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Effect of Improved Illumination on Traffic Operations: I-76 Underpass in Philadelphia

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An experimental lighting system in an underpass on I-76 in Philadelphia was evaluated. The lighting system was designed to provide five levels of illumination ranging from 5382 lx (500 ft·c) horizontal to 22 lx (2 ft·c) horizontal. Low-pressure sodium-vapor lamps were used. The internal level was automatically set by a series of photocells external to the underpass and provided a ratio of internal to external illuminance of approximately 10 percent. Four measures were used to determine the effect of the improved illumination on traffic operations. These were (a) the effect on the number of traffic accidents, (b) the effect on vehicle-velocity maintenance, (c) the effect on deceleration (braking) characteristics, and (d) the effect on subjective responses of drivers to the new lighting. The photometric characteristics of the new lighting were evaluated and the Illuminating Engineering Society and the American Association of State Highway and Transportation Officials tunnel-lighting recommendations were compared. The results indicated that (a) the new lighting caused decreases in the velocity variability and in brake applications at the portal, (b) in general, as the internal lighting level increased, both the velocity variability and the number of brake applications decreased, indicating safer and smoother traffic operations, (c) drivers responded positively when the internal lighting levels were increased and there were no noticeable adverse effects caused by the low-pressure sodium-vapor lamps, (d) the Illuminating Engineering Society recommendations for tunnel lighting appear to be preferable to those of the American Association of State Highway and Transportation Officials, and (e) there was a reduction in the number of accidents inside the underpass and at the portal in the 6 months after installation of the new lighting.

The first object of this program was to evaluate the effects on traffic operations of lighting improvements in the eastbound section of the Thirtieth Street underpass on I-76 in Philadelphia. The improvements included a variable-level lighting system, the resurfacing of the roadway, and new reflective walls (both the side wall and a temporary center wall).

The second object was to determine whether the se-

lected luminaires are adequate for their purpose and to compare whether Illuminating Engineering Society (IES) (1) or American Association of State Highway and Transportation Officials (AASHTO) (2) recommendations are better design guidelines for tunnel lighting.

SYSTEM DESCRIPTION

Original Lighting System

The original daytime lighting system (the before condition) consisted of two rows of 1500-mA fluorescent lamps supplemented by thirteen 400-W mercury-vapor lamps in the first 73 m (240 ft) of the underpass. The illumination provided by this system during the daytime was approximately 355 lx (33 ft·c) at an average position and about 538 lx (50 ft·c) at the portal entrance.

Present Lighting System

The present lighting system (the after condition) consists of five continuous rows of overhead fixtures in the first 49 m (160 ft) of the underpass, one row of fixtures in the next 30 m (100 ft), and the original fluorescent lamps for the remainder of the tunnel. Each fixture in a row houses two 180-W low-pressure sodium-vapor lamps, except that, in the center row, a 90-W lamp is substituted for one of the 180-W lamps in every eighth fixture.

The electrical circuitry is designed so that five different lighting configurations are possible. The control is monitored by a series of four photoelectric cells mounted outside the underpass. The inside design levels, the outside illuminations at which the circuits are ener-

gized, and the configurations are summarized below (1 lx = 0.093 ft • c).

Circuit	Illumination (lx)		Configuration
	Inside	Outside	
N1	27	Night	All 90-W lamps, one in every eighth fixture in center
D1B	538	54	Center row, one lamp in every fixture
D1A	1076	5 382	Center row, two lamps in each fixture
D11	3220	21 529	D1A plus one lamp in each fixture of remaining four rows
D21	5382	43 057	All lamps

PROCEDURES AND RESULTS

Experimental Method

The following interrelated experiments were designed to evaluate the effectiveness of the new lighting and to compare the IES and AASHTO recommendations:

1. A measure of driver performance in terms of individual speed profiles near the tunnel portal,
2. A measure of driver performance in terms of the number of brake applications near the tunnel portal,
3. A survey of accident histories near the tunnel portal,
4. A photometric measure of the illumination (and luminance) of the new luminaires, and
5. A survey of subjective driver responses to the new lighting system.

Driver Performance in Terms of Individual Speed Profiles

All of the velocity-profile data were collected by using the tape-switch system designed by the Franklin Institute Research Laboratories (3). The records of velocity variability (with the temporary center wall in place) as indicated by the individual standard deviation for each measured vehicle were grouped into six groups stepped in one-half sigma units, and χ^2 tests of significance, based on the unique independent variable (clear, cloudy, D1A, D11, D21, and nighttime), were made on each of these matrices.

A review of the raw variability data indicated that the velocity maintenance was least variable at night. This is presumably because of the relatively low visual difficulty or of a more stable visual-difficulty level in the transition from the exterior to the interior of the underpass and suggests that the nighttime driver behavior represents the optimum case of velocity maintenance. The statistical comparison of the velocity variability for the before and after conditions versus nighttime driver performance (shown below) demonstrates the relative success of each of the lighting alternatives at achieving this minimum variability level.

Condition	Probability Versus Nighttime	Condition	Probability Versus Nighttime
Before		After (clear day)	
Clear	0.005	D1A circuit	0.005
Cloudy	0.25	D11 circuit	0.10
		D21 circuit	0.25

The nighttime case, when compared to the clear case (unmodified lighting on a bright day) is statistically significant to a convincing degree. The D1A case clearly indicates the inadequacy of this system, and the progressively lower significance levels of the other alternatives indicate the increasing visual quality that the

higher lighting level represents.

Figures 1 through 5 illustrate the speed profiles in the various before and after lighting conditions. Figure 1 illustrates the mean and 85th percentile speed profiles for clear, cloudy, and nighttime conditions for the before lighting condition. Figure 2 compares the nighttime (optimal) condition with each of the three after lighting conditions during clear weather. (The higher velocity for the nighttime condition is attributed to lower traffic volumes; only the change or variability in velocity is of significance here.) Figures 3, 4, and 5 show that, for the D1A case, there is a significant decrease in velocity as vehicles approach the entrance to the underpass and that this decrease is substantially reduced in the D11 and D21 conditions. The after cloudy condition shows no significant differences between the nighttime (optimal) condition and the D11, D1A, and D1B conditions.

The records of velocity variability after removal of the temporary center wall showed no significant differences among any of the after lighting conditions (D1A, D11, or D21). In comparison with the before cases in which nighttime is the optimum and a clear day is the worst, the D11 after condition has the least velocity variability and is closest to the optimum nighttime-before case. The D1A case shows a decrease in velocity at about 30.5 m (100 ft) inside the portal. The D21 case shows a decrease in velocity before the tunnel portal that is maintained for at least 61 m (200 ft) (the limit of the recording equipment). None of the differences was significant. The results are summarized in Figure 6.

Driver Performance in Terms of Brake Applications

With the hypothesis that, as the internal lighting was increased, the frequency of braking, which indicates driver uncertainty, would decrease, an observer was stationed downstream about 183 m (600 ft), with clear visibility into the southbound entrance. The brake lights that appeared at or directly inside the tunnel entrance were counted (unless the light was due to the braking of a lead automobile), and the horizontal illumination and the traffic volume in the southbound lanes were measured continuously (every half hour). Figure 7 summarizes the results of this experiment (with the center wall in place). As the lighting in the underpass increased under a relatively constant outside illumination, the number of drivers activating their brakes at or near the entrance to the underpass steadily decreased, which indicates that, as the interior lighting levels decrease, the decreasing visibility causes driver uncertainty and a greater tendency to brake near the tunnel entrance. The same effect was observed after removal of the center wall and is shown in Figure 8.

Accident Analysis

The before-condition accident data were obtained from the Pennsylvania Department of Transportation (PennDOT) for the period of 1969 to 1972 and from the city of Philadelphia for the period of 1968 to mid-1973. The after-condition accident data were available only from the city of Philadelphia for the period of June to November 1974. Any conclusion drawn from these results will be considered as tentative. These data are summarized below.

Location	Accidents			
	Before Condition		After Condition	
	Total	No./Year	Total	No./Year
Entrance ramp, tangent section, and underpass	194	35	16	32
Tangent section and underpass	156	28	10	20
Underpass only	108	20	4	8

There are not sufficient data for further meaningful stratification, but these comparisons seem to indicate a reduction in the number of accidents.

Photometric Measure of New Luminaires

The illumination provided by the before-condition lighting

Figure 1. Velocity versus distance from portal for three before lighting conditions.

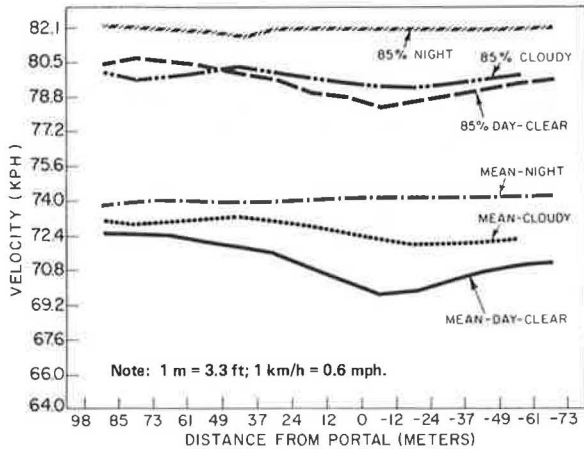


Figure 2. Velocity versus distance from portal for three after lighting conditions.

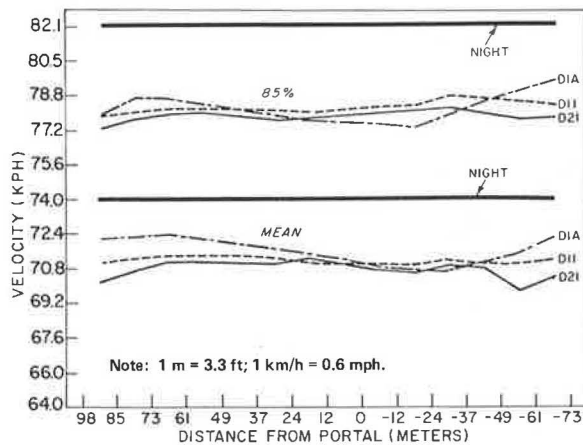
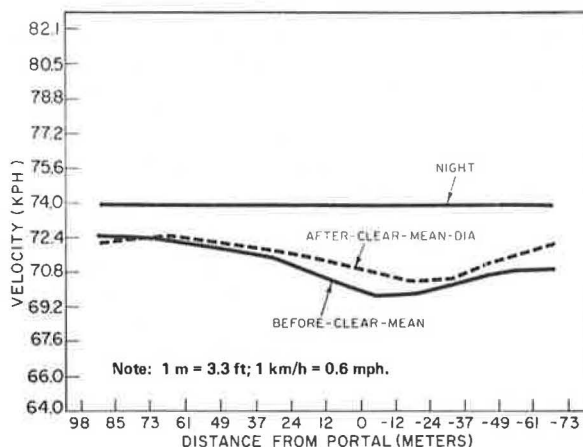


Figure 3. Velocity versus distance from portal for one before and one after lighting condition (D1A case).



system was measured by using automatic recording equipment (4); the results are shown below.

Condition		Illumination (lx)			
		Horizontal		Vertical	
External	Internal	Avg	Avg/Min	Avg	Avg/Min
Day	Day	355	3.0	—	—
Night	Day	237	2.0	92	1.7
Night	Night	58	11.0	—	—

(During the daytime there is a significant amount of illumination provided by the sunlight entering from the sides, so that the average during the day is higher than that during the night for the same lighting configuration.)

The same procedures and the same equipment were used to measure the illumination provided by the new lighting system; these results are shown below.

Internal Condition	Design Level	Illumination (lx)			
		Horizontal		Vertical	
		Avg	Avg/Min	Avg	Avg/Min
N1 (night)		26	4.0	22	5.1
D1B	538	1195	—	377	—
D1A	1076	2164	—	721	—
D11	3229	5167	—	1776	—
D21	5382	7427	—	2992	—

Figure 4. Velocity versus distance from portal for one before and one after lighting condition (D11 case).

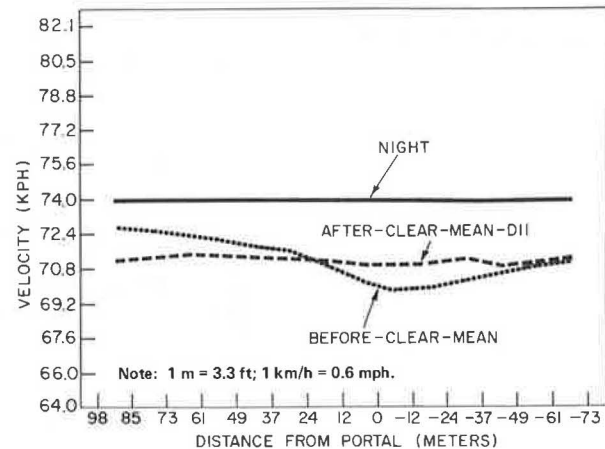


Figure 5. Velocity versus distance from portal for one before and one after lighting condition (D21 case).

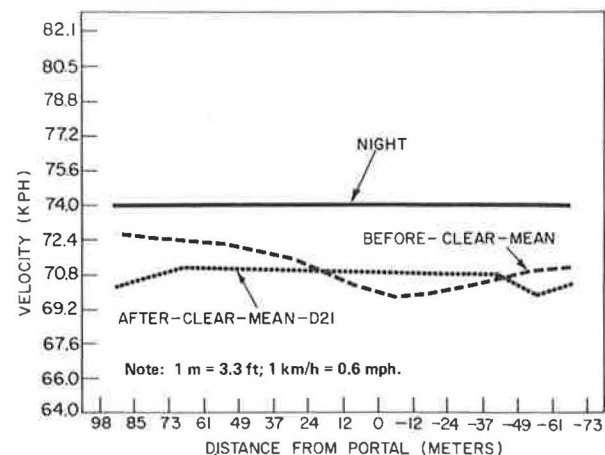


Figure 6. Velocity versus distance from portal for three after lighting conditions.

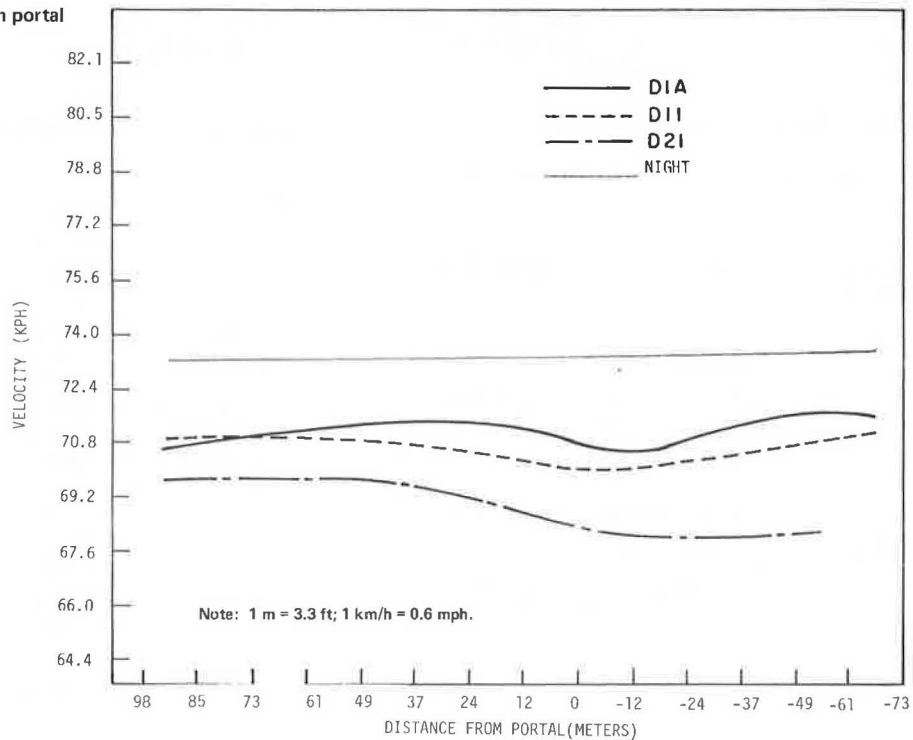
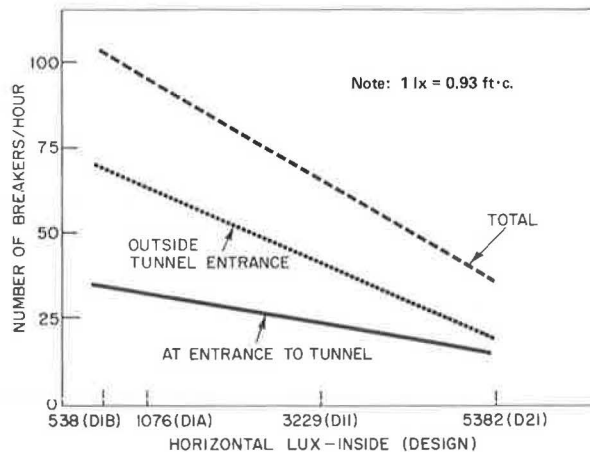


Figure 7. Number of brakers versus inside tunnel lighting (with center wall).



A complete goniometric analysis of the low-pressure sodium-vapor luminaire was also performed (5).

Driver Survey

The purpose of the survey was to determine the subjective response of the driving public to the new lighting system. Since the survey was short, required no postage by the driver, and was given to him or her immediately after the trip through the underpass, a high return rate and consistent answers were expected, but this did not occur. The response rate was low (10 percent), and discrimination between the different lighting levels was not possible. The following questions were asked.

1. How would you rate the lighting in this tunnel?
2. How was your trip through the tunnel?

3. How do you feel about this tunnel?
4. How do you feel about tunnel driving in general?
5. How can this tunnel be improved? (List in order of preference: more light, less noise, wider lanes, fewer cars, fewer trucks, cleaner, higher ceiling, or higher speeds.)
6. Do you object to using tunnels?
7. Do you have any general comments about this tunnel or tunnel driving?

Approximately 1000 mail-back surveys were distributed to motorists who had driven south through the I-76 tunnel with the center wall in place during a clear day [approximately 80 732 lx (7500 ft·c) horizontal illumination] by handing the forms to them as they exited at the South Street off-ramp. The return rate was almost equally distributed among the four daytime internal-lighting levels.

There were few data from the responses to questions 1 to 4 that could be used to discriminate statistically among the four levels of illumination. Some of this may be attributed to the fact that, in most cases, there was a lag between the time the survey was distributed and the time it was returned. Since many drivers use the underpass frequently, repeated passages under different lighting levels may have confused the results.

The responses to questions 5 and 6 were more significant. Drivers consistently chose more light and

wider lanes as important variables and considered higher ceilings and higher speeds less important. Drivers who passed through the tunnel under the two lowest levels of illumination objected to using tunnels twice as often as did drivers who passed through the tunnel under the two brightest illumination levels (25 versus 12.5 percent respectively) possibly indicating a more negative attitude under lower lighting levels.

A survey of motorists who had driven through the tunnel after the removal of the center wall produced responses that were similar to those to the first survey

Figure 8. Number of brakings versus inside tunnel lighting (without center wall).

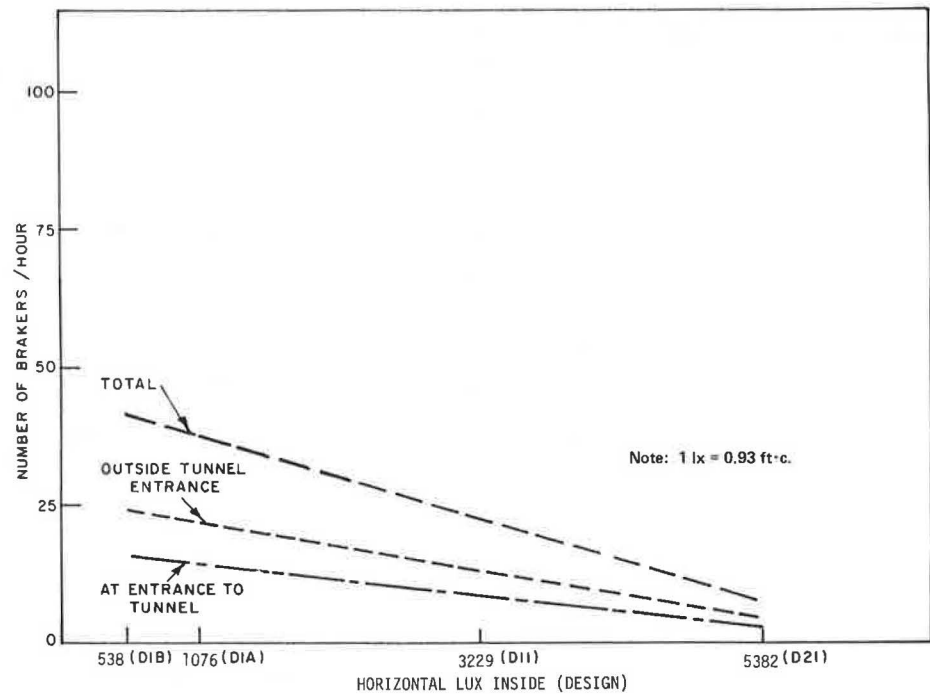
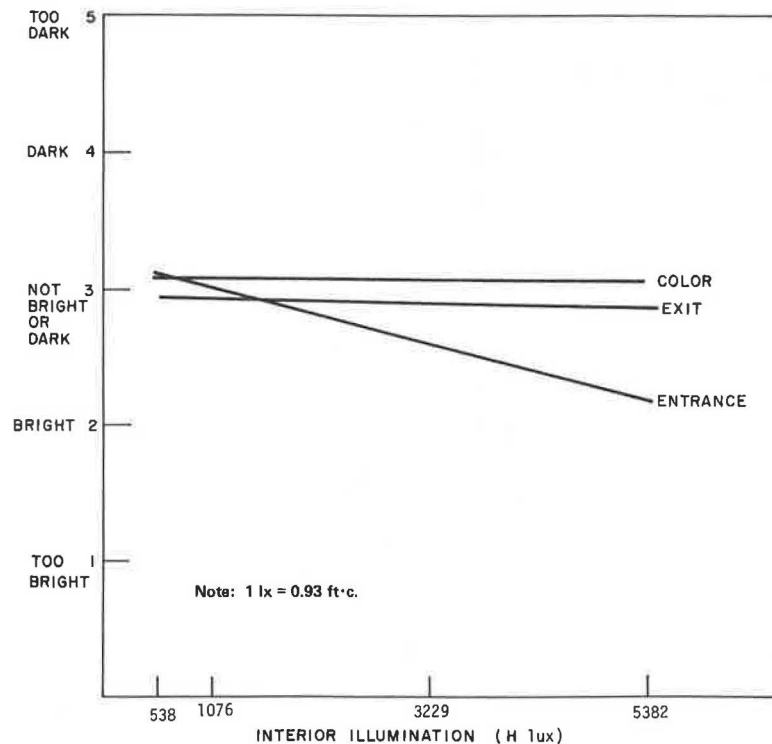


Figure 9. Subjective driver response versus interior lighting condition.



and did not differentiate among the various lighting conditions.

To supplement this survey, 84 drivers were stopped and asked question 1 after passing through the tunnel under the four different lighting conditions (D21, D11, D1A, D1B). These personal responses indicated that the effect of increasing the entrance lighting has been positive; i.e., as the level of lighting increased from D1B to D21, drivers subjectively responded that the tunnel entrance lighting appeared brighter. There was no difference in response for exit lighting, which would be

expected since the exit lighting was the same for all four entrance lighting conditions. The results are illustrated in Figure 9.

COMPARATIVE EVALUATIONS

The objects were to compare the IES and AASHTO tunnel-lighting recommendations and the two after conditions (i.e., with and without the center wall in place).

Figure 10. Velocity versus distance from portal for four luminance ratios.

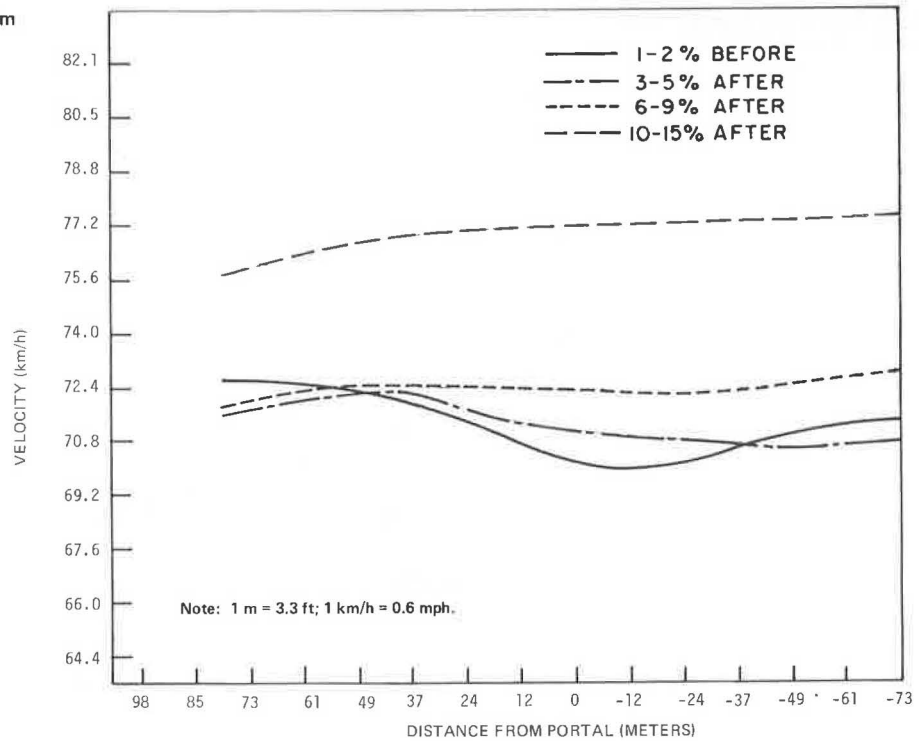
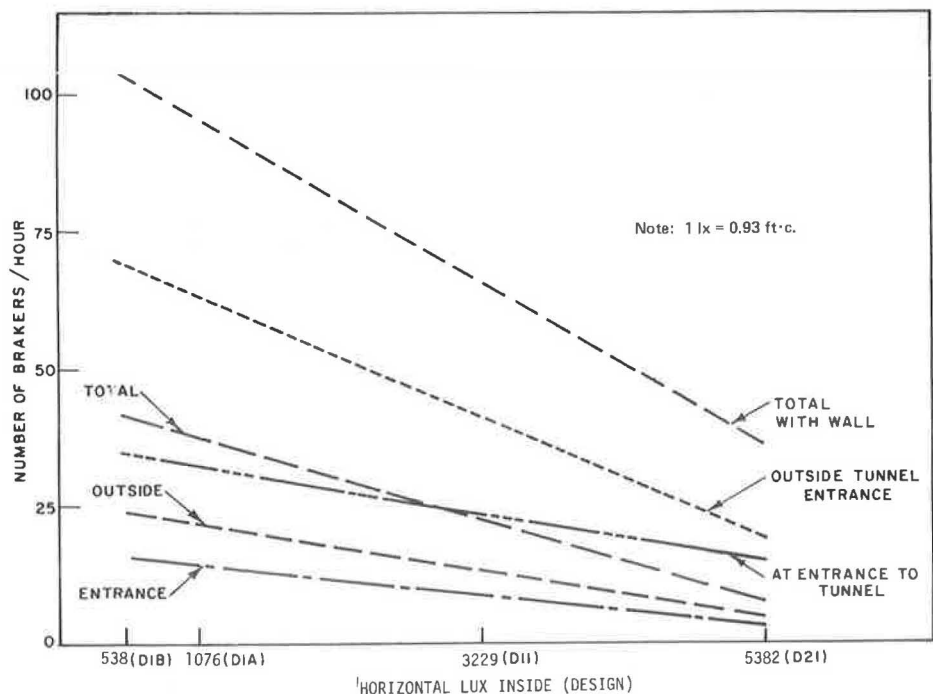


Figure 11. Summary of number of brakings versus inside tunnel lighting.



IES Versus AASHTO Recommendations

An internal horizontal illumination of about 5382 lx (500 ft·c), as provided by the D11 condition, appeared to optimize driver velocity-maintenance performance. The D21 condition provided a slightly reduced variability in the after-condition experiment with the wall in place, but the results were not significantly different from those of the D11 condition. The IES Standard recommends 5382 lx (500 ft·c) for the threshold illumination, which lasts 2 s [about 46 m (150 ft) at highway speeds] (1), but the AASHTO Standard recommends only 323 to 646 vertical lx (30 to 60 ft·c) on the tunnel wall (somewhat less than that measured for the D1B lighting condition), which was inadequate.

These standards were derived for illuminance measurements only. However, the luminances of sky, pavement, portal, and interior walls were also measured during the data collection. A preliminary evaluation of the effect of the ratio of external (sky) to internal (wall) luminance on driver performance is illustrated in Figure 10.

The before case is the worst case and has a ratio of internal to external luminance of between 1 and 2 percent. The three after cases had ratios of 3 to 5, 6 to 9, and 10 to 15 percent respectively. For the 3 to 5 percent case there is still a decrease in velocity at the portal, indicating insufficient luminance inside the tunnel, but the velocity remains stable for both the 6 to 9 and 10 to 15 percent cases. These results indicate that the ratio of internal to external luminance should be greater than 5, and probably between 6 and 9 percent.

If 7.5 percent is used as a design figure, then, for outside luminances of 17 130 to 34 260 cd/m² (5000 to 10 000 ft·L) (bright day conditions), the internal luminance should be 1285 to 2570 cd/m² (375 to 750 ft·L). These values are in the D11 to D21 lighting-system range, again indicating that the IES recommendations are better.

The results are similar for illuminance ratios. The velocity profiles at 3 to 5 percent showed a significant decrease in speed preceding the portal, those at 6 to 10 percent showed a slight reduction in speed, and those at 11 to 15 percent showed no decrease.

Effect of Center Wall

Three measures were used to evaluate the effect on driver performance of the temporary reflective center wall. These were velocity maintenance, braker data, and survey responses. The most meaningful comparisons were those from the braker data. Figure 11, which combines Figures 7 and 8, shows that the absolute number of brakings decreased after the wall was removed, although the effect of increasing the internal illumination was the same in both after cases.

The velocity measurements with the wall in place clearly showed that the D1A condition was inadequate, but with the wall removed the significant differences disappeared. This indicates a better visual field and better driver performance without the wall.

CONCLUSIONS

1. The new tunnel lighting system in the Thirtieth Street underpass on I-76 has provided a substantial improvement in visibility, velocity maintenance, and driver performance. The measured luminances (1 cd/m² = 0.292 ft·L) for the four lighting conditions are summarized below.

Internal Condition	Luminance (cd/m ²)	
	Wall	Pavement (avg)
D1B	394	343
D1A	480	411
D11	1182	771
D21	1199	891

2. The optimum lighting levels for bright days are provided by the D11 system.

3. The IES tunnel-lighting recommendations appear to be more accurate than the AASHTO recommendations.

4. The effect of the center wall was not positive; driver performance was slightly better after the wall was removed.

5. The system meets or exceeds the IES lighting recommendations in terms of horizontal illumination on the pavement surface.

6. The responses of drivers to the increased light indicated an apparent awareness of it and no apparent dislike of the monochromatic lamps.

7. Six months of after-condition accident data indicate a reduction in the number of accidents inside and preceding the tunnel.

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