

Effect of Alternative Reduced Lighting Techniques on Hazard Detection

MICHAEL S. JANOFF AND LOREN K. STAPLIN

In this paper, the design and conduct of a controlled field experiment to measure the effect of five alternative reduced lighting techniques on individual driver detection of a simulated hazard on the road surface of an urban freeway are discussed. The results of this experiment demonstrate significant decrements in drivers' ability to detect a 6-in.-high, semi-hemispherical, 18 percent reflective gray target under normal freeway traffic conditions as alternative reduced lighting tactics are implemented. In relation to a roadway fully lit by 200-W high-pressure sodium lamps at 68 to 88 ft, staggered spacings, and 30-ft mounting heights, test subjects could detect the simulated hazard only as the distance to the target was progressively shortened for the following conditions: uniformly dimmed at 75 percent power, uniformly dimmed at 50 percent power, every other luminaire extinguished, one side of roadway extinguished, and no lighting. Further, subjective ratings of target visibility under these test conditions were in general agreement with the detection response data. Pavement luminance and horizontal illumination were both strongly associated with the pattern of results in the controlled experiment, whereas calculated visibility index (V.I.) values showed a slightly diminished but still strong association with the behavioral data.

With the renewed interest in energy conservation by highway and lighting agencies and the availability of modern, solid state dimming circuitry for HID lamps, the potential exists for reducing the levels of freeway lighting during periods of low traffic volumes to yield considerable savings in energy use. However, before such lighting techniques can be implemented, it is necessary to quantify their effects on traffic operations and safety.

Previous work has described the potential costs, energy reduction benefits, and legal implications of such lighting techniques (1) and has provided a conceptual framework for an analytical evaluation of reduced lighting (2). The present paper extends the later work by quantifying the effects of five different light reduction techniques on driver hazard detection performance.

The specific objective in this paper is to describe the effect of alternative reduced lighting techniques on driver performance during periods of low traffic density on freeways. To meet this objective, a controlled experiment to measure the effect of each reduced lighting technique on individual driver detection of a simulated hazard on the roadway of an urban freeway was designed and conducted.

The research described in this paper was part of a study conducted by Ketrion Inc. for the FHWA to determine if fixed

roadway lighting on freeways can be reduced or eliminated during nighttime periods when traffic volume is much lower than design capacity, without causing significant reductions in the ability of drivers to control their vehicles in a safe and effective manner.

The remainder of this paper discusses the methodologies and results of the controlled field experiment.

CONTROLLED FIELD EXPERIMENT

In this section, the following topics are discussed: (a) site selection, (b) independent variables (lighting conditions), (c) dependent measures, (d) target characteristics, (e) lighting control, (f) sample characteristics, and (g) experimental design.

Site Selection

A 6-mi portion of I-95 in Philadelphia and Bucks County, Pennsylvania, was used for all data collection efforts. This section is primarily an urban and suburban freeway that is fully lit in Philadelphia for 5 mi but unlit for 1 mi in Bucks County. The lighting system consists of 200-W HPS lamps mounted 30 ft high at spacings of between 68 and 88 ft in a staggered arrangement. The roadway typically has three but sometimes four lanes in each direction. Figure 1 shows the freeway.

This road was selected because it had a complete, relatively modern lighting system that was group controllable, as well as a contiguous section that was unlit; also it was in an area both convenient to the research team and under the jurisdiction of a very cooperative lighting agency.

Independent Variables (Test Conditions)

The lighting conditions selected for study included the following:

- Full lighting (full),
- One (opposite) side extinguished (one side),
- Every other luminaire extinguished (every other),
- Uniform dimming, 75 percent power/50 percent light,
- Uniform dimming, 50 percent power/30 percent light, and
- No lighting.

These conditions were selected on the basis of previous research (1) and covered a wide range of light reduction techniques.

Illuminance, luminance, contrast, and visibility were measured under each of the five lighting conditions, excluding no lighting. The measures are presented in Table 1.

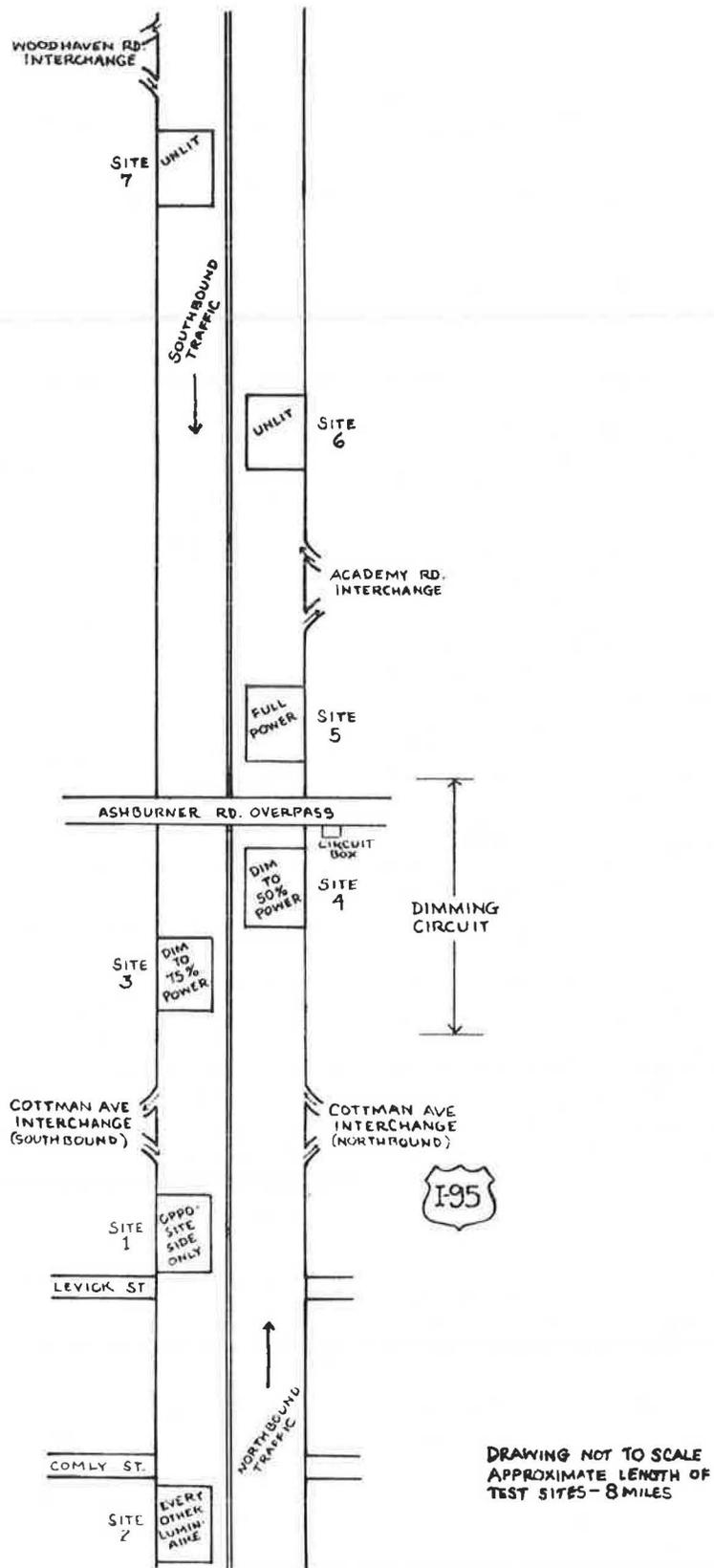


FIGURE 1 Highway section containing test sites for controlled field experiment.

TABLE 1 SUMMARY OF PHOTOMETRIC MEASUREMENTS

PHOTOMETRIC MEASURE	LIGHTING CONDITION					
	All On	75% Power(1)	50% Power(2)	Every Other	One Side(3)	No Lighting
Horizontal Illumination- E_h (fc)	1.15	0.58	0.35	0.58	0.04	0.01
Uniformity (E_h /min)	4.50	4.14	4.19	14.50	-	-
Average Pavement Luminance- L_b (fL)	0.58	0.29	0.15	0.27	0.049	0.016
Object Luminance L_t (fL), 18% reflectant gray	0.23	0.17	0.12	0.18	0.10	0.03
Veiling Luminance L_v (fL)	0.39	0.19	0.07	0.25	0.14	0.01
Contrast ($L_t - L_b$)/ L_b	-0.60	-0.41	-0.20	-0.33	1.04	0.88
Visibility Index V.I. = $C \times RCS_L \times DGF^*$ b	8.78	4.43	1.66	2.93	2.82	1.57

(1) Approximately 50% light, relative to full condition.

(2) Approximately 30% light, relative to full condition.

(3) Values shown are for opposite (unlit) side; lit side same as All On.

$$* DGF = \frac{L_b \times RCS_{L_{b'}}}{L_{b'} \times RCS_{L_b}}, \text{ where } L_{b'} = \frac{L_b + L_v}{1.074}$$

Dependent Measures

The principal dependent measure selected was the distance to target at which an individual driver could first detect a simulated hazard in the roadway ahead of his vehicle. This same measure has been successfully used in past lighting and visibility research to quantify the effect of visibility on a similar form of driver performance (3).

It was hypothesized that as the lighting was reduced, the distance at which the driver detected this simulated hazard would change and this change would serve as a surrogate measure of the relative change in safety under the various reduced lighting conditions.

Additional dependent measures include brief subjective ratings of target visibility and responses to a postexperimental questionnaire, as discussed subsequently.

Target Characteristics

The target selected as a simulated hazard was a 6-in. hemisphere with a 6-in.-diameter skirt, shown in Figure 2, and used

by the same researchers in previous visibility and lighting studies (4).

The target was fabricated out of styrofoam with a latex cover to prevent it from causing damage if struck by a vehicle. The size of 6 in. was selected to agree with the object height used in the AASHTO computation of safe stopping distance. The target was painted a flat, 18 percent reflectant gray color.

The target was placed in the shoulder lane of the roadway at two locations for each lighted condition: the points of maximum and minimum horizontal illumination. For both the no-lighting and the one-sided conditions, there was negligible longitudinal variability in horizontal illumination, so only one target position was employed in these conditions.

Lighting Control

The every other, one-side, no-lighting, and full-lighting test sections, shown on Figure 1, were fixed during the entire data collection period. Full and no lighting required no changes in the lighting circuit, whereas the other two conditions were derived by removing fuses from the appropriate electrical circuits.

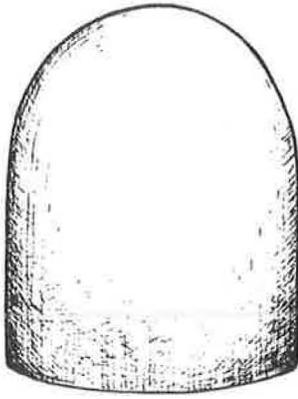


FIGURE 2 Three-dimensional target.

The two dimmed conditions were obtained on the same section of roadway (see Figure 1). This was accomplished by installing a specially designed dimming circuit in the electrical control box and changing the settings on this circuit to obtain either 50 or 75 percent power.

Sample Characteristics

Based on a desire to (a) measure changes in detection distance as small as 40 ft (0.5 sec at 55 mph) with a variance of no more than 80 ft; (b) maintain an alpha level of 0.05; and (c) maintain a value of 0.90 as the power of the statistical test, a sample size of 24 subjects per test condition was defined (5).

The sample of 24 subjects was stratified by sex (50 percent of each) and age (in proportion to that of the driving population). A more detailed explanation of the statistical approach and description of the sample demographics are provided in the final report to this study (2).

Experimental Design

A repeated-measures design was used in the controlled field study, in which all 24 test subjects generated detection responses under each of the six lighting conditions examined in this experiment. To control for a possible bias from order effects in the data, a counterbalancing scheme was used that distributed starting points for data collection evenly across the six conditions, and ensured that no particular sequence for presenting the various conditions to subjects occurred with a disproportionate frequency. Further, for those lighting conditions including two target positions, one-half of the sample of test subjects was randomly assigned to provide responses to the target under maximum horizontal illumination, and one-half responded to the target under minimum illumination.

All subjects participated in this study on a one-at-a-time basis, and the total duration of the experiment was approximately 1½ hr. This interval included a simple reaction time test (i.e., a button-push response to a high-contrast visual stimulus), the on-the-road segment of six test trials, and a brief postexperimental questionnaire.

DATA COLLECTION PROTOCOL

The data collection protocol in the controlled field study involved the experimenter who rode in an instrumented test vehicle with a single subject, plus an assistant stationed out of view slightly off the shoulder of the roadway. The vehicle was instrumented with a counter device linked directly to the transmission that measured traversed distance from a designated zero point, as well as a response button mounted in the center of the steering wheel that was wired into the counter device.

During a trial, the experimenter would direct the subject to pull off onto the shoulder of the road at a reference point located at least ¼ mi upstream of the target position. Radio contact between the experimenter and the assistant was surreptitiously established at this time, to alert the assistant to be ready to activate a pulley system to introduce the target into the shoulder (i.e., right-hand) lane as the test vehicle approached. The test vehicle then reentered the traffic stream when a gap in traffic occurred, and at the same time the counter device was engaged. In all cases, subjects were required to drive at the 55-mph speed limit.

When the subject first detected the target in the roadway ahead, he actuated the response button, which in turn froze the counter display at the amount of distance traversed since the reference point of radio contact. This display reading was then subtracted from the total premeasured interval from reference point to target to yield the number of feet away from the target at which the response button was pushed. After each detection response, subjects were asked to rate target visibility on a 10-point bipolar scale.

Also, because each detection response involved a discrete reaction time (RT) that varied from individual to individual, a simple test was performed before the beginning of the first test trial that required a subject to push the response button as quickly as possible following the actuation of a red hood-mounted LED by the experimenter. The results of this simple RT test were later used to correct each subject's distance-to-target data; again, because the psychomotor response component of the present measure of effectiveness (MOE) varied from person to person, and because it was the study's objective to isolate the detection-recognition component, this procedure was deemed necessary to remove the contribution of simple reaction time from the overall observed response magnitude. Further, it was assumed that simple RT, that is, motor latency independent of any response selection process, would remain constant for each person from the pretest measure to the time the MOE was obtained, as there was no compelling reason to believe that the arousal and fatigue factors that influenced this aspect of performance had changed significantly.

At the completion of the test trials for the six lighting conditions, each subject was presented a brief questionnaire to obtain subjective measures of target adequacy (i.e., its realism as a roadway hazard) and the perceived effects on safety of implementing reduced lighting tactics.

Visual performance data for each subject were also obtained in a separate laboratory session using a standard Snellen chart to measure acuity and a novel wall chart that varied the orientation of sets of sine wave diffraction grating stimuli to measure contrast sensitivity. Two ambient light (i.e., target luminance) levels of 0.4 and 4.0 fL were used for the collection of each visual performance measure.

DATA ANALYSIS

The RT-corrected distance-to-target data were subjected to a one-way repeated-measures analysis of variance (ANOVA) to test for significant differences in detection performance across the six lighting conditions. Where main effects were demonstrated, additional post hoc analyses were performed to isolate the source of differences; these analyses included the Scheffe test for all comparisons of interest among the various treatment conditions, as well as a linear trend analysis.

Pearson product-moment correlations were calculated to describe the degree of association between the visual acuity and contrast sensitivity indices and the primary behavioral (i.e., detection) data. The differences in subjects' responses on the rating of target visibility were evaluated with an additional ANOVA, and again, Scheffe post hoc tests were used to localize the sources of main effects. The linear regression coefficient for the association between the detection performance data and lighting and visibility measures of interest (e.g., pavement luminance and illuminance, V.I.) were calculated, and descriptive statistics for the responses to the postexperimental questionnaire were prepared.

RESULTS

The results for the primary measure dependent on distance to target are shown in Table 2. The best mean detection performance was achieved under full lighting conditions, with orderly decrements in performance noted for the uniform dimming and 75 percent power, uniform dimming and 50 percent power, and every-other-luminaire conditions, respectively. The one-sided (opposite) lighting and the no-lighting conditions were clustered together at the poorest levels of performance.

The repeated-measures ANOVA of these data demonstrated highly significant main effects ($F = 6.58$; $df = 5$ and 115 ; $p < 0.001$), even with a considerable amount of variability in subjects' performance. Further, the apparent linear pattern in the detection data was confirmed through a trend analysis, which identified a significant linear component ($F = 10.1$; $df = 1$ and 23 ; $p < 0.01$).

The post hoc Scheffe tests that were conducted to localize the sources of this treatment effect demonstrated significant differences at the 0.05 level, for those contrasts involving the following specific comparisons of interest:

1. The individual comparisons between full lighting and each of the two conditions associated with the poorest performance (i.e., one-sided and no lighting);
2. The weighted, multiple comparison between full lighting and the other five treatment conditions included in the study.

Additional individual comparisons between full lighting and the every-other-luminaire, 75 percent power, and 50 percent power conditions did not demonstrate significant (0.05) differences, nor did a weighted multiple comparison between the two uniformly dimmed conditions versus the two dimmed conditions involving the simpler, fuse-pulling tactics (i.e., every-other-luminaire and one-sided).

Standard deviation values shown in Table 2 indicate much greater variability in performance as lighting level is increased. This increase suggests a floor effect, where the worst (10th percentile) performers do not derive any substantial benefit from fixed lighting systems over headlights-only viewing conditions. Whether this finding can best be explained in terms of available visual information, driver motivation (i.e., confidence in detection judgments), or both, is unfortunately left unresolved by this research.

TABLE 2 RESULTS OF CONTROLLED FIELD EXPERIMENT

Lighting Condition	Behavioral Data: Distance-to-Target		Subjective Data: "How well could you see the target?" (1=very poorly; 10=very well)	
	Mean Detection Distance (ft.)	Standard Deviation (ft.)	Mean	Std. Dev.
Full	287.9	190.3	7.9	2.1
75% Power	232.6	124.8	7.1	2.1
50% Power	223.8	97.0	7.3	2.1
Every Other Luminaire	204.8	92.5	6.8	2.3
One (Opposite) Side	163.4	73.8	6.3	2.7
No Lighting	163.2	44.1	7.0	2.8

TABLE 3 CORRELATIONS BETWEEN DETECTION PERFORMANCE AND VISUAL SCREENING INDICES

Lighting condition	Acuity (Snellen)		Contrast sensitivity					
	Low luminance (0.4 fL)	High luminance (4.0 fL)	Low luminance (0.4 fL)			High luminance (4.0 fL)		
			Spatial frequency=			Spatial frequency=		
			1.5 Hz	3 Hz	6 Hz	1.5 Hz	3 Hz	6 Hz
Full (continuous) lighting	-.34	-.29	.37	.41	.37	.33	.34	.39
75% power/ (50% light output) Uniform dimming:	-.26	-.18	.31	.54	.31	.43	.36	.27
50% power/ (30% light output) Uniform dimming:	-.36	-.34	.34	.36	.42	.45	.24	.48
Every other luminaire	-.19	-.24	.36	.44	.36	.44	.17	.37
One (opposite) side only lit	-.03	-.02	-.20	-.23	-.07	-.33	-.46	-.18
No lighting	.29	.12	.13	.06	.26	.13	-.03	.14

The subjective ratings of target visibility, also presented in Table 2, resulted in (a) markedly higher mean ratings under full lighting; (b) a cluster of moderate ratings under the various dimmed, every-other-luminaire, or totally extinguished lighting conditions; and (c) a somewhat isolated lower rating for the one-sided condition. An ANOVA performed on these data also demonstrated significant differences ($F = 2.92$; $df = 5$ and 115 ; $p < 0.05$), although not nearly as strong as those observed for the detection measure. A subsequent Scheffe test identified the source of this main effect to be the contrast between the full-lighting and no-lighting conditions, specifically; no other post hoc comparisons among the subjective data showed significant differences at the $p < 0.05$ level.

The correlations between the visual acuity/contrast sensitivity indices and detection performance were found to be quite low; typically, less than 15 percent of the variance in detection performance was accounted for by these indices. Table 3 presents these correlation values.

Next, the linear regression was computed between the detection performance data and several lighting/visibility indices. The resulting coefficients are (a) with pavement (horizontal) illumination, $r = 0.95$; (b) with pavement luminance, $r = 0.94$; and (c) with V.I. values, $r = 0.83$. As defined in Table 1, V.I. represents the product of pure contrast (C), times the relative contrast sensitivity (RCS), times the disability glare factor (DGF) for existing conditions.

Finally, responses to the postexperimental questionnaire were summarized as follows:

1. When asked to use a 10-point bipolar scale to answer the question, "How well did the target simulate a hazard in the road?" with 1 = very poorly and 10 = very well, subjects replied with a mean rating of 7.4 (standard deviation = 2.2);

2. When asked, "In general, how safe is it to reduce the level of lighting on freeways late at night when traffic volume is low?" with 1 = very unsafe and 10 = very safe, subjects replied with a mean rating of 4.8 for tangent (straight) sections of roadway (standard deviation = 3.2) and 3.3 for ramps/interchanges (standard deviation = 2.4).

A t -test on the responses to Question 2 showed significant differences at the 0.05 level ($t = 1.86$; $df = 23$), indicating that subjects were somewhat negative toward the idea of using reduced-lighting tactics on straight sections of roadway, but were significantly more opposed to the use of this strategy on ramps and at interchanges.

SUMMARY AND CONCLUSIONS

The present investigation has demonstrated significant decrements in drivers' ability to detect a 6-in.-high, semihemispherical, 18 percent reflective gray target under normal freeway traffic conditions as alternative reduced lighting tactics are implemented. In relation to a roadway fully lit by 200-W high-pressure sodium lamps at 68 to 88 ft, at staggered spacings, and at 30-ft mounting heights, test subjects could detect the simulated hazard only as the distance-to-target separation was progressively shortened for uniformly dimmed/75 percent power,

uniformly dimmed/50 percent power, with every other luminaire extinguished, one side of roadway extinguished, and no-lighting conditions, respectively. Further, subjective ratings of target visibility under these test conditions were in general agreement with the detection response data. Both pavement luminance and horizontal illumination were strongly associated with the pattern of results in the controlled experiment, whereas calculated V.I. values showed a slightly diminished but still strong association with the behavioral data.

The highway safety implications of this research may be gauged in terms of AASHTO minimum braking distance requirements (6) in which design braking distance = $V^2/30f$, where V = vehicle velocity in mph and f = coefficient of friction. Under the existing dry and level conditions with a worn portland cement surface and using average new tires, the detection distances obtained under full lighting and both uniformly dimmed lighting conditions all exceed the current design requirement, and the distance-to-target results associated with the every-other-luminaire condition provide for 98 percent of the minimum requirement. However, when worst-case conditions (e.g., wet pavements and worn tires) are considered, none of the detection distances obtained in this study are large enough to insure a safe stop. Because design criteria within this context cannot reasonably be fixed in terms of the absolute worst-case scenario, however, and because a motorist's response to a perceived hazard while driving on a freeway is typically a combination of braking and lateral movement—not braking alone—a generalized distance-to-target criterion was calculated in this study to express the relative impact of the alternative reduced-lighting tactics on highway safety. This generalized criterion is the average of the existing and worst-case braking requirements, based on the presented braking distance formula; in the present case, a value of 252 ft is obtained. Measured against this criterion, only the full lighting condition evaluated in this experiment provided a detection distance adequate for safe and effective vehicle control.

REFERENCES

1. M. S. Janoff and N. L. Zlotnick. Costs, Benefits and Legal Implications of Reduced Freeway Lighting. *Lighting Design and Application*, Vol. 15, No. 8, Aug. 1985, pp. 35-42.
2. L. K. Staplin, M. S. Janoff, and L. E. Decina. *Reduced Lighting During Periods of Low Traffic Density*. Final Report RD-86/018. FHWA, U.S. Department of Transportation, Aug. 1985.
3. V. Gallagher, B. Koth, and M. Freedman. *The Specification of Street Lighting Needs*. Report FHWA-RD-76-17, FHWA, U.S. Department of Transportation, Nov. 1975.
4. M. S. Janoff et al. *Effectiveness of Highway Arterial Lighting*. Final Report FHWA-RD-77-37, FHWA, U.S. Department of Transportation, July 1977.
5. B. Winer. *Statistical Principles in Experimental Design*. McGraw-Hill, New York, 1971.
6. *Handbook of Traffic Engineering*. Institute of Traffic Engineers, Washington, D.C., 1976, p. 611.