Effect of Bridge Lighting on Nighttime Traffic Safety

MICHAEL S. JANOFF

Extensive research has indicated the existence of adverse neurological effects of flickering or rhythmic lights, referred to as photic stimulation. Although regularly flickering light rarely exists for more than a few seconds in the natural environment, some types of artificial lighting, such as that found on long bridges or in long tunnels, can provide a photic stimulation for a sufficient time (i.e., minutes) to cause such adverse effects. These effects, theoretically, could result in an increase in nighttime traffic accidents. About 20 years ago, a few highway agencies began to design and install low-mounted, lineal-type lighting systems—almost all of which produce a flicker—on a number of bridges under the assumption that such lighting was an improvement over conventional lighting systems. This assumption was never validated. One such installation was the San Mateo Bridge over San Francisco Bay. Theoretically, the length of this bridge should provide sufficient exposure to this lighting to induce the adverse neurological effects. The availability of detailed accident records for the San Mateo Bridge provided a basis for determining whether the nighttime safety on this bridge was in any way related to the amount of time a motorist was exposed to this lighting system. The analyses of the accident data have shown that the nighttime safety on the bridge has been adversely affected by the lineal lighting, that the effect occurs after only about 3 min exposure to the lineal lighting, and that replacement of this type of lighting with conventional overhead lighting promotes a safer nighttime traffic environment.

Laboratory research as early as the 1930s revealed the existence of adverse neurological effects of flickering or rhythmic lights (photic stimulation). Such effects can include somatic, mental, and emotional changes ranging from mild physical discomfort or drowsiness up to complete loss of consciousness (*1–3*). Although regularly flickering light rarely exists for more than a few seconds in the natural environment, some types of artificial lighting, such as that found on long bridges or in long tunnels, can provide such a photic stimulation for a sufficient time (i.e., minutes) to cause these adverse effects. These effects, theoretically, could result in an increase in the frequency of nighttime traffic accidents.

The Illuminating Engineering Society (IES) has reported that in tunnels, the effects of flicker may produce undesirable behavioral sensations that in extreme cases include dizziness, drowsiness, queasiness, or seemingly hypnotic states in motorists and have caused seizures in people who have convulsive disorders (*4*). Lott has summarized the critical ranges of frequencies that produce these adverse effects and hence should be avoided in tunnel lighting designs: 5 to 10 cycles per second (*5*).

JMJ Research, P.O. Box 144, Newtown, Pa. 18940.

On bridges, about 20 years ago, a few highway agencies began to design and install low-mounted, lineal-type lighting systems—almost all of which produced a flicker. The assumption was that such lighting provided better illumination and delineation than could be provided by conventional overhead lighting, was more glare-free than conventional lighting systems, provided superior visibility, and ultimately, should provide a safer nighttime environment (*6, 7*). However, such hypotheses were never validated.

One such installation was the San Mateo Bridge over San Francisco Bay. For over 20 years, this bridge has had a low-mounted, lineal lighting system that produces a noticeable flickering light (*6*). In theory, the length of this bridge (about 7 mi) provides sufficient exposure to this lighting to induce the adverse neurological effects described previously.

The availability of detailed accident records for this bridge, covering 7 years (1976 to 1982), provided a basis for determining whether the nighttime accident frequency on this bridge was in any way related to the amount of time that a motorist was subjected to the lighting system. If the nighttime safety on the bridge decreased in proportion to the time spent on the bridge, given that all other factors were controlled or accounted for, it would provide additional proof in an actual traffic environment of the original laboratory research.

In addition, because the lineal lighting on part of the bridge was later changed to a conventional pole-mounted system, an opportunity was available for a before-after accident analysis to determine the effect of this lighting change on nighttime safety.

DESCRIPTION OF SAN MATEO BRIDGE

The San Mateo Bridge is a multilane span, ~7 mi long, divided into two sections: a 5-mi level causeway section with two traffic lanes in each direction and a 2-mi raised section with three lanes in each direction. A medial barrier, 30 in. high, separates eastbound and westbound traffic. Average speeds on the bridge are 50–60 mph, similar to a limited access divided highway. The surface is portland cement.

DESCRIPTION OF LINEAL LIGHTING SYSTEM

The original lighting system, installed ~1966, consisted of 10-ft-long lineal fixtures containing 8-ft fluorescent aperture lamps. The remainder of each fixture contained the ballast. The fixtures were arranged end to end and mounted on the top of the medial barrier. The average horizontal illuminance on the causeway part of the bridge was ~1.25 fc with a uniformity (av/min) of about 1.7:1. On the raised part the values were about

1.0 fc and 5:1 uniformity. The lighting on this part of the bridge was changed in 1979 to a conventional pole-mounted high-pressure sodium (HPS) system, with average illumination over 2 fc.

The lineal lighting system used on the San Mateo Bridge generates a light pulse every 10 ft. At 55 mph (81 ft/sec), the pulse rate, or flicker, is 8 cycles per second. This flicker is very noticeable in the visual periphery, especially to drivers in the leftmost lane, closest to the lighting system. The flicker rate is in the center of the frequency range that should be avoided in lighting installations, according to the work of Lott (*5*).

FIRST ANALYSIS: EFFECT OF LINEAL LIGHTING ON SAFETY

Dependent Factors

The dependent factors chosen for the first analysis were the frequency of nighttime and daytime accidents, the night-to-day accident ratios, and the percentage of nighttime accidents. These factors were analyzed using accident data for the period 1976–1982 from the 5-mi causeway section of the bridge.

Objective

The overall goal of this first analysis was to determine the change, if any, in the preceding safety factors as a function of the length of time that a motorist drives under such lineal lighting. Because the volume on the bridge is constant over its entire length and the analysis of daytime accidents would account for any effects of the length of the bridge itself, excluding the lighting, it was felt that any change in safety at night would be attributed to the effects of the lighting system.

Analysis

To meet the stated goal, all accidents were classified by

- Light condition (day or night);
- Location on the causeway part of the bridge (mile marker); and
- Date (year).

The data for these three classifications were taken from accident report summaries obtained from the state of California. The statistic "accidents per mile" (APM) was computed for each of the five 1-mi sections of the causeway for each direction of traffic separately and for the entire 7-year period. The nighttime data are illustrated in Figures 1 and 2, and the daytime data are illustrated in Figure 3.

Results

Accidents per Mile

APM for the first and last miles of travel for both directions of travel and for both day and night were used for this analysis. The data are illustrated in Table 1.

It is quite evident that for both day and night, in both directions of travel, the APM are greater for the last mile than the first. However, the nighttime increases, as illustrated in Table 1 (+85 percent and +175 percent for eastbound and

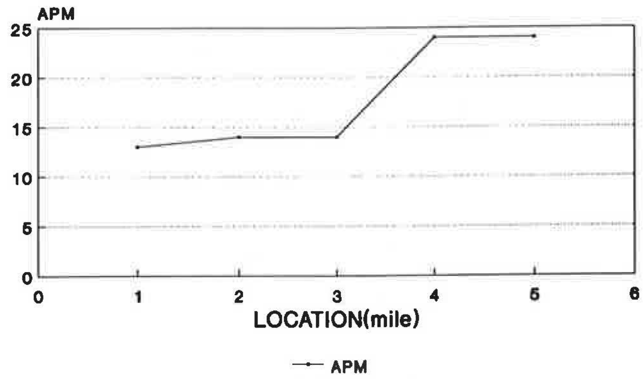

FIGURE 1 APM by location (nighttime, east).

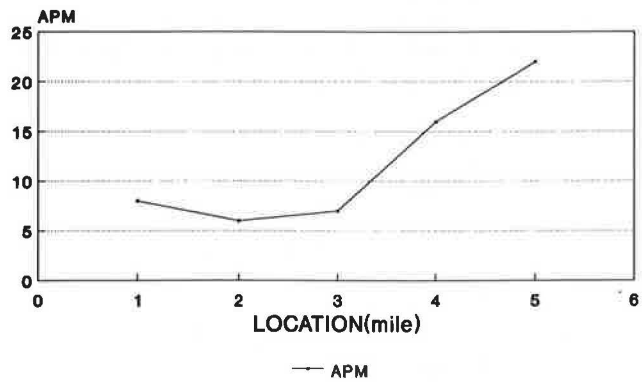

FIGURE 2 APM by location (nighttime, west).

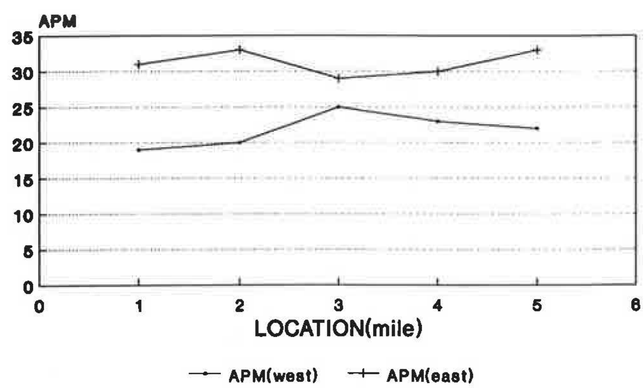

FIGURE 3 APM by location (daytime, east and west).

TABLE 1 ACCIDENTS PER MILE, DAY VERSUS NIGHT

Direction	Light Condition	Location: First Mile	Location: Last Mile	Change (%)
Eastbound	Day	31	33	+6
	Night	13	24	+85
Westbound	Day	15	22	+47
	Night	8	22	+175

westbound, respectively), are much greater than the daytime increases (+6 percent and +47 percent, respectively). This difference indicates a substantial decrease in safety at night between the first and last mile of travel.

Night-to-Day APM Ratios and Percentage of Night APM

Combining the night and day accidents per mile into night-to-day ratio (NDR) and percentage of night accidents (PNA),

$$\text{NDR} = \frac{\text{night accidents per mile}}{\text{day accidents per mile}} \quad (1)$$

$$\text{PNA} = \frac{\text{Night accidents per mile}}{\text{Day + night accidents per mile}} \quad (2)$$

which are considered to be better indicators of nighttime safety, yields the data in Table 2. It is again evident that both factors increase substantially (between 40 and 89 percent), indicating a decrease in nighttime safety between the first and last miles of travel for both directions of traffic.

TABLE 2 NIGHT-TO-DAY AND NIGHT PERCENTAGES

	Location		
Direction	First Mile	Last Mile	Change (%)
Eastbound			
Night-to-day	0.42	0.73	+72
Night percentage	0.30	0.42	+40
Westbound			
Night-to-day	0.53	1.00	+89
Night percentage	0.35	0.50	+43

Summary

The preceding analysis has shown that the nighttime safety on the San Mateo Bridge noticeably decreased, in both directions of travel, between the first and last 1-mi sections of the bridge. Because volume and environmental conditions such as weather are all constant over the entire length of the bridge and the increase in daytime accidents between first and last mile is far less than the increase at night (both directions), it is concluded that the lighting system, with its pronounced flicker, is the primary cause of this decrease in safety.

For both directions of travel, the nighttime safety does not decrease until the motorists have traveled at least 3 mi under such flickering lights. This is evident from the shape of the curves presented in Figures 1 and 2, which are flat until the fourth mile of travel in both directions. Hence the effect of the flicker is not evident until a driver has been exposed to it for about 3 min. The equivalent daytime results (Figure 3) show negligible change in APM over the 5-mi length in both directions.

The implication of the first result is that it is quite possible that the flicker produced by the low-mounted lineal lighting is inducing adverse neurological effects that cause a loss of driver control and result in this increase in nighttime accidents. The second result implies that the adverse effects will not occur instantaneously but require some minimum amount of driver exposure to such lighting before they become evident.

SECOND ANALYSIS: EFFECT OF LIGHTING CHANGE ON NIGHTTIME SAFETY

Dependent Factors

The dependent factors chosen for the second analysis were the frequency of nighttime and daytime accidents, the daytime and nighttime accident rates, the night-to-day accident ratios, and the percentage of nighttime accidents.

Objective

The overall goal of this analysis was to determine the effect of the lighting modification on the nighttime safety of motorists traveling that part of the bridge where the lighting was modified (referred to in the remainder of this paper as the changed section) and on the section where the lighting remained lineal (unchanged section).

Analysis

To meet the preceding goal, accident and volume data for 1976–1982 were obtained, and all accidents were classified by

- Time (date of occurrence, before or after),
- Location on bridge (changed or unchanged part), and
- Light condition (day or night).

Because the lighting modifications occurred in 1979, this year was excluded from the analysis. This was done because the exact completion date of the modification was unknown and because the effect of the actual lighting construction on traffic and safety could not be quantified. The remaining data (6 years, 1976–1978 and 1980–1982) were then classified as just described to yield eight distinct classifications or cells: two times (before or after); two locations (changed or unchanged); and two light conditions (day or night).

Accident frequencies and accident rates (frequency/volume) were computed for each of the eight cells. Additionally, night-to-day accident ratios and percentage of night accidents were computed for the four combinations of location and time. The results are discussed in three parts: effect on accident frequencies, effect on accident rates, and effect on night-to-day accident ratios and percentage of night accidents.

Results

Accident Frequencies

The accident frequencies for each of the eight cells are summarized in Table 3. From these data it can easily be seen that on the changed part of the bridge,

- Night accidents decreased 21 percent and
- Day accidents increased 43 percent;

and on the unchanged part of the bridge,

- Night accidents increased 74 percent and
- Day accidents decreased 3 percent.

These changes indicate an increase in nighttime safety on the changed portion while safety was decreasing at night on the

TABLE 3 ACCIDENT FREQUENCIES

	Light Condition	Location	
		Changed	Unchanged
Before	Day	41	106
	Night	28	39
After	Day	59	103
	Night	22	68
Change (%)	Day	+43	−3
	Night	−21	+74

unchanged part (the "control" section) and safety was decreasing during the daytime on the changed part.

Accident Rates

The average annual daily traffic (AADT) on the bridge rose by 18 percent between the before and after time periods (both day and night). Thus if after accident frequencies are divided by 1.18, the effect of the volume change is eliminated.

Adjusting the "after" data in Table 3 in the manner just described yields the data in Table 4. From these data it can be seen that on the changed part of the bridge,

- Night accident rates decreased 32 percent and
- Day accident rates increased 22 percent;

and on the unchanged part of the bridge,

- Night accident rates increased 49 percent and
- Day accident rates decreased 18 percent.

TABLE 4 VOLUME ADJUSTED ACCIDENT FREQUENCIES (ACCIDENT RATES)

	Light Condition	Location	
		Changed	Unchanged
Before	Day	41	106
	Night	28	39
After	Day	50	87
	Night	19	58
Change (%)	Day	+22	−18
	Night	−32	+49

Again, these changes indicate an improvement in nighttime safety on the changed part of the bridge while safety was decreasing on the unchanged part. During the daytime on the changed part, safety was also decreasing.

Night-to-Day Accident Ratios and Percentage of Night Accidents

Tables 5 and 6 summarize the NDR and PNA computations. It is obvious that on the changed part of the bridge,

- NDR decreased 46 percent and
- PNA decreased 34 percent;

TABLE 5 NIGHT-TO-DAY ACCIDENT RATES

	Location	
	Changed	Unchanged
Before	0.68	0.37
After	0.37	0.66
Change (%)	−46	+78

TABLE 6 PERCENTAGE OF NIGHT ACCIDENTS

	Location	
	Changed	Unchanged
Before	0.41	0.27
After	0.27	0.40
Change (%)	−34	+48

while on the unchanged part,

- NDR increased 78 percent and
- PNA increased 48 percent.

Both of these results indicate that the modification from lineal lighting to conventional overhead lighting improved the nighttime safety on the changed part of the bridge, whereas on the unchanged part a decrease in safety occurred.

Summary

This second analysis has shown that the nighttime safety on the changed part of the San Mateo Bridge improved when the lighting system was modified from rail-type lineal fluorescent fixtures to conventional pole-mounted, high-pressure sodium.

SUMMARY AND INTERPRETATION OF RESULTS

The analyses have provided two major results. First, the nighttime safety of motorists on the part of the San Mateo Bridge that retained the rail-type lineal lighting decreases after ~3 min exposure to such lighting. Second, when the lineal lighting was replaced by a conventional pole-mounted lighting system on part of the bridge, the nighttime safety improved on that part, whereas the nighttime safety decreased on the part that retained the lineal lighting.

The implication of the first result is that the lineal lighting, with its noticeable flicker, is causing this decrease in nighttime safety. The second result reinforces this interpretation because the nighttime safety improved substantially when the lineal lighting was replaced by a conventional pole-type system on part of the bridge.

Returning to the original hypothesis concerning the adverse neurological effects of such flickering light, it definitely appears possible that the decrease in safety results from neurological disorders caused by the flicker, compounded by the considerable light blockage and resulting shadow patterns caused by trucks and buses in the left lane. An alternative hypothesis is that the lineal lighting system itself, instead of the

TABLE 7 STATISTICAL ANALYSES (CHI SQUARE TESTS)

	Light Condition	Location	Factor	Significance Level
First Analysis				
Direction				
East or west	Night	First vs. last	APM	ns
East	Night	First vs. last	NTD	0.08
West	Night	First vs. last	NTD	0.02
Second Analysis				
Time				
Before and after	Night	Changed and unchanged	Accident frequency and rate	0.05
Before and after	Day and night	Changed and unchanged	Accident frequency and rate	0.05
Before and after	Day and night	Changed and unchanged	NTD	0.001

flicker, may be inducing the decrease in nighttime safety because of its design (i.e., light emanates from the side rather than above, as in all other driving situations, including daylight). Although this is an interesting hypothesis, there is no way of easily testing it. In any case, it is obvious that it is the lineal lighting that is causing the decrease in nighttime safety, for whatever reason.

A last suggested hypothesis is that the increase in illuminance provided by the newer HPS system is the sole cause of the increase in nighttime safety and that the lineal system was unsafe only because it did not provide sufficient light. If this hypothesis were true, then the graphs of nighttime accident frequency per mile illustrated in Figures 1 and 2 would be flat. Clearly, both of them increase at almost the same point (i.e., at 3 mi), indicating a time-dependent effect. This effect would be expected to result from a flicker but not from lighting alone. In addition, Box (*8*) has found that some increase in lighting (about 0.3 to 0.6 fc) increases nighttime traffic safety but that further increases do not. It should be noted that both the lineal and HPS systems have averages above Box's values. Finally, Janoff (*9*) found a direct relationship between average illuminance and nighttime safety: as the average illuminance increased, so did the nighttime accident rate. It is therefore felt that this last hypothesis is false.

IMPLICATIONS AND RECOMMENDATIONS

The implication of the preceding analyses and results is that bridge and tunnel lighting designers should avoid the lineal type of lighting system with luminaire configurations that produce such a noticeable flicker, especially for long bridges and tunnels. On the basis of the results presented by Lott, the critical range of flicker that should be avoided is 5–10 c/s.

STATISTICAL ANALYSES

The results of the statistical analyses for both analyses are presented here (Table 7). In general, for both analyses, the changes in simple accident frequencies, rates, and accidents per mile (APM) were often not significant, but the changes in night-to-day ratios, which are considered to be better indicators of nighttime safety, were always significant.

REFERENCES

1. W. G. Walter et al. Analysis of the Electrical Response of the Human Cortex to Photic Stimulation. *Nature*, Oct. 19, 1946.
2. V. J. Walter and W. G. Walter. The Central Effects of Rhythmic Sensory Stimulation. *Journal of Electroencephalography and Clinical Neurophysiology*, Vol. 1, 1949.
3. H. Ithoh. Photic Driving Response and Visually Evoked Response in Eye-Opened State. *Japanese Journal of Physiology*, Vol. 19, 1969.
4. *American National Standard Practice (Proposed) for Tunnel Lighting*. Illuminating Engineering Society of North America, New York, March 1986.
5. L. Lott. King's Cross Tunnel Lighting. *IES Lighting Review*, Vol. 30, No. 3, June 1976.
6. D. M. Finch. Lighting System for San Mateo Hayward Bridge. Special Report 576. Institute of Transportation and Traffic Engineers, University of California, Los Angeles, Aug. 1964.
7. W. M. McCarty and J. G. Fred Hiss, Jr. *Lensed Rail Lights for Pavement Illumination*. Research Report 21. New York Department of Transportation, Dec. 1973.
8. P. Box. Freeway Accidents and Illumination. In *Highway Research Record 416*, HRB, National Research Council, Washington, D.C., 1972, pp. 10–20.
9. M. S. Janoff et al. *Effectiveness of Highway Arterial Lighting*. Report RD-77-37. FHWA, U.S. Department of Transportation, July 1977.

Publication of this paper sponsored by Committee on Visibility.