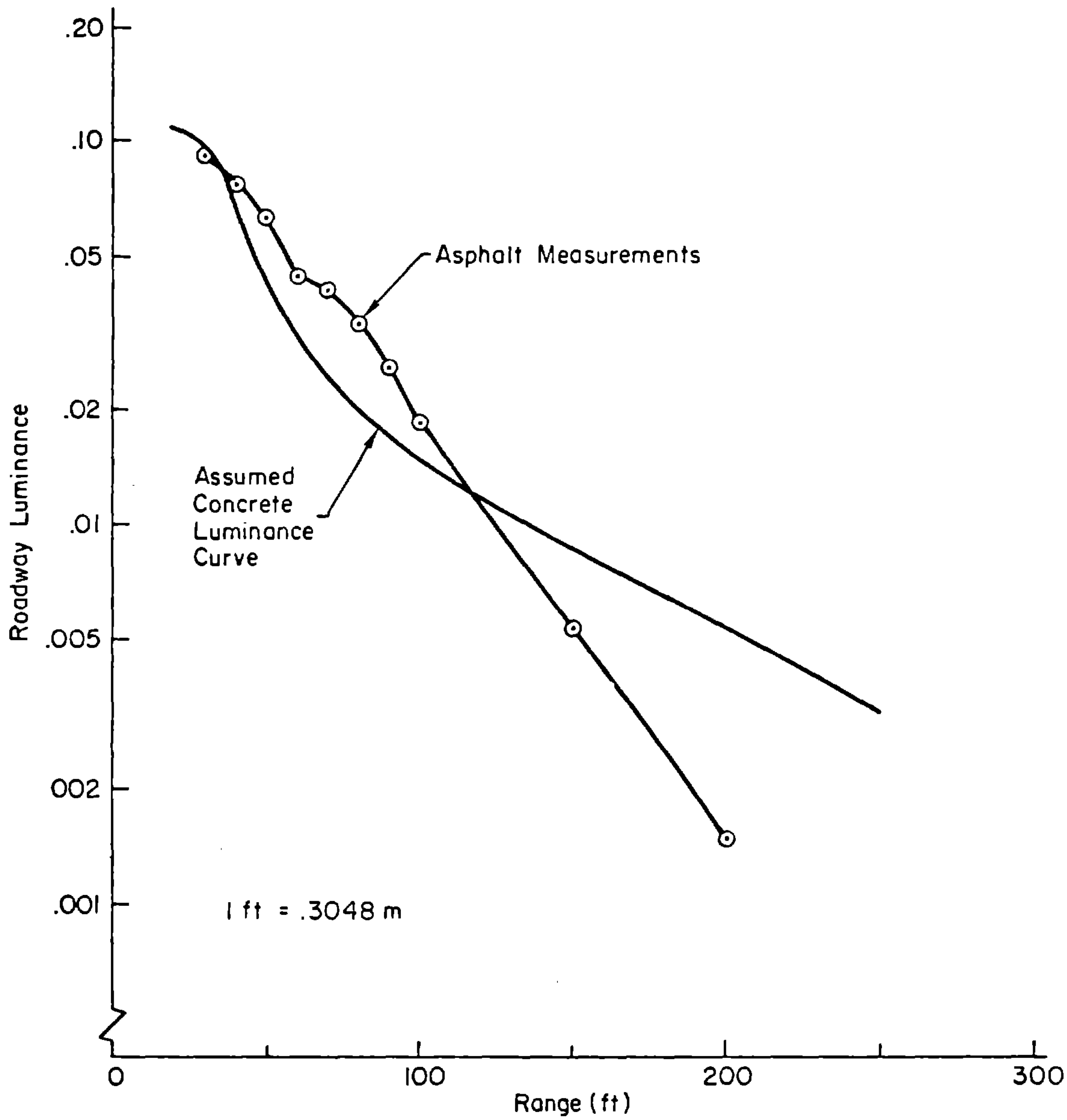

Figure 57. Night Road Luminance at the Driver's Eye Due to Head Lighting Averaged Over Lateral Bands and Plotted as a Function of Range Ahead of the Driver

sites compared to the new black asphalt surface used to measure the luminance headlight pattern of Table 23 and Fig. 56. The resulting assumed roadway luminance as a function of range ahead of the driver is illustrated in Fig. 57. This assumed distribution was found to be comparable with luminance measurements made at the field test sites.

I-80 TEST SITE MEASUREMENTS

It was originally intended to make all highway photometric measurements with the test vehicle positioned in the center of the right lane of the test locations. This would allow determination of the roadway and delineation luminance as actually seen by the drivers participating in the experiment. It was impossible, however, to obtain permission to block the lane at the I-80 test site. Consequently, all photometric measurements were made with the vehicle positioned off the right shoulder of the roadway with the van oriented approximately 10 deg off the direction of travel. Since contrast is defined as the ratio of the difference between object and background luminance divided by background luminance, this measure is not dependent upon absolute luminance levels. Therefore, the location of the van off the roadway with the headlights aimed over the roadway is satisfactory for obtaining relevant luminance levels with which to compute delineation contrast. Unfortunately, since the headlight distribution pattern on the roadway is not representative of the headlight pattern of a vehicle actually traveling on the roadway, meaningful measures of roadway luminance as seen by the driver cannot be presented.

Procedures

All photometric measurements were made at night beginning a minimum of 2 hr after sunset and ending at least 2 hr before sunrise. All measurements were taken with the roadway illuminated only by the headlights of the test vehicle when other vehicles were absent from both directions of travel on the roadway. During the taking of measurements the test vehicle engine was run at least at 1500 rpm to ensure that the headlight intensity was the same for all measurements.

At each measurement site the front of the vehicle was positioned on an imaginary line extending perpendicular to the direction of travel and intersecting the end of a painted segment of the lane line. Figure 58 is a schematic representation of the major features and dimensions of the test roadways and the location of the van in relation to the roadway during photometric measurements. The actual angle of the van in relation to the roadway was not measured, but it was positioned to maximize the amount of light falling on the roadway over a distance of approximately 300 ft.

At each of seven distances ranging from 25 to 300 ft (7.6 to 91.5 m) along the road, seven photometric measures were taken, if possible. These points of measure from right to left were: 1) the shoulder immediately adjacent to the right edge of the roadway; 2) the roadway immediately adjacent to the right shoulder; 3) the roadway immediately to the right of the lane line; 4) the lane line; 5) the roadway immediately adjacent to the left of the lane line; 6) the roadway immediately to the right of the left shoulder; and 7) the left shoulder immediately adjacent to the edge of the road. The circled numbers shown in Fig. 58 indicate the points at each distance along the road at which the photometric measures were taken. To facilitate having accurate distance measurements, the points for measurement along the roadway were chosen to correspond to the middle of successive lane line segments. Since the middle of each lane line segment is a distance of 24 ft (7.3 m), successive points were chosen in intervals of 24 ft or multiples of 24 ft. Also, because the van was appreciably offset from the roadway, the actual straight line distance between the center of the front of the van to the point of measurement, the true distances were calculated using the Pythagorean theorem. Table 24 shows the actual distance from the front of the van to the edges of the traveled way and lane line at each of the seven measurement distances. At each of the eight measurement sites, the center of the front of the van was 6 ft (1.8 m) to the right of the edge of the shoulder. The actual distance from the edge of the shoulder varied within ±1 ft (0.3 m). Since this variation has a negligible effect on the calculation of the true distance to the point of measurement, an average of 6 ft is used to simplify the calculations and presentation of the data.

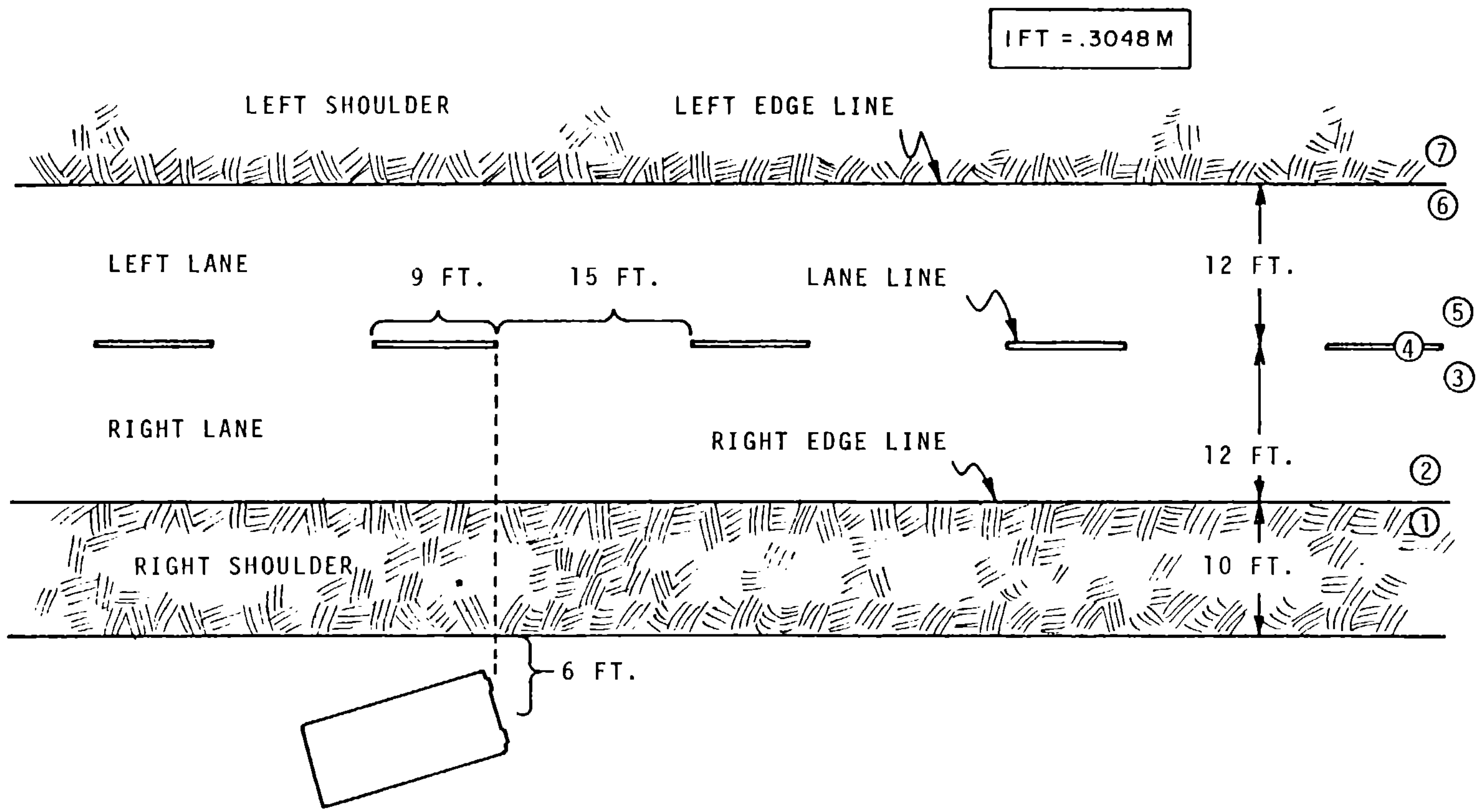

Figure 58. Schematic Representation of Major Features and Dimensions of Roadway and Location of Van in Relation to Roadway During Photometric Measurements. (Circled Numbers indicate location across road at which photometric measurements were made. These measurements were reported at each of seven distances along the roadway at each site.) See text for further explanation.

TABLE 24

TRUE DISTANCE IN FEET BETWEEN POINTS OF PHOTOMETRIC MEASUREMENT AND FRONT OF VAN (CENTER OF HEADLIGHTS LOCATED 6 FEET TO RIGHT OF RIGHT SHOULDER) (1 ft = .3048 m)

SPOT ON ROADWAY	DISTANCE ALONG CENTER OF ROADWAY, ft						
	19.5	43.5	67.5	91.5	139.5	187.5	283.5
Right edge of traveled way	25.2	46.4	69.4	92.9	140.4	188.2	283.9
Lane line	34.1	51.7	73.1	95.7	142.3	189.6	289.9
Left edge of traveled way	44.5	59.1	78.5	99.9	145.1	191.7	286.3

The measurement procedure was the same in all cases. The photometer located at the driver's eye position was checked for calibration prior to each series of measurement of the seven points on the road at each distance. The 6 min aperture of the photometer was used for all measurements with the exception of the most distant, where a 2 min aperture was used. It was necessary to use the smaller aperture since at approximately 300 ft (91.5 m) the 4 in. (10.2 cm) width and projected length of a delineation line, such as a lane line, subtends a visual angle of only slightly greater than 2 min. Use of the larger 6 min aperture at the extreme distances would integrate luminance from the roadway adjacent to the lane line which would tend to give a lower luminance reading than the luminance of the line itself.

At each distance, the seven points on the road previously described were measured consecutively from left to right or right to left. To compensate for possible slight misalignments of the photometer when measuring the lane line, the position of the photometer was adjusted slightly in the horizontal and vertical direction until the maximum luminance value was obtained. The extent of the five horizontal and vertical adjustments never exceeded 2 min of arc. The luminance values were displayed directly on the photometer control unit and recorded on a data sheet. Often the measurement to be made was near the lower sensitivity limit of the photometer. To ensure accuracy of the measurement in these cases, several readings were taken and the luminance of the small area measured was derived by taking the mean of the repeated measurements. During the measurements, the interior of the van was completely darkened to preclude any reflected veiling luminance from the interior of the windshield. Each series of measurements proceeded from the nearest distance to the farthest. In some cases, particularly when the paint was worn, it was impossible for the individuals making the measurements to determine the location of the lane line, and no measurements were made.

Results

All obtained luminance data were converted to contrast data using the familiar formula:

$$\text{Luminance Contrast} = (L_T - L_B)/L_B \qquad (32)$$

which is non-dimensional, where

L_T = Target luminance

L_B = Background luminance

Delineation lines were always taken to be target luminance. For shoulder to roadway contrast, the choice of designating the roadway or shoulder as being the target or background is arbitrary. Since the left roadway was generally brighter than the left shoulder, the roadway was specified as the target; and since the right shoulder was generally brighter than the right roadway, the right shoulder was specified as the target.

Two assumptions are incorporated in the results. The first is that the headlight illuminance on each local area of measurement, i.e., in the vicinity of the delineation lines or shoulder edge, was uniform. This assumption was reasonably satisfied by the headlighting pattern described previously. The second assumption is that the directional reflectance properties of the roadway and the delineation is the same at small angles diagonally across the roadway as it is parallel to the traveled way. That is, since the van was located off the road, the horizontal angle of incidence and reflection was at some angle across the road, depending upon the distance of measurement, rather than parallel to the road.

Three sets of photometric measurements were taken at eight sites on U. S. Highway I-80 in the vicinity of Grass Valley, California. The characteristics and exact location of the eight sites are described elsewhere in this report (Article IV.C). The three sets of measurements designated M1, M2, and M3 in the accompanying tables refer to three periods of measurement. The first set of photometric measurements, M1, was taken on the nights of October 28 and 29, 1975. This was approximately 3 weeks after the test sites had been delineated with a different ratio of glass beads per gallon of paint at each test site by normal Caltrans maintenance personnel and equipment. The actual amount of beading used was shown earlier, in Article IV.C. In general, increasing amounts of beading were used from Test Sites 1 to 4 in both directions. The original intention was that corresponding pairs of test sites for the two directions of travel, e.g., Site 1 westbound and Site 1 eastbound, would have the same proportion of beading per gallon of paint used. Subsequent laboratory analysis of the actual proportion of beading per gallon of paint revealed that only rough equivalence for each corresponding pair of test sites was achieved. The M1 measurements were made at all seven points across the road and at seven distances from the vehicle as described earlier.

The second set of photometric measurements, M2, was made on March 16, 1976, when the painted delineation was badly degraded from winter weather, snow plowing, road salting and sanding, and traffic abrasion. The M2 measurements were principally confined to the lane line and the immediately adjacent roadway. In a few instances measurements of the shoulder and the roadway adjacent to the shoulder were also made. The measurements were made at the same locations of each of the eight test sites that the M1 set of measurements was made.

The third set of photometric measurements, M3, was made on the night of April 24, 1976, approximately 2 weeks after the I-80 test sites had been delineated with the conventional amount of glass beads per gallon of paint (nominally, 6 lb/gal; 0.72 kg/l) used on California highways. The M3 measurements were made only at Test Sites 1 and 4 in the eastbound and westbound directions. Both shoulders, the roadway, and the lane line were measured when possible.

The computed contrast for each set of measurements for each test site and the average of all test sites is given in Tables 25 through 27. In addition, Table 28 shows the mean lane line to roadway contrast, averaged across all distances for each test site.

Detailed interpretation of these photometric results should be approached cautiously since in most instances the contrast was computed for a single measurement of the target and background location. Variations in the texture of the road, the presence of dirt or other foreign objects could easily influence the computed contrast values. Obtaining the photometric measurements was a time-consuming process, so it was not possible to make repeated measures in most instances.

It can be seen in Table 25 that the contrast of the right edge of the roadway to the right shoulder was on the order of one (1.0) or less at all test sites and all distances measured, although the roadway was concrete and the shoulder asphalt.

The contrast of the lane lines to the center of the roadway immediately adjacent to it, given in Table 26 generally increases at all test sites to a distance of about 150 to 200 ft (45.8 to 61.0 m) and declines thereafter. Marked differences in the contrast values for the M1 set of measurements at different sites are apparent. These differences are attributable mainly to the differences in the amount of beading per gallon of paint. The M2 set of measurements, after the paint had been worn, shows a general reduction of contrast to values between 0 and 1.0, and perhaps a slight increase in contrast with distance.

The contrast of the left shoulder to the left edge of the roadway is given in Table 27. No left shoulder measurements were possible at Site 1 due to a homogeneous lane/shoulder asphalt surface. Except for Site 2, the contrast of the left shoulder to the roadway is similar for all sites and quite low, as was the case for the right shoulder.

TABLE 25

CONTRAST VALUES FOR THE RIGHT SHOULDER AND ROADWAY FOR THREE SETS OF MEASUREMENTS AT SEVEN DISTANCES ON THE EIGHT I-80 TEST SITES

		DISTANCE (FEET)																				
	ALONG LANE LINE	19.5			43.5			67.5			96.5			139.5			187.5			283.5		
	FROM VAN	25.22			46.35			69.37			92.89			140.41			188.18			283.95		
	SITES	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
EASTBOUND	1	-.174	---	4.333	-.117	.043	.036	-.088	---	.042	-.234	---	-.122	-.191	---	-.143	-.048	---	0.000	---	---	-.167
	2	.327	---	---	.319	---	---	1.778	---	---	.825	---	---	.600	.059	---	.500	---	---	.200	---	---
	3	.270	---	---	.348	---	---	.728	---	---	.822	---	---	1.467	---	---	2.514	---	---	---	---	---
	4	.797	---	.137	1.232	---	.415	1.664	---	.500	2.846	---	.417	4.593	---	.250	3.688	---	.444	---	---	1.333
WESTBOUND	1	.737	---	-.164	1.396	---	-.351	.600	---	-.127	1.244	-.469	-.104	.152	---	-.103	.462	---	-.176	---	---	-.125
	2	.374	---	---	1.169	---	---	.558	---	---	.475	---	---	-.051	---	---	.200	---	---	---	---	---
	3	.940	---	---	.571	---	---	.214	---	---	.301	.463	---	.030	---	---	.034	---	---	.133	---	---
	4	.193	---	.067	.081	---	.369	.345	---	.103	.270	.543	.692	.667	---	.750	.714	---	1.000	---	---	-.400
	MEAN OF SITES	.423	---	1.093	.625	.043	.117	.725	---	.130	.819	.179	.221	.908	.059	.188	1.008	---	.423	.167	---	.160

Contrast = $(L_T - L_B)/L_B$; where L_T = right shoulder and L_B = far right roadway.

1 ft = 0.3048 m

TABLE 26

CONTRAST VALUES FOR THE LANE LINE AND ROADWAY FOR THREE SETS OF MEASUREMENTS AT SEVEN DISTANCES ON THE EIGHT I-80 TEST SITES

	ALONG LANE LINE FROM VAN	DISTANCE (FEET) 19.5 / 34.12			43.5 / 51.73			67.5 / 73.08			91.5 / 95.69			139.5 / 142.28			187.5 / 189.58			283.5 / 284.85		
	SITES	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
EASTBOUND	1	2.872	1.000	1.000	3.104	1.520	1.345	3.351	---	1.484	5.316	1.186	1.522	4.111	1.723	2.129	3.455	---	2.000	4.000	---	2.040
	2	2.494	2.905	---	4.157	1.936	---	3.847	2.242	---	5.076	2.711	---	4.678	2.155	---	3.221	---	---	3.667	---	---
	3	5.429	.765	---	11.116	2.900	---	10.200	2.207	---	11.173	2.194	---	15.867	2.634	---	12.469	---	---	---	---	---
	4	12.487	.100	4.300	15.456	.333	6.708	19.340	.333	7.000	17.110	.450	7.186	10.600	.289	14.111	12.766	---	9.864	---	---	9.889
WESTBOUND	1	1.162	.212	5.095	3.213	.489	7.579	5.337	.242	7.412	5.967	.573	9.690	5.064	.722	11.370	5.667	---	10.333	---	---	7.330
	2	5.859	.440	---	6.872	.897	---	3.492	.727	---	6.073	1.017	---	7.873	.644	---	4.574	---	---	---	---	---
	3	2.065	.535	---	7.608	1.867	---	9.280	1.949	---	9.537	1.820	---	14.184	1.788	---	15.790	1.926	---	16.241	---	---
	4	3.080	1.174	2.628	8.556	2.174	3.099	13.175	2.224	3.447	10.228	1.882	3.476	17.947	3.493	4.081	9.957	---	4.103	---	---	1.571
	MEAN OF SITES	4.431	.891	3.256	7.510	1.515	4.683	8.503	1.418	4.836	8.810	1.479	5.468	10.041	1.681	7.923	8.487	1.926	6.575	7.969	0.000	5.208

Contrast = $(L_T - L_B)/L_B$; where L_T = lane line and L_B = roadway center

1 ft = 0.3048 m

TABLE 27

CONTRAST VALUES FOR THE ROADWAY AND LEFT SHOULDER
FOR THREE SETS OF MEASUREMENTS AT SEVEN DISTANCES
ON THE EIGHT I-80 TEST SITES

	DISTANCE (FEET)																					
	ALONG LANE LINE	19.5			43.5			67.5			91.5			139.5			187.5			283.5		
	FROM VAN	44.50			59.10			78.46			99.86			145.12			191.72			286.31		
	SITES	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
EASTBOUND	1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	2	1.308	---	---	4.870	---	---	9.556	---	---	3.242	---	---	1.500	---	---	5.667	---	---	3.222	---	---
	3	.100	---	---	1.211	---	---	.250	---	---	0.000	---	---	.200	---	---	.053	---	---	---	---	---
	4	1.667	---	.333	.865	---	1.250	-.032	---	---	.344	---	-.154	-.091	---	-.357	-.189	---	-.091	---	---	-.231
WESTBOUND	1	.120	---	-.200	.400	---	1.000	.117	---	0.000	.222	---	.143	-.062	---	0.000	.142	---	0.000	---	---	.250
	2	-.055	---	---	.271	---	---	-.117	---	---	-.018	-.226	---	-.359	---	---	.032	---	---	---	---	---
	3	.739	---	---	.529	---	---	.320	---	---	.200	-.091	---	.189	---	---	.923	---	---	.135	---	---
	4	---	---	.200	---	---	.143	---	---	.176	---	---	0.000	---	---	.100	---	---	.238	---	---	-.563
	MEAN OF SITES	.646	---	.111	1.358	---	.798	1.682	---	.086	.798	-.158	.005	.229	---	-.129	1.104	---	.074	1.679	---	-.181

Contrast = $(L_T - L_B)/L_B$; where L_T = far left roadway and L_B = left shoulder   1 ft = 0.3048 m

TABLE 28

MEAN, STANDARD DEVIATION (SD), AND NUMBER OF OBSERVATIONS (N) FOR I-80 LANE LINE CONTRAST MEASUREMENTS FOR EIGHT SITES. MEANS ARE AVERAGE CONTRAST OVER ALL DISTANCES MEASURED.

		HIGHWAY MEASUREMENT SITE							
		EASTBOUND				WESTBOUND			
		1	2	3	4	1	2	3	4
	MEAN	3.7	3.9	11.0	14.6	4.4	5.8	10.7	10.5
M1	SD	.82	.87	3.39	3.27	1.86	1.57	5.10	4.93
	N	7	7	6	6	6	6	7	6
	MEAN	.9	2.4	2.1	.3	.4	.7	1.6	2.2
M2	SD	.65	.40	.82	.13	.22	.22	.55	.84
	N	4	5	5	5	5	5	6	5
	MEAN	1.6	--	--	8.4	8.4	--	--	3.2
M3	SD	.42	--	--	3.16	2.16	--	--	.89
	N	7	--	--	7	7	--	--	7

M1 = Measurements for variable glass beading (lbs/gal) of paint for lane line.

M2 = Measurements for deteriorated lane line.

M3 = Measurements for repainted lane line with standard glass beading (lbs/gal).

The results of the M1 and M3 measurements seem to contradict common experience because these show increasing contrast with distance. Recall, however, that the contrast computations are independent of absolute luminance. Since the contrast sensitivity of the eye is highly dependent on luminance, which decreases rapidly with distance from the vehicle, it appears to an observer that the contrast is decreasing. The reason for the photometric increase in contrast with distance is apparently due to the differential retroreflectance properties of the glass beading and/or paint; a relatively greater proportion of headlight light is reflected from delineation as the angle of incidence increases with increasing distance.

In Article IV.F field test results are compared with measured delineation contrasts. Average contrast over a number of observations for each test site and measurement period are given in Table 27.

GENERAL COMMENT ON THE MEASUREMENT OF DELINEATION CONTRAST

The relatively small amount of contrast data obtained during this study was achieved at a relatively high cost in equipment and labor. This methodology would not be practical or economical for a highway engineer wishing to measure the contrast of the painted delineation on a highway for determining whether it must be repainted. Ideally, the highway engineer should have a vehicle-mounted sensor which can simultaneously measure the luminance properties of delineation and roadway integrated over some distance. For simplicity and low cost it would be desirable to use a solid-state sensor or sensor array looking down on the roadway and delineation. Some possibilities are discussed in Article V.D.

There are two problems which must be kept in mind in taking this approach. First, the primary measure of interest is the contrast of the delineation as it would appear to the driver. Therefore, the incident angle of the illumination source and viewing angle of the sensor must be similar to that of the driver/headlight system (i.e., equivalent to 80 to 89 deg). The specific angle should approximate typical driver viewing points down the road on the order of 100 ft (30.5 m).

A second problem has to do with the spectral characteristics of the typical, inexpensive sensor and the spectral reflectance properties of the roadway and delineation materials. A photometer, by its very name, implies that it measures radiance in a manner which corrects for the known spectral sensitivity function of the human eye. Photometers are expensive primarily due to the necessity for implementing these rather exact spectral corrections. The typical solid-state photosensor is maximally sensitive to wave lengths around 900 mm, having a rapid falloff in sensitivity for longer and shorter wave lengths. The use of one of these devices as a contrast measurement device presumes the ability to translate roadway and delineation material reflectance, within a restricted range of wave lengths, to the wave lengths within the visible spectrum. The spectral characteristics of new and aged highway and delineation materials have not been systematically cataloged, so care must be taken in choosing and/or adapting the sensor for an inexpensive field test unit.

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