Effects of Roadway Delineation and Visibility Conditions on Driver Steering Performance

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Visual input provides drivers with the primary cues for vehicle steering control. An empirically based model for analyzing the effects of the visibility of roadway delineation on driver steering performance in terms of lateral lane deviations and probability of lane exceedance is described. The model is based on experimental data collected in both an interactive driving simulator and an instrumented vehicle on the open highway.

Drivers receive their primary cues for vehicle steering control visually. A variety of elements, including road boundaries and roadside obstacles, can serve to indicate the desired path. Early programs (1) demonstrated the value of roadway markings, or delineation, for providing positive guidance to the driver, and delineation is now universally applied and accepted. The effectiveness of delineation is determined by its visibility, which in turn is determined by the physical characteristics of the markings, lighting factors, and atmospheric conditions. New delineation under daylight conditions can be optimal, whereas worn delineation under night and/or fog conditions might be marginal or inadequate.

A basic theory for the use of delineation that takes into account physical conditions and driver psychophysical and perceptual motor properties has been presented (2). This work was based on driver steering and speed-control performance measured in an interactive driving simulator. More recently, the effects of delineation visibility on the steering-control behavior of drivers (using control theory models) have been presented (3).

In this paper, simulator experiments in the use of delineation are compared with related experiments conducted in an instrumented vehicle on the open highway. The comparison is made by using a model of delineation visibility, which is analyzed to demonstrate the effects of various factors on the use of roadway delineation, such as road-marking contrast and configuration (mark and gap sizes), atmospheric conditions, and headlighting characteristics.

EXPERIMENTS IN DRIVER STEERING PERFORMANCE

Simulator

A fixed-base but otherwise fully interactive driving simulator was used to test drivers under a wide variety of visibility and delineation-configuration conditions. The simulator had a high-quality, wide-angle video projection display of roadway markings. Display perspective and motion were correctly represented with respect to driver eye position, and the electronic display generator was designed to control delineation and visibility. 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. The simulator is described in detail elsewhere (4).

The simulator tests involved a range of visibility dis-

tances, delineation configurations, and driving speeds. Desired visibility distances for each run were adjusted according to the driver's subjective impression of the point at which the displayed delineation disappeared. This procedure controlled for variations in the equipment and differences in the visual characteristics of the subjects. Lane deviations measured on a simulated winding road were used in the analysis described here.

Field Test

Open-highway tests were conducted in a specially instrumented van that included an electro-optical device for measuring lateral lane position relative to the delineation of the left edge (5, Appendix C). Tests were conducted at night over a winding 64-km (40-mile) section of I-80 in the Sierra Nevada mountains. The primary tests were conducted under two conditions: (a) after the highway delineation markings were freshly painted in 16-km (10-mile) segments (a different glass-bead-to-paint ratio was used for each segment to obtain variations in delineation brightness) and (b) after the spring thaw and prior to repainting, when snowplows and tire chains had severely degraded the delineation. Lane-position data were tape recorded as the subjects drove both directions over the highway circuit, and these data were then reduced on a digital computer to give the standard deviation of lateral lane position.

The delineation contrast was determined from photometer measurements made under night headlight conditions from the driver's eye position in the instrumented vehicle. In this paper, contrast is defined as the differential luminance between delineation (L_D) and roadway background (L_B) divided by background luminance [$C = (L_D - L_B)/L_B$]. This reproduced the exact photometric conditions observed by the driver subjects. Photometer measurements were obtained at several points in each highway segment.

COMPARISON BETWEEN SIMULATOR RESULTS AND FIELD TEST

The results of the simulation led to an empirical relation among lateral lane deviation, speed, and delineation visibility and configuration (2). Ignoring speed effects, this relation can be expressed as

$$y = b_1 + a_2 C_v \tag{1}$$

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 previously defined (2). C_v can be partitioned into configuration (e.g., dash and gap length) and visibility components, as follows:

$$C_v = b_2/x_v \tag{2}$$

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; in the field study, measured delineation contrast quantified the experimental treatment. Thus, to compare these data sets, visual range must be expressed as a function of delineation contrast, as described below.

The visibility of a given target is defined by its size and contrast. Well-known data of Blackwell and Taylor (6) give the contrast required (i.e., the threshold) for a target to be detectable. These thresholds are functions of target size, background luminance, and target contrast. If the apparent size of delineation marks as a function of distance down the road is combined with Blackwell threshold contrast characteristics, then the dependence of contrast threshold on visual range can be roughly approximated by a straight-line relation (5), as follows:

$$\log C_T = \log C_{T_0} + c_1 x_v \qquad (3)$$

where the parameter c_1 is determined by target size and background luminance and the parameter C_{T_0} defines the vertical location or zero-distance intercept of the threshold characteristics and thus includes the effects of multiplying field factors applied to the Blackwell data on contrast threshold.

We can now combine Equations 1, 2, and 3 to obtain an analytical relation between threshold contrast and performance:

$$y = b_1 + \{a_2 b_2 c_1 / [\log (C_T + C') - \log C_{T_0}]\} \qquad (4)$$

where the residual contrast C' has been added to account for other road cues that would provide some guidance in the absence of delineation.
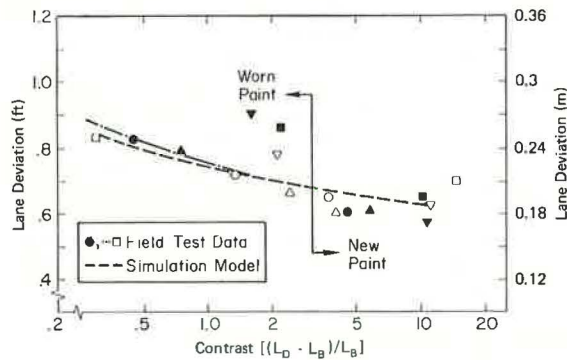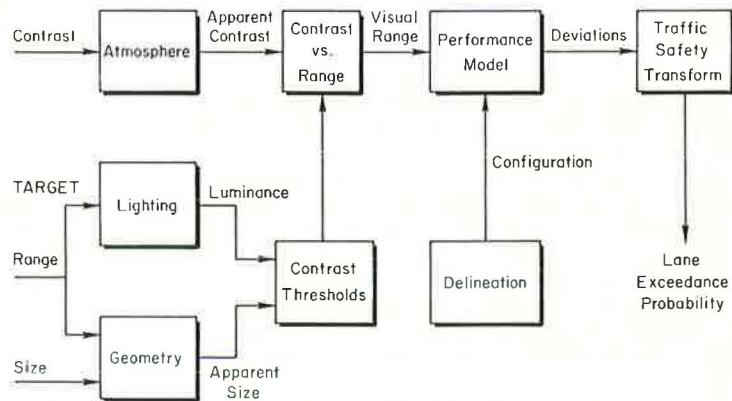
Figure 1 shows field-test data on lane deviation, averaged for six subjects, as a function of delineation contrast measured on a clear night under headlights. The measurements for contrast values higher than 3 were obtained under new-paint conditions, and the data at contrasts below 3 were obtained under worn-paint conditions. The different symbols in Figure 1 for field data correspond to different sections of the experimental highway circuit, and some of the variability in the data can be explained by variations in curvature among the sections. Even so, there is a clear trend in Figure 1 between driver performance in keeping to the lane and measured delineation contrast.

The prediction of the simulator performance model is also shown in Figure 1. It can be seen that the model response as a function of contrast is in fairly good agreement with the field data. As a result of accounting for the absence of an edge line, the current model predictions plotted in Figure 1 are different from and much better than previously published results (5).
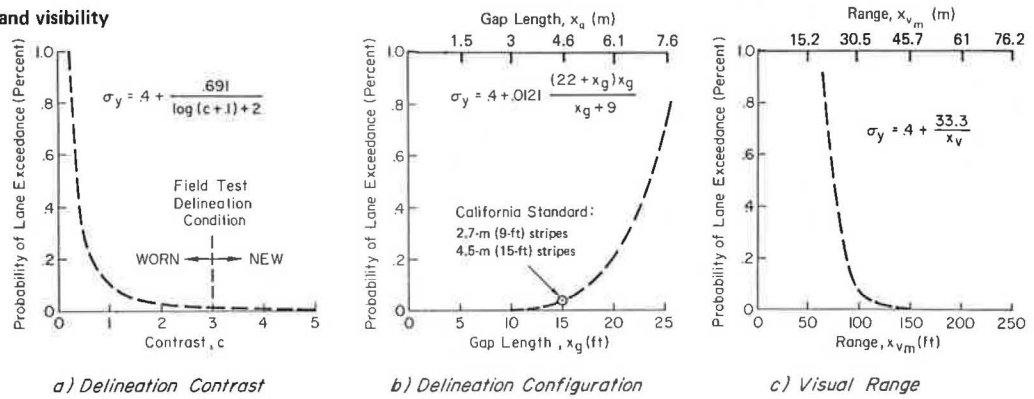
PERFORMANCE MODEL SUMMARY

A summary of the model of delineation visibility and driver performance developed in this paper is shown in Figure 2 in the form of a block diagram. The basic model of driver steering performance is given by Equation 4. This relation was derived from the simulation tests and validated in open-highway field trials. Steering performance, as given by Equation 4, is basically a function of delineation configuration and driver contrast threshold at a given visual range.

The visual range of delineation targets is a function of the characteristics of the driver's visual contrast threshold and the apparent contrast of the target. Apparent target contrast decreases with range, and visual contrast threshold increases with range; the point at which target contrast becomes less than the driver's visual threshold then defines the driver's maximum visual range.

Apparent target contrast can be affected by atmospheric conditions and light-source characteristics. Under adverse climatic conditions such as fog, snow, dust, and rain, light is scattered as it passes through the atmosphere to the driver's eye. Under daylight conditions, contrast decreases with range and particle density according to the simple Koschmieder law (7). Under nighttime conditions, apparent contrast drops off even more rapidly because of headlight scattering, which attenuates the light reaching and returning from the target, and also because of the veiling luminance created by backscattered light.

Visual contrast thresholds are a function of background luminance and apparent target size. Apparent

Figure 1. Comparison of field-test data and simulation performance model.

Figure 2. Block diagram of steering-performance model.

Figure 3. Analysis of delineation and visibility effects by steering-performance model.

$$\sigma_y = .4 + \frac{.691}{\log(c+1)+2}$$

Field Test Delineation Condition

WORN ⟵ | ⟶ NEW

a) Delineation Contrast

$$\sigma_y = .4 + .0121\,\frac{(22+x_g)x_g}{x_g+9}$$

California Standard:
2.7-m (9-ft) stripes
4.5-m (15-ft) stripes

b) Delineation Configuration

$$\sigma_y = .4 + \frac{33.3}{x_v}$$

c) Visual Range

target size and background luminance can be specified as a function of range, which then allows contrast thresholds to be specified as a function of visual range (Equation 3).

Lateral lane deviations provide a useful measure of intermediate performance, but it is desirable to obtain a measure that is as closely related to traffic safety as possible. Small lane deviations are of little consequence, but as lane deviations increase, the probability of interference with other traffic increases. A useful measure for quantifying this effect is the probability of exceeding the lane boundaries. If we assume that lane deviations are Gaussianly distributed, then a useful standard approximation for the area of the tails of Gaussian distribution is given by

$$P(y > w) = \sqrt{2/\pi} \cdot (\sigma_y/w) \exp(-w^2/2\sigma_y^2) \qquad (5)$$

where $2w$ is the difference between lane width and vehicle width and σ_y is the standard deviation of lateral lane deviations.

We now have three measures by which to evaluate delineation utilization: As Figure 2 shows, the first is maximum visual range; the second is steering performance σ_y, which takes into account delineation-configuration factors that might be considered a measure of delineation "quality"; finally, the probability of lane-edge exceedances is used as a traffic safety measure, which tends to weight large lane deviations more heavily than small values.

MODEL APPLICATION

Delineation Contrast

By using Equation 5, the probability of lane exceedance can be computed as a function of delineation contrast, as shown in Figure 3a. The figure shows a knee in the curve in the 1-2 contrast range. Although the probabilities in this region are small (approximately 0.004-0.01 percent), the simulator study showed that drivers attempt to keep lane deviations below 0.3 m (1 ft) (2), and the field-test lane deviations in the 1-2 contrast region were approximately 21-27 cm (0.7-0.9 ft). The knee of the curve in Figure 3a is also consistent with the demarcation point between the fresh-paint and worn-paint conditions in the field study (Figure 2).

Delineation Configuration

Let us now consider the effect on steering performance of the length of gaps between delineation marks. Equation 4 was evaluated for single-sided delineation with 2.7-m (9-ft) long marks and an apparent low contrast

value (0.5) that might be typical of worn paint and some atmospheric scattering. The probability of lane exceedance is shown in Figure 3b for the range of gap values. Note that, as the length of gaps between delineation marks extends beyond the standard length of gaps in California, the probability of lane exceedance increases dramatically.

Visual Range

Among the conditions that might affect visual range are atmospheric scattering (e.g., fog) and headlight pattern. A combination of conditions determine visual range; here we consider the basic effect of variations of visual range. The probability of lane exceedance is plotted as a function of visibility range in Figure 3c for one-sided delineation that consists of 2.7-m (9-ft) long marks and 4.5-m (15-ft) gaps. Here we see performance deteriorating to a visual range of less than 45 m (150 ft) and deteriorating rapidly below 30.0 m (100 ft). This result may have implications for the design of headlight beam patterns.

CONCLUSIONS

The effects of delineation visibility on driver performance have been reviewed in two experimental situations: a driving simulation and open-highway vehicle tests. The results have shown reasonable consistency when related through a visibility model that includes characteristics of visual contrast threshold.

The results and the model would be useful in various analysis applications. Driver performance or probability of lane exceedance can be used as a figure of merit in comparing delineation treatments and headlight patterns. The model can also be incorporated in cost-benefit analyses by using probability of lane exceedance as an indication of potential accident rate.

Further development of the model might be useful. Computerization would make it possible to include contrast-threshold and background-luminance distributions more precisely. Other delineators, such as retroreflectors, might also be accounted for. Finally, some of the previously identified dynamic aspects of delineation perception as a function of vehicle speed (3) might be included.

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Use of Child-Passenger Safety Devices in Tennessee

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The combined impact of a Tennessee law on child-passenger safety and a promotional campaign for child-restraint devices on the rates of use of such devices is evaluated, and characteristics of users and nonusers are compared. A basic statewide public information and education (PI&E) program called for distribution of brochures and posters through such facilities as pediatricians' offices and hospitals. The comprehensive PI&E program consisted of an extensive mass-media campaign in addition to the basic program. Six target areas, including the five major metropolitan areas of the state, were chosen for the evaluation. The major findings are that the combination of the law and the basic PI&E program is effective in increasing the rates at which child-restraint devices are used, and the comprehensive program ensures an even higher rate of use. Cross tabulations of such use with other variables reveal that use of child-restraint devices is associated with (a) the age of the child, (b) all socioeconomic variables such as family income and education level, (c) other demographic and vehicle data, and (d) the wearing of safety belts. A market segmentation strategy for future PI&E programs is proposed.

Mandatory passenger-safety requirements have an uneven record in terms of public acceptance. For example, safety-belt interlock systems were rescinded by law after the public outcry against them, and, although the presence of safety belts has been accepted, their use has not. Recent legislation on child-passenger protection in Tennessee has created an opportunity to study the public reaction to a more limited passenger-safety law designed to protect children under four years of age.

After an extensive promotion campaign led by pediatrician Robert Sanders (1), the legislation was passed in 1977 and became effective on January 1, 1978, the first such state law in the nation. It requires in part that

Every parent or legal guardian of a child under the age of four (4) years residing in this state shall be responsible, when transporting his child in a motor vehicle owned by that parent or guardian operated on the roadways, streets, or highways of this state, for providing for the protection of his child and properly using a child passenger restraint system meeting federal motor vehicle safety standards or assuring that such child is held in the arms of an older person riding as a passenger in the motor vehicle.

Since mere passage of the law does not ensure a reduction in the number of traffic deaths and injuries to Tennessee children, the National Highway Traffic Safety Administration (NHTSA) and the Tennessee Governor's Highway Safety Program jointly established the Child Passenger Safety Program in Tennessee. The purpose of this program is to publicize the law, educate the people of the state about the importance of child-restraint devices, and evaluate the effectiveness of these efforts. The project was implemented 3 months before the law went into effect so that baseline data on the use of child-restraint devices (CRDs) could be collected and public information and education (PI&E) programs could be designed and developed. The project began on October 1, 1977, and will continue for a 36-month period.

This paper is restricted to describing a portion of the results from the first nine months of the Child Passenger Safety Program; this comprises the three-month baseline period and the first six months of the PI&E program that began with the inception of the law. The descriptions of the sampling plan and the PI&E program have been limited to what is germane to the reported results. The purposes of this paper are to

1. Review the literature on the effectiveness and use of CRDs and on the efficacy of past PI&E programs,
2. Describe the characteristics of CRD user and nonuser groups,
3. Evaluate the effectiveness of PI&E programs in conjunction with the law, and
4. Suggest marketing strategies to improve the impact of PI&E on the rate of CRD use.

REVIEW OF LITERATURE

According to National Safety Council reports (2), children four years old and under sustained 1600 motor-vehicle-related deaths and injuries in 1976. Furthermore, the reports indicate that automobile accidents are the leading cause of death among children over one year of age. In Tennessee, 18 children under the age of five lost their