

AN ASSESSMENT OF THE NEED FOR A SUNSCREEN AT THE
HAMPTON ROADS BRIDGE-TUNNEL

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(The opinions, findings, and conclusions expressed in this
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ABSTRACT

Several aspects of the Hampton Roads Bridge-Tunnel facility were investigated to determine if a sunscreen was needed at the north entrance to the second tube. The analysis included accident records, measurements of the speed of vehicles entering the north portal of the old tube, photometric characteristics of this entrance, a study of visual performance while entering the tunnel, and the results of a survey of motorists using the facility.

The survey and visibility studies indicated that severe difficulty in seeing into the tunnel is experienced under some conditions. Accident records showed that this difficulty has not been a significant safety hazard, but radar measurements revealed a significant reduction in speed at the approach to the mouth of the tunnel. This slowdown was attributed to difficulty in seeing into the tunnel and to a perceived constriction of the roadway caused by the narrow curved descent to the portal and the presence of oncoming traffic. The perceived constriction of this roadway will be reduced when the second tube is opened.

The investigators recommend lighter surfaces of the tunnel walls at the portal and edge striping of the roadway as ways of increasing visibility into the tunnel. In spite of the existence of a real visibility problem, they do not recommend construction of a sunscreen until these simple modifications have been evaluated.

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SUMMARY OF FINDINGS AND CONCLUSIONS

Findings

The results of this investigation are summarized in the paragraphs below.

Accident Analysis — Analysis of the 181 accidents occurring in the vicinity of the Hampton Roads Bridge-Tunnel over a three-year period revealed no mention of a sun related visibility problem as a causative factor. The accident rate for traffic entering the north portal was not different from the accident rate for the tunnel facility as a whole. While there does not seem to be a significant accident problem at the north portal, it is possible that motorists could be adjusting to a visibility problem by reducing the speed of their vehicles.

Traffic Flow Analysis — Radar measurements showed that motorists significantly reduced their speeds as they entered the tunnel at the north portal. Motion pictures of southbound traffic revealed that over 50% of all motorists applied brakes while entering the tunnel. The reduction in speed may be due in part to a visibility problem at the tunnel entrance but is most likely a result of the geometrics of the tunnel approach.

Human Performance Visibility Study — Three of four subjects experienced more difficulty in identifying the orientation of a visual target placed 100 feet inside the north portal than they experienced with similar targets placed outside and further inside the tunnel.

Photometric Visibility Study — Supporting the human performance data, photometric measurements indicated that outside-inside ratios of both illumination and luminance exceeded recommended maximum ratios by factors of 8 to 1, or more.

User Survey — Finally, a survey of motorists revealed that approximately 38% had at some time experienced difficulty seeing another vehicle at the tunnel entrance.

CONCLUSIONS

It was concluded that —

1. under some conditions it is very difficult for motorists to see into the north entrance to the tunnel;

2. there is a measurable slowdown at this entrance that is mainly attributable to the apparent constriction of the roadway caused by the curved descent to the portal and the presence of oncoming traffic, with difficulty in seeing into the tunnel being a contributing factor.
3. the elimination of oncoming traffic with the opening of the second tube (which is wider) will reduce the perceived constriction.

RECOMMENDATIONS

Based on the findings of this investigation, the following recommendations are made.

1. Because there is no evident safety hazard, construction of a sunscreen seems warranted only if it can be expected to affect traffic flow at the north portal. Since the observed reduction in speed is not attributed to visual factors alone, the authors do not believe that a sunscreen is justified at the present time.
2. The dark gray area associated with the tide gate at the portal of the first tube acts as a very effective light trap, preventing spill-in of light to the tunnel interior. This expanse of raw concrete should be eliminated by extending the reflective tiling of the interior to the mouth of the tunnel.
3. To increase motorists' confidence and speed, edge striping should be applied to the roadway beginning at the top of the open approach and continuing throughout the tunnel.

Should the two simple modifications recommended above fail to sufficiently increase visibility into the tunnel, such additional measures as increased threshold lighting and flaring of the tunnel portal should be given consideration as relatively less expensive alternatives to a sunscreen.

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INTRODUCTION

Every transportation system must meet three criteria if it is to function successfully: (1) it must be safe; (2) it must be efficient in terms of smooth traffic flow and adequate volume; and (3) it must be acceptable to the user. Inadequate visibility can have a detrimental effect in terms of all three criteria. A study by David A. Mintz Associates (1972) indicated that there was a visibility problem for southbound traffic entering the north portal of the Hampton Roads Bridge-Tunnel. This problem was attributed to the reflection of the top of the dashboard in the windshield, which constitutes a veiling luminance superimposed on the driver's view of the portal and makes it difficult for him to see into the tunnel. (See Figure 1.) The magnitude of this effect is largely determined by the amount of light falling on the dashboard. Thus it is generally most pronounced in the summer months, especially between the hours of 10:00 a.m. and 2:30 p.m., when the sun is highest in the sky. The problem was regarded by Mintz as being serious, and he proposed the installation of a novel type of sunscreen consisting of a series of glass panels of sequentially increasing density toward the portal entrance. A scale model of the sunscreen and tunnel portal was constructed and the proposed sunscreen appeared to be effective in reducing the veiling luminance from the windshield reflections.

The Mintz report concentrates almost exclusively on the veiling luminance problem and downplays or ignores altogether several other factors generally acknowledged to affect visibility in tunnel entrances. The first of these is the "black hole" effect wherein the driver sees the tunnel entrance as a black hole while he is still on the open roadway approaching the tunnel (Narisada 1972; Schreuder 1967). The black hole appears as a homogeneous black spot, relieved only by sufficiently intense tunnel luminaires. Other vehicles and the roadway itself simply disappear at the portal. This may be especially disconcerting on a curved approach as the driver cannot see whether the curve continues into the tunnel. When

faced with such a situation, the motorist's most likely reaction is to reduce speed. While this may appear to be a sensible course of action for the individual driver, it creates a bottleneck at the entrance that reduces the flow of traffic. A black hole results when an object within a tunnel entrance cannot be seen because its luminance* and that of its immediate surroundings is much lower than the luminance to which the eye is adapted. The luminance to which the eye is adapted is determined in large part by the terrain surrounding the tunnel portal (Illumination Engineering Society [IES] 1972).



Figure 1. Tunnel entrance photographed through reflection of dashboard on windshield. Car in direct sunlight just outside the portal. Lines converging toward center are tunnel luminaires.

*Luminance is a photometric term referring to the intensity of the light emitted by a light source or a reflecting surface toward the eye of an observer. It is measured in foot-Lamberts (fL) or candelas per meter squared (cd/m^2). Illuminance, on the other hand, is a photometric term referring to the light flux falling onto a surface. It is measured in terms of footcandles (fc) or lux. Luminance and illuminance are related to each other by the reflectance of the illuminated surface. For example, if an object or surface that reflects 20% of the light falling on it is illuminated by 10 fc, its luminance will be 2 fL.

A related, although conceptually distinct, problem is that of transitional adaptation (Ketvirtis 1975; Narisada 1972; Schreuder 1966, 1967, 1972, 1975). The visual system adjusts to provide maximum contrast sensitivity under prevailing levels of illumination. This process is known as visual adaptation, and requires a finite amount of time. Until adaptation is complete, objects require a greater than normal contrast to be seen, and objects that are normally only marginally visible may become totally invisible. Thus, as the motorist drives from the relatively high levels of illumination provided by bright sunlight outside the tunnel to the relatively low levels in the tunnel entrance zone and interior, there may be a loss in visibility resulting from the inability of the eye to make the rapid adjustment necessary for good seeing. The extent to which transitional adaptation contributes to loss of visibility in tunnel entrances has not been resolved. Adaptation may begin as soon as the tunnel portal occupies a significant portion of the field of view. However, the driver's task requires that he constantly shift his fixation, looking back and forth between brightly illuminated objects (e.g., other vehicles, signs, and road surface) in front of the tunnel and the dim interior. Therefore, the process of dark adaptation is constantly being interrupted, and it is unlikely that much significant adaptation takes place before the driver is within a few yards of the tunnel entrance.

Laboratory studies have shown that the degree of visibility loss in transient adaptation depends primarily upon background luminance differences (Boynton 1967; Rinalducci 1972; Rinalducci and Beare 1974). Larger ratios of background luminance differences generally result in larger losses in visibility. The black hole effect is also produced by large luminance ratios, as are windshield reflections or the veiling luminance effect. Therefore, much of the reported research and many of the published recommendations have been directed to the specification of an acceptable ratio between outdoor ambient light levels and those within the tunnel threshold zone that will reduce this effect. The tunnel threshold zone begins at the portal and extends into the tunnel for a distance determined by traffic speed and the expected safe stopping distance. The function of the threshold zone lighting is to provide a gradual transition between exterior and interior illumination levels. Thus, in the daytime this zone is more brightly lit than the interior zone, though at night it may be of the same or a lower level. At the present time the International Commission on Illumination (CIE 1974) recommends that the threshold zone luminance be on the order of 1,000 cd/m² or 300 fL. Achievement of such a level would require a horizontal illumination of 1,500 to 1,800 fc. The IES (1972) recommends a luminance level of 300-350 cd/m² or 88-102 fL, which

would require approximately 500 fc. The CIE recommends that the acceptable ratio of outdoor ambient luminance and that within the tunnel threshold zone or the adjacent zones within long tunnels be of the order of 10 to 1. The IES recommends that, under daytime conditions, the illumination levels in adjacent zones of long tunnels also be of the order of 10 to 1. However, these ratios require high levels of illumination, which may be difficult to achieve and demand large expenditures for operation. Japanese recommendations, based primarily on Narisada's research (Narisada 1972), suggest that an acceptable luminance ratio may be as large as 40 to 1, depending upon traffic speed and anticipated level of service. Acceptance of the higher ratio depends in part upon the acceptance of the idea that adaptation begins at the point at which the driver first fixates on the tunnel entrance (termed the "fixation point" by Narisada). Narisada and Yoshikawa (1974), using eye marker techniques, have shown that the driver actually begins to fixate the tunnel portal at a point at least 150 m from the entrance. Thus, adaptation may be well under way before the driver actually enters the tunnel. Schreuder (1972, 1975) uses a similar concept called the "adaptation point," which is defined as that point at which the state of adaptation of the driver's visual system will begin to change because he is looking into the tunnel. Although these concepts have much in common there are subtle differences which have resulted in different estimates of an acceptable luminance ratio. Schreuder has advocated the 10 to 1 ratio which has been incorporated into the CIE recommendations.

Recently, Narisada and his associates (Narisada 1975; Narisada and Yoshikawa 1974) have revised their estimates of tunnel entrance luminance requirements upwards by a factor of two, i.e., a ratio of 20 to 1, to take account of the situation in which the tunnel entrance is partly blocked from the driver's view by a preceding vehicle. If the rear end of the preceding vehicle has a high reflectance under bright sunlight, the driver's adaptation may be hampered. A curved approach to the tunnel entrance could also act to reduce adaptation to the lower luminances of the tunnel interior. It should be noted that the new Japanese recommendations are more in line with those of the CIE and the IES.

Ketvirtis (1975), a Canadian authority, has proposed that a luminance ratio of 25 to 1 should be acceptable, depending upon several factors which may vary from one tunnel to the next. However, Ketvirtis points out that the application of simple rules of thumb such as recommended lighting ratios will not always result in optimum lighting because visibility in the tunnel entrance is affected by many variables. These include:

- (1) traffic speed and volume (for example low-speed and low-volume

tunnels require less lighting); (2) tunnel design factors such as the presence of oncoming traffic, the design of tunnel portals and approaches, tunnel portal and interior surface treatment (use of reflective tiles, etc.); and (3) geographic factors such as latitude (which determines length of periods of peak ambient outdoor light, the intensities experienced, and the amount of snow, which may greatly increase the brightness of the surrounding terrain), the orientation of the tunnel entrance with respect to the position of the sun, and the general nature of the surrounding terrain (e.g., a forested hillside will reflect less light into the driver's eyes than will an equal expanse of gray rock).

The foregoing brief review suggests some of the complexities encountered when attempting to evaluate the adequacy of a tunnel lighting system. A more complete review of the relevant literature can be found in the annotated bibliography in Appendix A.

A description of the Hampton Roads Bridge-Tunnel in terms of the factors enumerated by Ketvirtis suggests the probability of an exceptionally difficult problem at this installation. The tunnel forms a part of Interstate-64, a high speed arterial highway. The speed limit within the tunnel is currently 40 mph, which is 15 mph less than that for the rest of the highway and 5 mph lower than that for the immediate approaches. Over the years 1972, 1973, and 1974 traffic averaged 658,828 vehicles per month, with the summer months providing the greatest volume. It is anticipated that the volume will increase. Traffic in the tunnel is currently two-way, with a single lane moving in each direction. When the second tube is completed, traffic in each tube will move in only one direction, thus eliminating oncoming traffic as a variable.

Traveling from Hampton to Norfolk, the driver approaches the tunnel from the northwest and faces southeast. The final open approach to the Hampton Roads tunnel is curved and about 600 ft. in length. There are gray walls on each side of the approach as the road descends below the surface of the island to the tunnel entrance. Thus, the entrance is not entirely visible to the driver until he is within about 400 ft. of the portal.

The walls of the open approach are nearly continuous with the walls in the tunnel interior. The entrance has a slight bevel but is not flared. In addition, the area adjacent to the tide gates at the entrance is a very dark gray and probably acts to absorb much of the light that might otherwise spill into the tunnel from outside. Beginning about 20 ft. to 30 ft. inside the tunnel, the walls are covered with tiles of a cream or buff color which help to reflect light within the tunnel. These

have been darkened with years of service despite regular washings. The ceiling of the tunnel is an off-white which has also been darkened somewhat by exhaust fumes. The roadway surface is black. The dark gray zone around the tide gates at the tunnel entrance, the lack of tile panels in the first 20 ft. to 30 ft. or so from the entrance, and the lack of flaring of the tunnel ceiling at the portal all combine to enhance the black hole effect.

The over-water approaches to the tunnel give rise to a particularly high degree of light adaptation just before the motorist enters the tunnel. The horizon is low and a large expanse of bright sky is visible. The water has a high degree of reflectance so that the area below the horizon can be almost as bright as the sky. In addition, there is frequently a high degree of specular reflection from the water adding to the visibility problem. All of these factors combine to produce an average luminance in the field of view many times higher than that usually encountered in an overland approach.

Visual problems inherent in an over-water approach are magnified by the geographic location. At this relatively southern latitude, both the magnitude and duration of the peak ambient sunlight are greater compared to those at similar installations in more northern regions. The ambient illumination is greatest during the summer months, when the volume of traffic through the tunnel is also at its highest. Thus, the most difficult visual conditions are present when it is most important that efficient traffic flow be maintained.

The orientation of the tunnel portal also plays a role in visibility. According to Thompson and Fansler (1968) one of the most difficult conditions for tunnel lighting occurs for south-facing portals (the driver is facing the southern sky on his approach). The Hampton Roads Bridge-Tunnel lies northwest to southeast and traffic approaching from the Hampton side faces southeast when entering the tunnel. Under these conditions drivers are facing the brightest part of the sky, with the sun itself often visible over the portal.

The present lighting system in the old tube is not sufficient to prevent a conspicuous black hole effect, particularly between 10:00 a.m. and 2:30 p.m. in the summer months. According to the specifications given in Thompson and Fansler (1968), the present lighting is designed to provide 24 fc of illumination for the first 225 ft. from the entrance, 12 fc for the next 225 ft., and 8 fc thereafter. Illumination is provided by fluorescent luminaires mounted high on each wall in a continuous double row

for the first 450 ft. and a single row thereafter. These luminaires are used in conjunction with the light colored ceiling and reflective wall tiles which begin about 20 ft. to 30 ft. from the entrance.

PURPOSE

The foregoing discussion of the characteristics of the Hampton Roads Bridge-Tunnel facility leads to the expectation that some visual problems will be encountered, especially when traversing the installation in the Hampton-to-Norfolk direction. The observations reported by Mintz (1972) confirm this expectation. The purpose of the research reported here was to provide objective data with which to determine the severity of these problems, and thus to assess the need for a sunscreen at the north entrance to the tunnel.

METHOD

As previously mentioned, a transportation system should be not only safe but also efficient from an operations standpoint and acceptable to the public for whom it is designed. These criteria dictated that the present investigation use a broad based approach to determine the nature and severity of visual problems encountered by drivers using the existing Hampton Roads installation. Several aspects of the bridge-tunnel system have been examined in an effort to detect evidence of such problems in terms of their practical consequences. This resulted in a four-pronged approach. The rationale and procedures employed in each separate approach are described below in the order in which they are addressed in this report.

Accident Analysis

Safety is a primary consideration in the design of any part of a public highway system. Good design maximizes safety and, conversely, design flaws are often reflected in high accident rates. Therefore, it was believed that a severe visibility problem at the north portal might contribute to a relatively high accident rate there, especially in the southbound lane.

Virginia law requires that a report be filed with the Division of Motor Vehicles giving the details of any accident resulting in death, personal injury, or property damage in

excess of \$250. Reports of accidents within the tunnel complex were analyzed for explicit mention of visual problems and for patterns that might reveal that reduced visibility was a contributing factor.

Traffic Flow Analysis

Smooth and efficient traffic flow is second only to safety in importance to the successful operation of a transportation system. Indeed traffic flow is a more sensitive indicator of the adequacy of the system than is safety: users will act to preserve their own safety and the increased caution will be reflected in reduced speeds. The analysis of traffic flow was conducted in two parts as described below.

a. Speed Analysis. The reaction of most drivers faced with a hazardous condition such as limited visibility is to slow down. Significantly reduced speed in the vicinity of the tunnel portal could thus be an indication of a perceived hazard and, conversely, maintained speed would indicate the absence of a perceived hazard.

The speed of vehicles entering the north portal of the Hampton Roads Bridge-Tunnel was sampled with an S-5 Radar Speed-meter. The radar unit was positioned so as to measure vehicle speeds at distances of 295, 135, and 0 ft. from the portal. In order to keep the unit as inconspicuous as possible, it was stationed atop the retaining wall of the open approach. Speeds were sampled on three days. The weather and visibility conditions were comparable for all three - partly cloudy and bright, with distinct shadows. For distances of 295 and 135 ft., speed samples were taken for 5 minutes of every 15 between 10:00 a.m. and 2:30 p.m. At the tunnel portal, samples were taken on the same schedule between 12:00 noon and 1:30 p.m.

b. Braking Patterns. An analysis of braking patterns was conducted as a supplement to the speed data to determine where motorists began slowing down and to detect erratic maneuvers near the tunnel entrance. Traffic on the last 145 ft. of the open approach was photographed with two super 8 mm motion picture cameras. The first camera was positioned atop the retaining wall 222 ft. from the portal and allowed the filming of traffic from 145 ft. to 15 ft. in front of the portal. The second camera was mounted 104 ft. from the portal and covered the area from 15 ft. outside to 50 ft. inside the tunnel. The overlapping fields of view allowed tracking of a vehicle's progress from 145 ft. outside the tunnel to 50 ft. inside it. As an aid in gauging the position of vehicles relative to the entrance, the series of vertical

stripes shown in Figure 2 were applied to the walls with white reflective tape. These were applied at 10-ft. intervals from approximately 110 ft. before the portal and at 5-ft. intervals for 50 ft. inside the tunnel. Three-minute motion pictures of vehicles approaching and entering the tunnel were taken every 15 minutes between 10:00 a.m. and 2:30 p.m. on August 5 and 6, 1975. These films show the distance from the portal at which the brakes were first applied, as indicated by the actuation of the vehicle's brake lights.

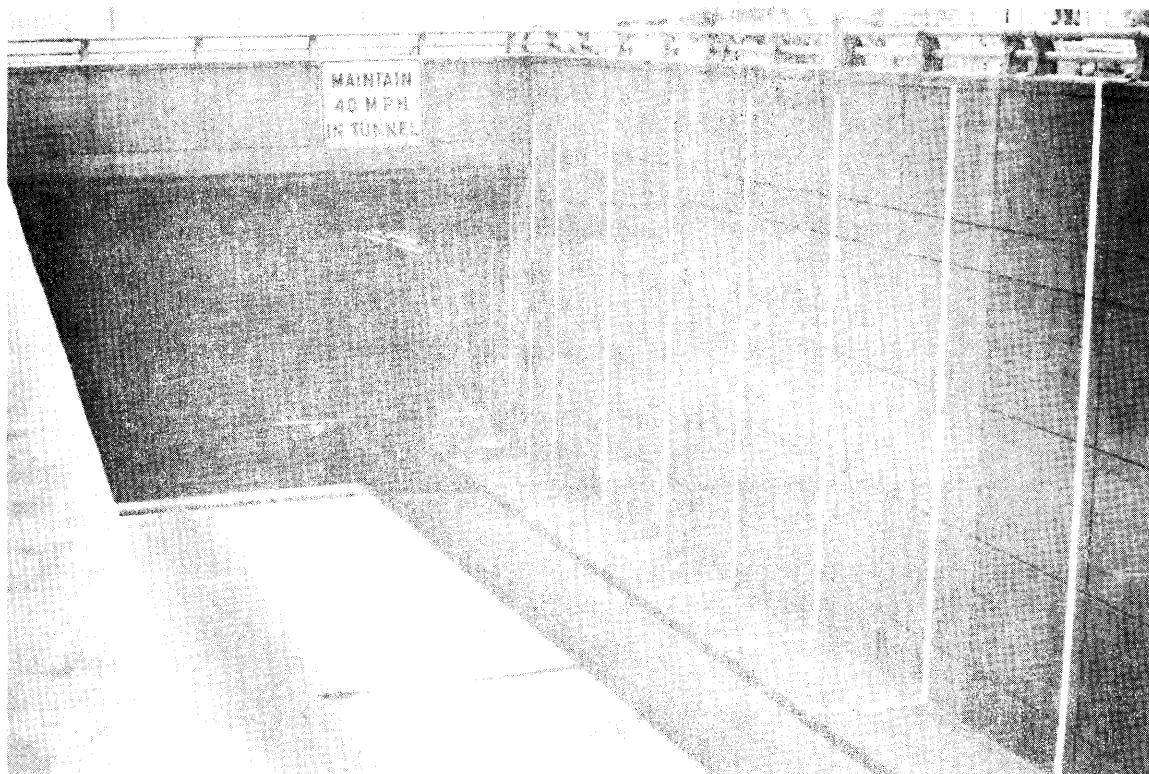


Figure 2. Stripes applied to south retaining wall as an aid to estimating the position of vehicles when they applied their brakes.

Visibility Studies

Two studies were undertaken to directly assess and describe the visibility conditions in the vicinity of the north portal.

Performance Study

A performance study directly assessed visibility at the north portal by determining how well subjects were able to perform a simple visual task as they entered the tunnel. The task consisted of detecting and reporting the orientation (up, down, left or right) of the gap in a Landolt C. The Landolt C is a standard visual acuity target consisting of a circle with a gap in it. In this experiment the width of the gap was equal to the width of the line forming the circle and the diameter of the circle was five times the stroke width. The stimuli were 7 in. in diameter with gaps of 1.4 in. At 200 ft. the gap subtended an angle of 2' of arc at the eye. The target was gray on a white background (see Figure 3), and had a contrast ratio of 27%. (Contrast is the ratio between the luminance of the background and the luminance of the target.)

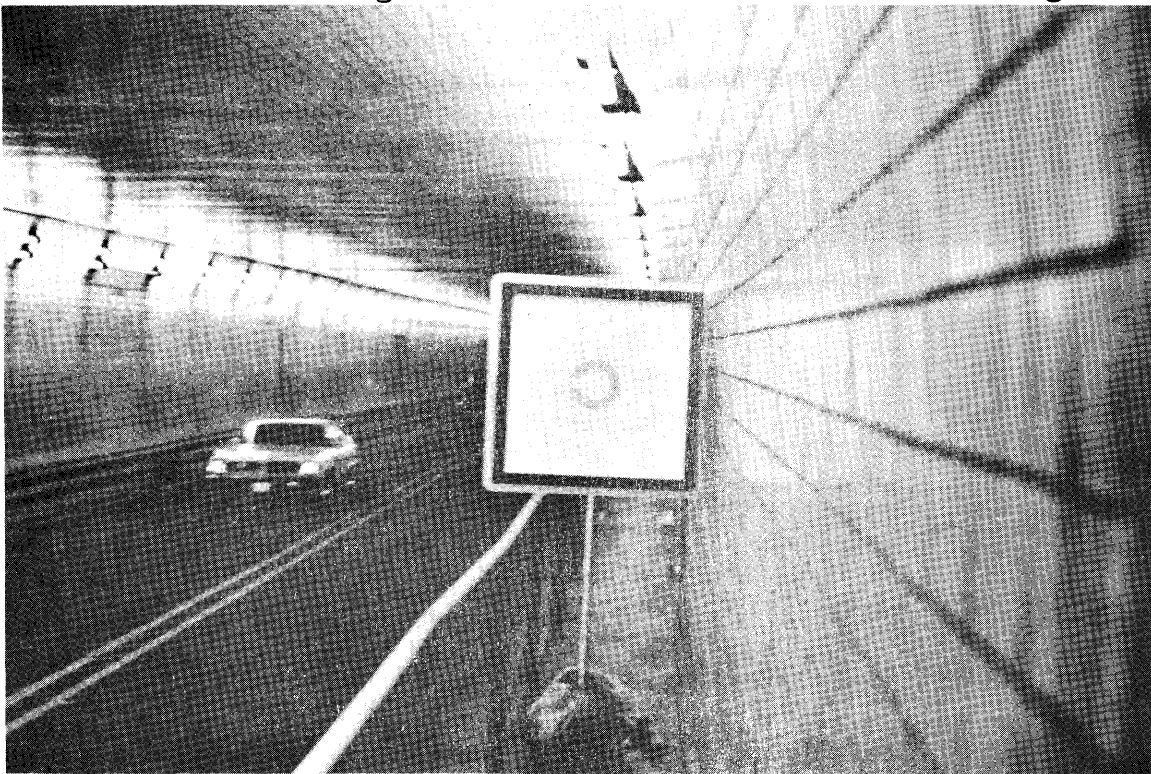


Figure 3. Acuity target used in visual performance study.

Targets mounted on signs of the kind shown in Figure 3 were placed on the walk 91 ft. in front of the portal, 100 ft. inside the tunnel, and 1,100 ft. inside of it. The orientation of each target was varied in random order before each presentation. The subject rode in the passenger's seat of an instrumented car.

(See Figure 4). A strip chart recorder driven by the odometer provided a record of distance traveled. The subject indicated the orientation of the gap in the Landolt C by pushing a small lever in the same direction (up, down, right, or left) as the gap. The distance of the car from the sign when the subject correctly identified the orientation of the Landolt C is termed the visibility distance (Mortimer 1974).

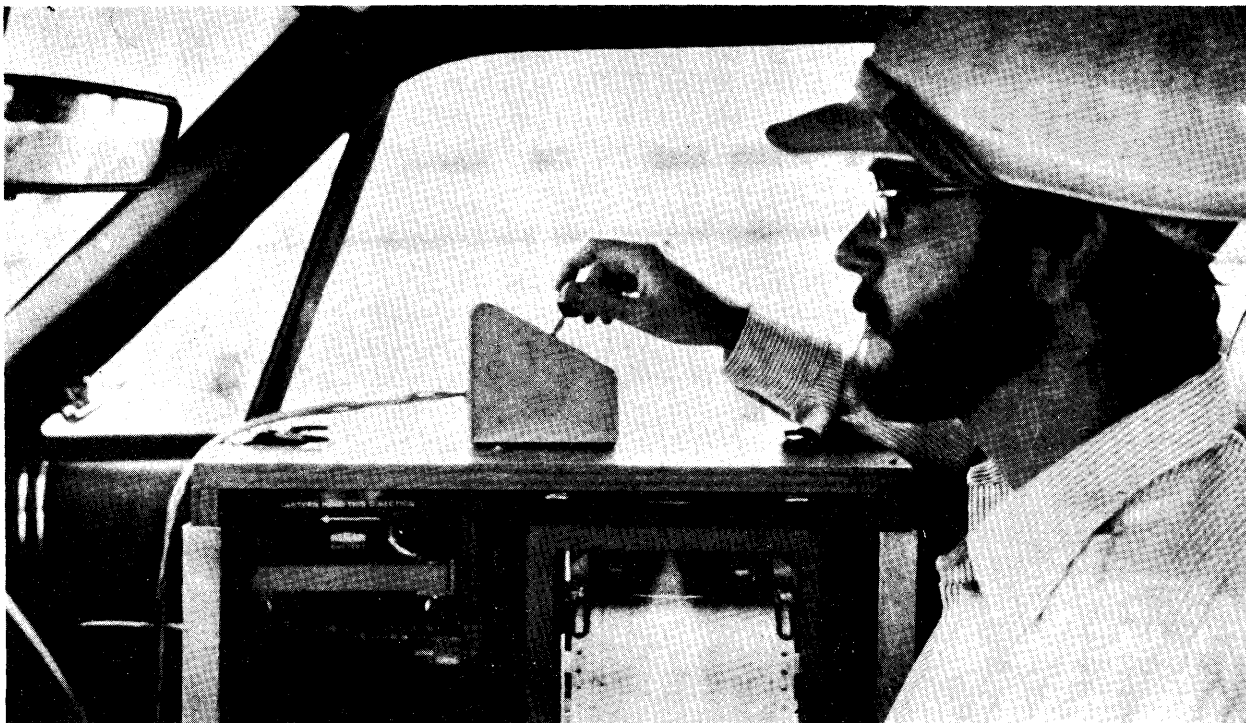


Figure 4. A subject operates the equipment used in the human performance visibility study.

Four subjects were employed in this study. Each subject was driven through the tunnel five or six times and responded to each of the three signs on each run. Traffic was halted for a short time during each run-through so that the test car could enter the tunnel with no vehicles ahead to slow it down or obstruct the subject's view. Three of the subjects were tested between the hours of 10:00 a.m. and 2:30 p.m.; the fourth between 2:30 and 3:30 p.m., when the reflection of the top of the dashboard in the windshield was less in evidence. Data were gathered on September 13 and September 14, 1975. Both days were bright with few clouds.

Photometric Study

To provide a simple description of the lighting environment that would allow comparison with published recommendations, a series of light level measurements were made with a Gamma Model 2009 Telephotometer. Luminance measurements were made from the walls in the interior directly in foot-Lamberts. Illumination measurements were made using the photometer in conjunction with a cosine receptor and were recorded directly in footcandles.

Luminance measurements inside the tunnel were made between 11:30 a.m. and 1:00 p.m. on September 27, 1975. The photometer was carried into the tunnel and operated from the catwalk. Luminance measurements were made at the portal from the dark gray concrete which is part of the tide gate system. Inside the tunnel, luminance measurements were made from the tiled walls.

Illumination measurements were made on September 13 and 20, 1975, primarily between the hours of 12:00 noon and 1:00 p.m. To make the illumination measurements, the photometer with cosine receptor was mounted on a tripod and secured in the rear of a station wagon. The photometer was aimed upwards and projected through the open rear window of the vehicle well above its roof. The system was leveled in order to measure horizontal illumination as accurately as possible. Illumination levels were determined on the island above and to one side of the entrance to the old tunnel (between the old and the new tubes), at two locations on the open approach, and at nine locations within the tunnel, beginning at the portal.

User Survey

A survey was conducted in order to learn to what extent motorists experience visibility problems in traversing the Hampton Roads Bridge-Tunnel. A four-item questionnaire in the form of a postage-paid card was distributed. (See Appendix B.) Motorists were asked how often they used the tunnel, whether they ever experienced difficulty seeing cars ahead of them, and if so, where and when these problems were greatest. In addition, space was provided for other comments about the tunnel environment. To encourage motorists' cooperation, an article describing the nature of this study was placed in a local newspaper. The survey was conducted on Thursday, August 21, 1975.

The above studies were conducted at the old tube, which is identical to the newer tube in the critical features of orientation of the tunnel entrance to the sun, the design of the portal, and the approach to the portal. Detailed specifications for both old and new tubes are presented

in Appendix C. A view of the north portal of the old tunnel appears on the cover of this report.

ANALYSIS

Accident Data

The tunnel complex extends from the toll plaza at the north exit to the southern end of the south approach bridge for a total of 3.57 miles. A total of 181 accidents were recorded within the complex during calendar years 1972, 1973, and 1974. In addition, there were an undetermined number of "nuisance accidents" not severe enough to be reported. The 181 reports available were analyzed for specific mention of a visibility problem as a contributing factor and for location and time of accident.

Only one accident could be directly attributed to a visibility problem: the driver's vision was obscured by accumulated sleet. Visibility was not mentioned in any of the other reports.

Table 1 shows the number of accidents that occurred in each section of the complex and the accident rate for each. The small number of accidents occurring in the shorter sections make the computed rates somewhat unreliable because the addition or subtraction of a single accident would change them drastically. Inspection of the table reveals that the approaches may be marginally more hazardous than the other sections of the complex.

If there were a severe visibility problem at the north portal, the accident rate, especially that for the southbound lane, should be elevated. This is not found to be the case (indeed this appears to be one of the safer sections of the complex). This finding must not be regarded as evidence against the existence of a visibility problem, however. In the words of Brass, Skoetsky, and Trospen (1957 p. 138), "although it seems reasonable that poor visibility within a tunnel would lead to a great number of accidents, data from this area does not bear this out. Most drivers confronted with poor conditions for visibility will drive with caution and with reduced speed." Following this logic, it could be argued that the lower accident rate may indicate a problem.

Because of the small number of accidents in the area of interest and the possibility of conflicting interpretations, the analysis of accident locations must be regarded as inconclusive. Additional accident data and analyses, less directly relevant to the considerations of the visibility problem at the north portal, are presented in Appendix D.

Table 1
Location of Reported Accidents, 1972-74

Location	Length, ft.	Number of Accidents		Accident Rates* (1972 to 1974)	
		SE	NW	SE	NW
Toll Plaza	500	3	0	.267	.000
N. Bridge	3,200	21	19	.288	.260
N. Island	208	1	1	.214	.214
N. Approach	598	2	7	.149	.521
Tunnel	7,429	24	24	.143	.143
S. Approach	598	5	4	.372	.298
S. Island	82	0	2	.000	1.086
S. Bridge	6,150	26	42	.188	.304
TOTALS	18,865	82	99	**	

*Accidents per 100,000 vehicle-miles.

**23,717,797 vehicles passed through the tunnel complex during the period 1972-1974. The overall accident rate for the complex was .214 per 100,000 vehicle-miles.

Traffic Flow

Speed Data

Traffic speed at three locations on the open approach was monitored by radar. For simplicity, speeds were recorded in 5 mph intervals. The sample taken 295 ft. from the portal includes 1,222 vehicles of all kinds; the sample at 135 ft. includes 1,095; and the sample at the portal, 312 vehicles.

The proportion of vehicles falling into each 5 mph speed category is shown in Figure 5. At 295 feet the median speed was 26.94 mph; at 135 feet it was 31.52 mph; and at the portal it was 21.27 mph, which is approximately half the design speed of the tunnel.

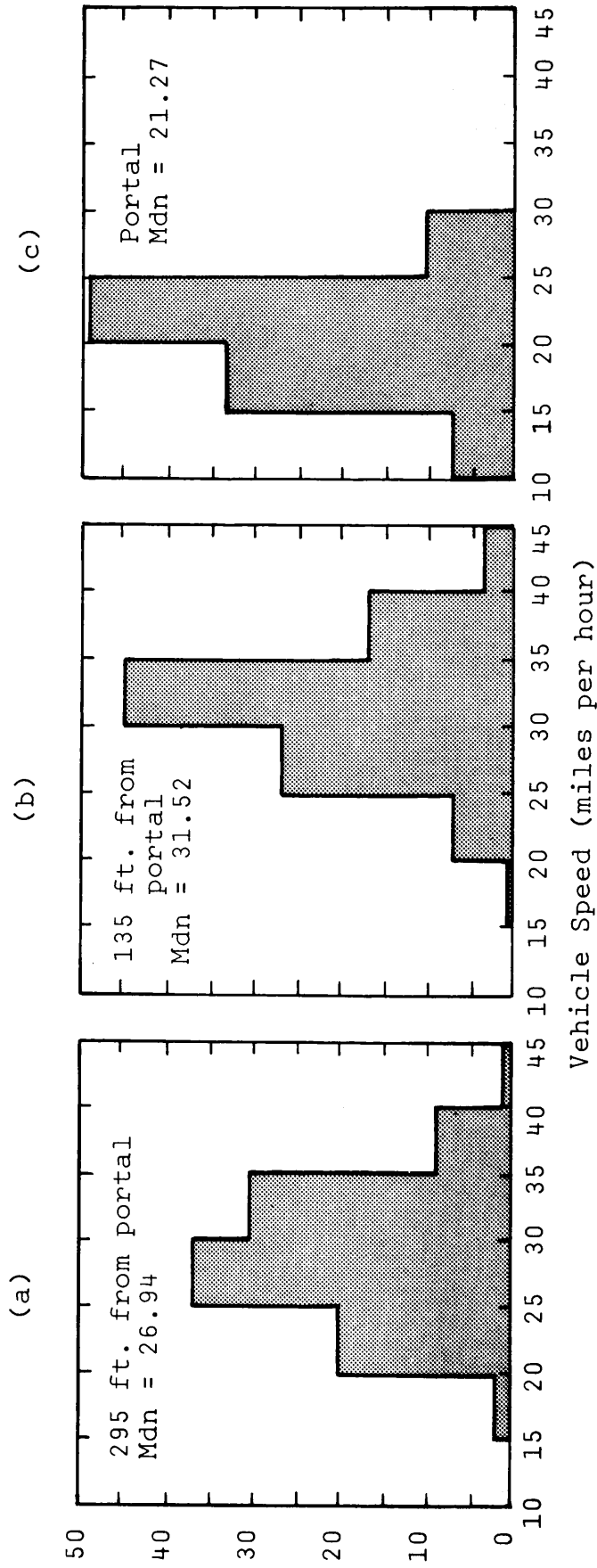


Figure 5. Speed of vehicles on the open approach to the north portal.

To make it as inconspicuous as possible, the radar unit was placed at a location above the tunnel and aimed downwards into the oncoming traffic. It should be noted that the unit sensor is usually aimed horizontally into oncoming traffic. According to the manufacturer, as the steepness of the angle of the sensor is increased, there is some tendency towards underestimation of vehicle speeds. The indicated speeds are reported: the true speeds, in all cases, may be somewhat higher. Nevertheless, observations of the investigators and the tunnel guards confirm the main inference drawn from the data presented in Figure 5 — vehicles tend to approach the tunnel portal slowly and slow down even more just before entering.

The above observation is consistent with the hypothesis that drivers are experiencing and reacting to some sort of visibility problem. As an additional test of this hypothesis, supplementary radar readings were taken on April 3 and 4, 1976, between 8:00 a.m. and 10:00 a.m. and again between 8:00 p.m. and 10:00 p.m. The median speeds are presented in Table 2.

Table 2

Supplemental Speed Data

Time	Distance from Portal, ft.	
	295	0
8:00 a.m. — 10:00 a.m.	35.52	27.16
8:00 p.m. — 10:00 p.m.	36.95	27.23

Compared with the 10:00 a.m. — 2:30 p.m. data, the average speeds were higher in these records, probably as a function of the smaller volume of traffic. However, the proportional reduction in speed during the last 295 ft. was about the same (approximately 30%), in spite of the fact that problems of visibility were not as pronounced. This finding suggests that the geometry of the approach also contributes to the reduction in speed. According to the Highway Capacity Manual (1965), three other factors may be at work. The apparent constriction of the roadway due to the proximity of the retaining walls and the slight constriction produced by a sidewalk on the open approach (turning into a catwalk atop an even closer wall in the tunnel interior) may result in a reduction of speed. In addition, the driver must follow a curved descent to enter the tunnel. This curve produces a somewhat reduced sighting distance, which, combined with the downgrade into the tunnel, may cause a driver to increase his following distance.

Braking Pattern Data

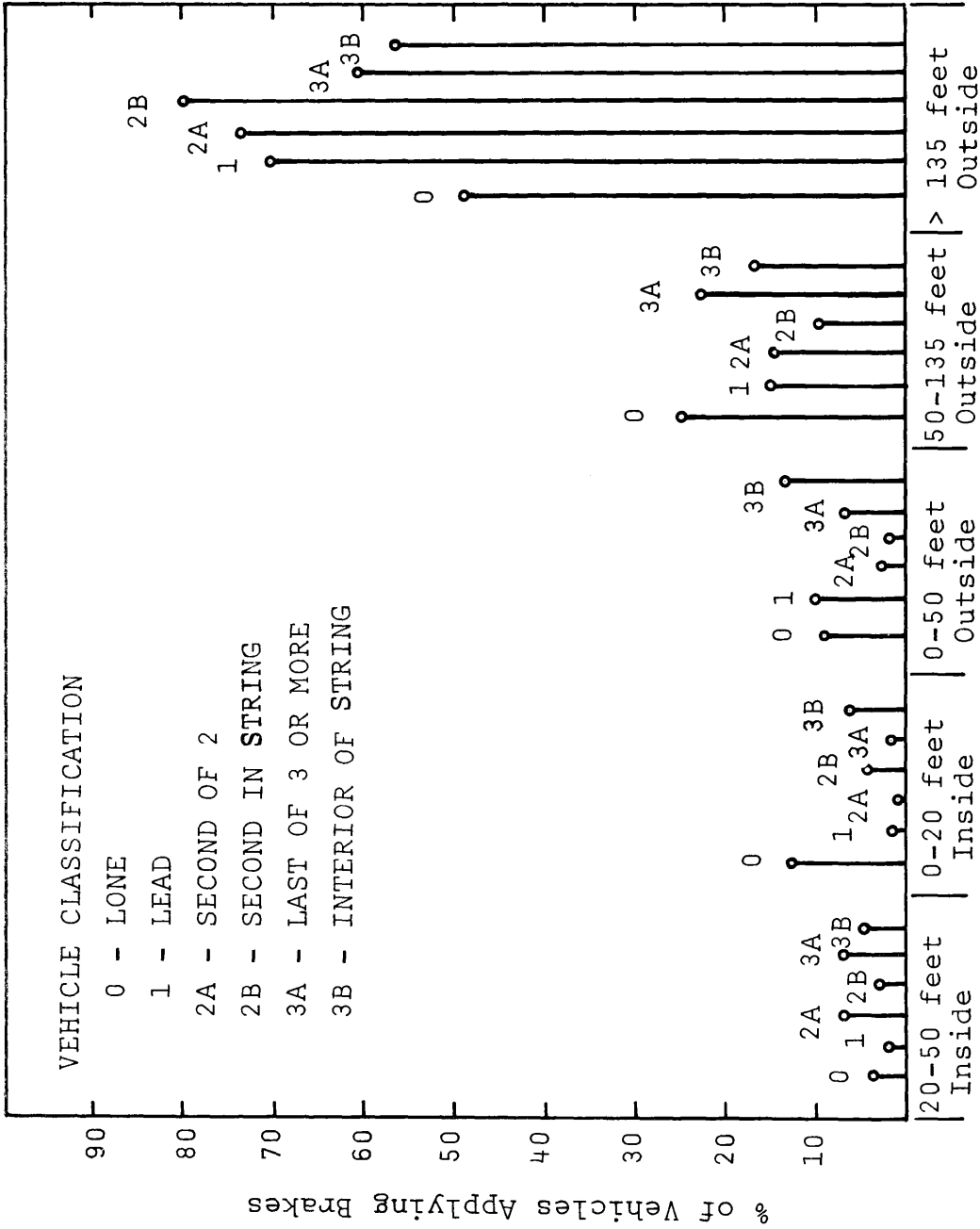
An analysis of braking patterns was undertaken in an effort to determine the point at which drivers began to apply their brakes. If slowing was in response to a reduction in visibility, this information would support some inferences as to the nature of the difficulty encountered. Braking just inside the portal might be indicative of a visibility loss resulting from transient adaptation, while braking just outside the portal could be due to the veiling luminance from the windshield reflections.

Motion pictures of vehicles entering the tunnel were made to determine the distance from the tunnel portal at which the brake lights came on. Analysis of the films was carried out to -

- (1) determine the proportion of motorists who apply their brakes prior to or immediately after entering the tunnel;
- (2) ascertain the effect of a vehicle's position in the stream of traffic upon the subsequent use of brakes; and
- (3) investigate possible differences in the distances at which motorists brake as a function of different time intervals between the hours of 10:00 a.m. and 2:30 p.m.

In order to classify each vehicle with respect to its relative position in the stream traffic, a coding system was adopted which differentiated between the behavior of lone or lead vehicles, whose braking patterns would not be affected by vehicles in front of them, and following vehicles, whose braking would be affected by preceding traffic. Additional information concerning the classification system and the braking patterns of following vehicles may be found in Appendix E.

Of all vehicles filmed, 63% to 70% applied their brakes at some point prior to or immediately following entrance to the tunnel. Figure 6 shows at what location brake lights first appeared for each vehicle classification (only those vehicles which braked are included). The data reveal a consistent pattern. Only a small proportion (2% to 7%) of vehicles (irrespective of classification) braked at distances from 20 ft. to 50 ft. inside the tunnel. Similarly, few vehicles braked at distances from 0 to 20 ft. inside (1% to 13%), 0 to 50 ft. outside (3% to 14%), or 50 ft. to 135 ft. outside the tunnel (2% to 25%). The greatest proportion of all vehicles (49% to 80%) braked at distances exceeding 135 ft. from the portal. The majority of these vehicles entered the field of view of the first camera at 145 ft. with their brake lights on.



Distance at which Brakes First Applied

Figure 6. Location at which brakes first applied for all vehicle types.

A slightly larger number of vehicles braked just after entering the tunnel (0 ft. to 50 ft. inside) than just prior to entering (0 ft. to 50 ft. outside). This observation does not allow inferences as to whether difficulties of transient adaptation or windshield reflections are the stimuli to which the motorist is responding because the majority of vehicles applied their brakes too early for either. It should be noted that the overall pattern of early braking is consistent with apprehension on the part of the driver aroused by perception of a black hole ahead. However, a more cautious approach may also be a response to the geometry of the approach way.

These general conclusions are supported by an analysis of the braking patterns of lone and lead vehicles. As previously mentioned, the behavior of these vehicles is of most interest because they are not constrained by the actions of other vehicles ahead of them. More than 65% of these vehicles applied their brakes when entering the tunnel. As Figure 7 shows, the majority of lone and lead vehicles also braked far in advance of the tunnel portal. Inspection of this figure reveals that leading vehicles were more likely to come into the field of the first camera with their brakes on than were lone vehicles. There seems to be a general tendency to apply the brakes earlier in the approach. It is a plausible conjecture that drivers of lead cars may be (consciously or unconsciously) signaling to following vehicles to reduce speed in order to create more maneuvering room for both.

A statistical analysis (chi-square) failed to reveal any relationship between the time of day (half-hour intervals between 10:00 a.m. and 2:30 p.m.) and the distance at which brakes were applied.

Speed data gathered by radar indicate that motorists slow down when entering the tunnel at the north portal. This may occur in response to a visibility problem or as a result of certain aspects of the geometry of the open approach. The braking study data indicate that the majority of motorists enter the tunnel with their feet on their brakes. Again, this caution could be due to a visibility problem, the geometry of the approach, or a combination of both. The data of the traffic flow studies indicate a definite slowdown at the north portal, but do not suggest its cause.

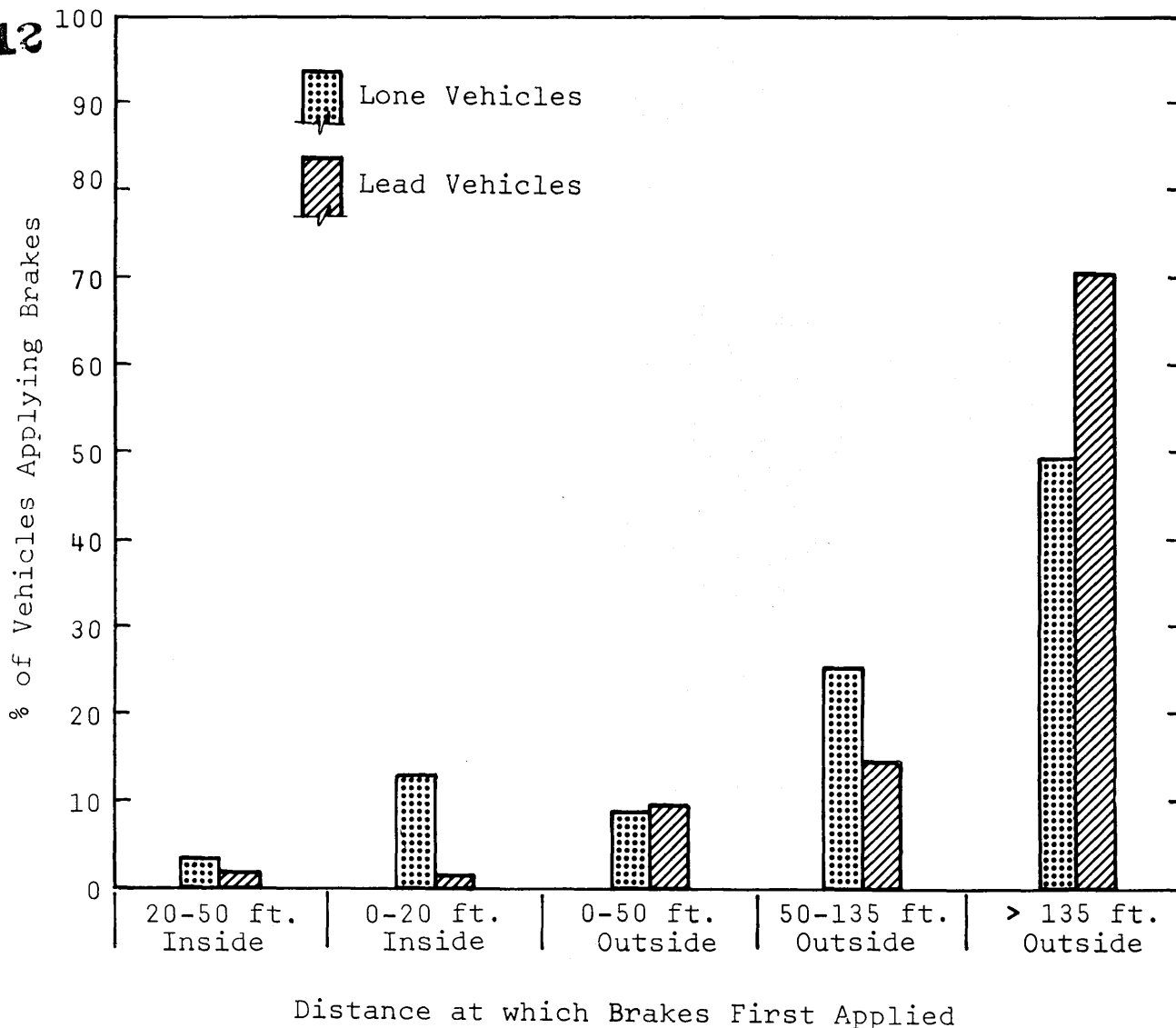


Figure 7. Location at which brakes first applied by lone (type 0) and lead (type 1) vehicles.
Visibility

Performance Data

A simple visual acuity task was employed to give a direct measure of human visual performance under the lighting conditions at the north portal. The acuity target was a Landolt C of 27% contrast. One of these was placed 91 feet outside the portal, one at 100 feet, and one at 1,100 feet inside the tunnel. The subject's task was to indicate the orientation of the gap in each of the three Landolt Cs as he was driven through the tunnel at 40 mph. His response and the distance at which it was made were recorded by a strip chart recorder in the instrumented car. The four subjects participating were all males with 20-20 vision, either corrected or uncorrected. Each subject was driven through the tunnel five or six times and responded to each of the signs on each run. These tests were run on September 13 and 14, 1975.

Table 3 presents the mean visibility distance for each of the four subjects. The visibility distance (VD) is defined as that distance at which the target is first correctly identified (Mortimer 1974).

Table 3
Mean Visibility Distances

Subject	(# Trials)	Target		
		1 (-91 ft.)	2 (+100 ft.)	3 (+1,100 ft.)
1	(6)	248.46	192.43	178.29
2	(5)	194.53	69.28	85.71
3	(6)	185.19	71.78	101.84
4	(6)	209.93	58.93	132.03

Subjects 2, 3, and 4 completed the experiment between 10:30 a.m. and 2:00 p.m., when the windshield reflections were quite noticeable. Data for subject 1 were obtained between 2:00 p.m. and 3:30 p.m., after the worst hours for this effect, and may therefore serve as a low-reflection control.

Two things are evident upon inspection of the data.

1. Targets inside the tunnel were harder to see (as indicated by reduced visibility distances) than the target outside it; and
2. for the three subjects affected by the windshield reflections, the target just inside the entrance was the hardest to see.

Given the small number of subjects and the wide variation in their individual performances, meaningful comparisons could be made only if differences due to subject variables such as visual acuity and response criteria could be minimized or eliminated. This was accomplished by calculating a relative visibility index, i.e., by describing a subject's performance on a given target in terms of his performance on another. Two such indices were calculated, and values for each are presented in Table 4, and graphically in Figures 8 and 9.

Table 4

Subject	Relative Visibility Indices					
	Relative Visibility ₁			Relative Visibility ₃		
No.	T1	T2	T3	T1	T2	T3
1	1.0	.11	.12	1.39	1.08	1.0
2	1.0	.36	.44	2.27	.81	1.0
3	1.0	.39	.55	1.82	.71	1.0
4	1.0	.28	.63	1.59	.45	1.0

$$RV_1 = VD(N)/VD(1)$$

$$RV_3 = VD(N)/VD(3)$$

The relative visibility index based on the visibility at target 1 (RV_1) (T1) was obtained by dividing VD at T2 and T3 by VD at T1. It gives an idea of how well the subject sees inside the tunnel as compared to outside it. Because the illumination level was low, no subject was expected to see as well inside the tunnel as outside it. A relative visibility index based on visibility at T3 (RV_3) was obtained in the same manner as RV_1 , this time using performance at T3 as the reference. The subject had been in the tunnel 16 seconds when he saw T3. He was then almost completely adapted to the interior illumination and any reduction of visibility distance at T3 (as compared to T1) was due to the lower illumination and not inadequate adaptation. The illumination at T2 (21 fc) was only slightly higher than that at T3 (8 fc). Since RV_3 takes the reduced illumination into account, the decrement for T2 in this index indicates the degree to which other factors associated with entering the tunnel reduced the visibility of the target encountered immediately after that transition.

Subject 1 showed no decrement for T2 on the RV_3 index, but the other three subjects displayed a substantial transitional effect (mean $RV_3 = .65$). Note also that these subjects signaled recognition of T2 at very nearly the same place (mean VD = 66.67 ft.). At 40 mph, this distance corresponds to an interval of about .82 second after the vehicle entered the shadow of the portal. This is a reasonable reaction time in view of the subject's task, which was to locate, identify, and respond to the target.

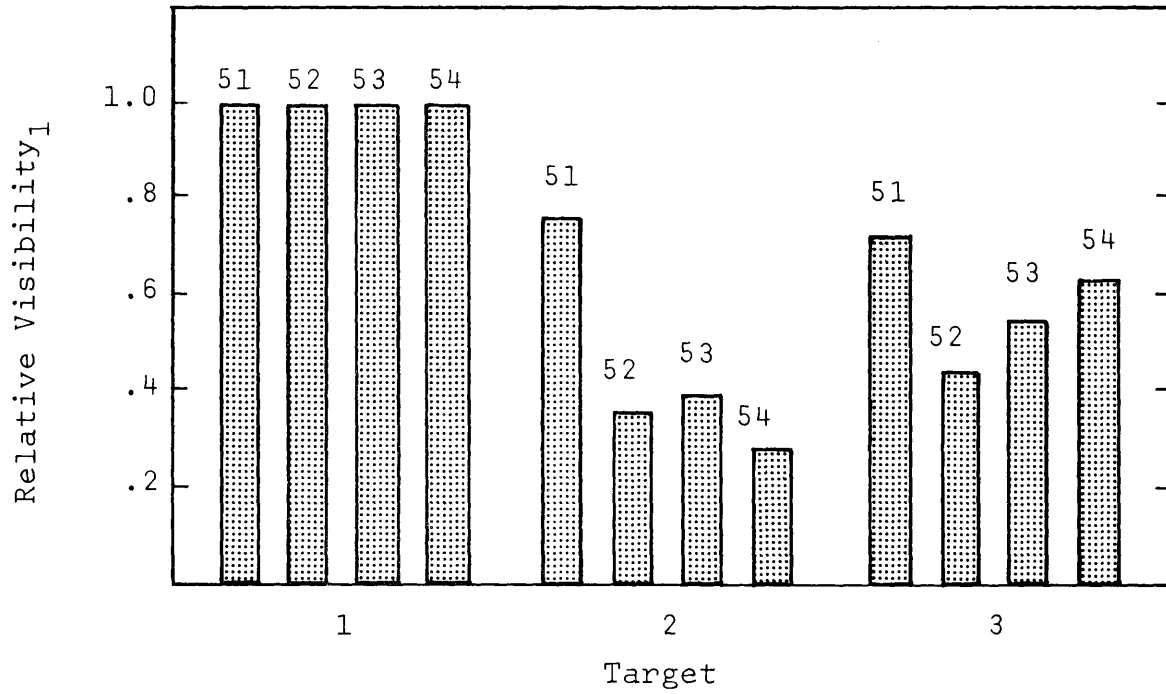


Figure 8. Relative visibility index₁ (RV₁) for four subjects.

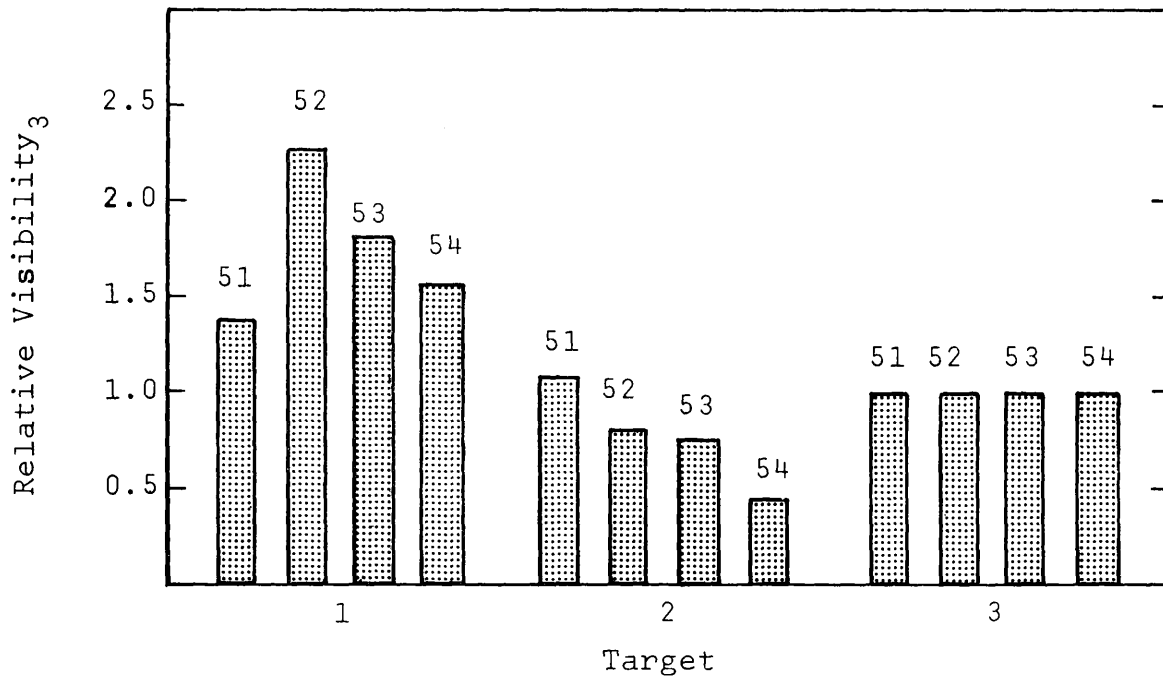


Figure 9. Relative visibility index₃ (RV₃) for four subjects.

In terms of transient adaptation (Rinalducci 1972; Boyton 1967), some decrement in subject 1's performance on T2 is to be expected, simply because of the large differences in luminance between T2 and T1. That the expected decrement is not evident is probably due to the fact that the dark tunnel portal and the southwest wall, which was in shadow, occupied most of his field of view (there were no vehicles ahead) for several seconds before he saw the second target. Under these circumstances, a large amount of adaptation may occur before the tunnel is actually entered.

Taken together, the above discussions suggest that much of the reduced visibility of T2 is due to the veiling of this target by reflections in the windshield.

Photometric Data

Light level measurements were made at the north portal of the tunnel with a telephotometer. Luminance measurements were made from the walls in the interior directly in foot-Lamberts (fL). At the portal readings were taken from the dark gray concrete which is part of the tide gate system. Inside the tunnel, luminance measurements were made from the tiled walls. Illumination measurements were made using the same telephotometer in conjunction with a cosine receptor and were recorded directly in footcandles (fc). (The system was leveled in order to measure horizontal illumination as accurately as possible.) Illumination levels were determined at a point on the north island above and to one side of the entrance to the first tube; at two locations on the open approach; at the portal; and at nine locations within the tunnel. The results of the horizontal illumination measurements are given in Table 5 and presented graphically in Figure 10.

Simple computation from the readings presented in the table shows that the ratio between the amount of light falling just outside the tunnel (at 91 ft.) and the average illumination in the first 100 ft. within the tunnel (not including the 317 fc at the tunnel portal) is approximately 408:1. If the illumination at the portal is included in the average, this ratio is lowered to 73:1. Both ratios are considerably larger than the 10:1 ratio recommended by the IES (1972).

Table 5

Illumination Measurements in Footcandles and Lux
(12 noon to 1:00 p.m., September 13 and 20, 1975)

<u>Location</u>	<u>fc</u>	<u>Lux</u>
North island (above entrance)	9,513	102,360
Open approach by guardhouse	8,936	96,151
Open approach 91 ft. in front of tunnel portal (-91 ft.)	8,763	94,290
Entrance (0)	317	3,411
+ 50 ft. inside tunnel	22	237
+ 100 ft.	21	226
+ 200 ft.	20	215
+ 300 ft.	22	237
+ 400 ft.	15	161
+ 500 ft.	14	151
+ 1,000 ft.	8	86
+ 3,700 ft. (midpoint of tunnel)	7	75

Table 6 and Figure 11 display the luminance (amount of light reflected from the walls) measured at various locations within the tunnel. To allow the computation of indoor-outdoor luminance ratios, the luminance of an average background of medium reflectance was calculated for three locations outside the tunnel and are included in the table.

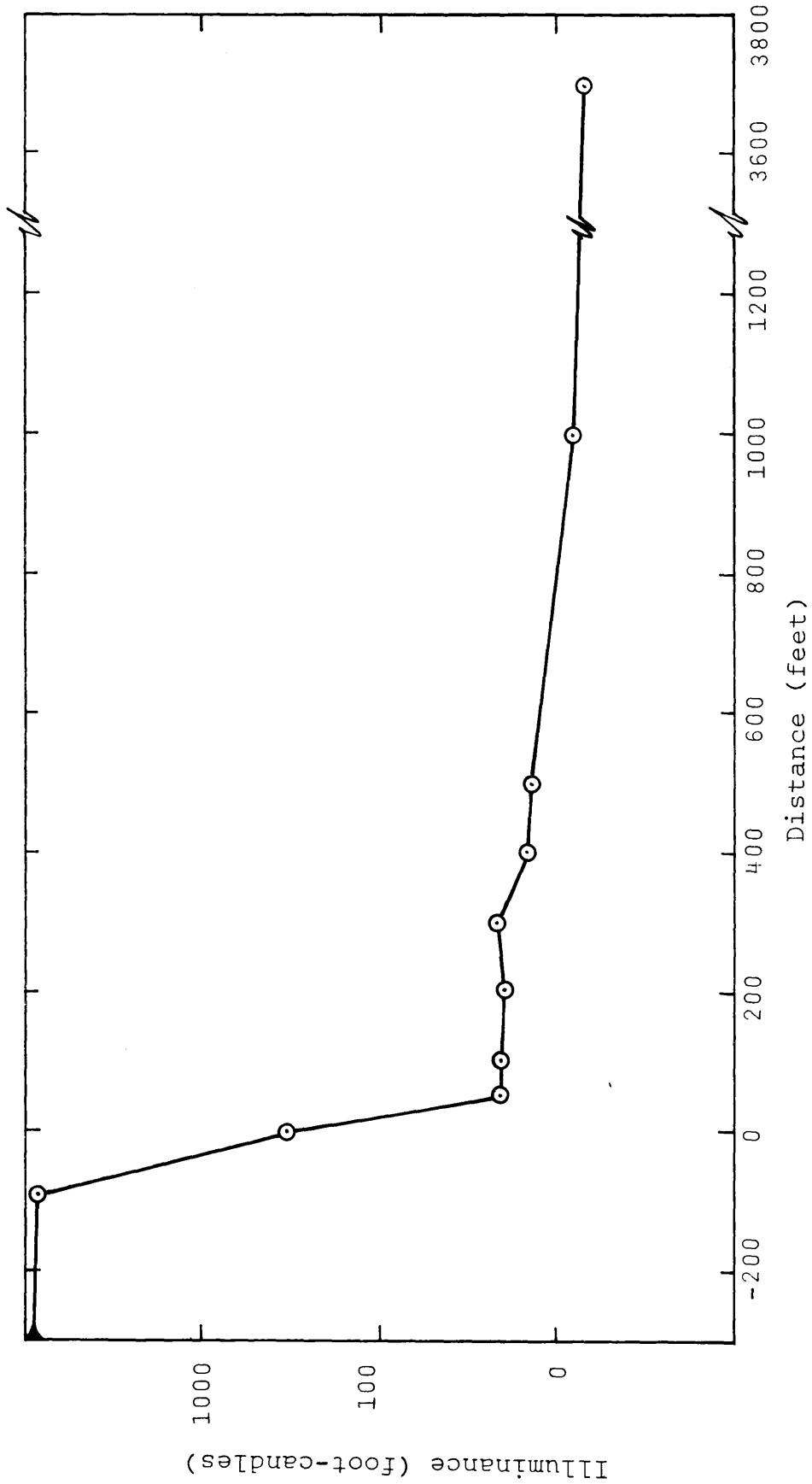


Figure 10. Illumination profile of the north entrance to the Hampton Roads Bridge-Tunnel. Note that the ordinates are logarithmic scales.

Table 6

Luminance Measurements in Foot-Lamberts
and Candelas/Meter²

<u>Location</u>	<u>fL</u>	<u>cd/m²</u>
North island (above entrance)	1,586*	5,430
Open approach by guardhouse	1,489*	5,101
Open approach 91 ft. in front of tunnel entrance	1,460*	5,002
Entrance (0 ft.)	6.8**	23.3
+ 26 ft. inside tunnel	11.2	38.4
+ 50 ft.	8.3	28.4
+ 100 ft.	6.5	22.3
+ 200 ft.	6.6	22.6
+ 300 ft.	5.8	19.9
+ 400 ft.	5.7	19.5
+ 500 ft.	3.9	13.4
+ 1,000 ft.	2.6	8.9
+ 3,700 ft.	2.7	9.2

*Based on fc measurements given in Table 5. The average luminance of a background averaging 25% reflectance was calculated according to formulas presented by Ketvirtis (1975). The procedure is elaborated in Appendix F.

**Values given for inside the tunnel are luminance measurements made directly from the tunnel walls.

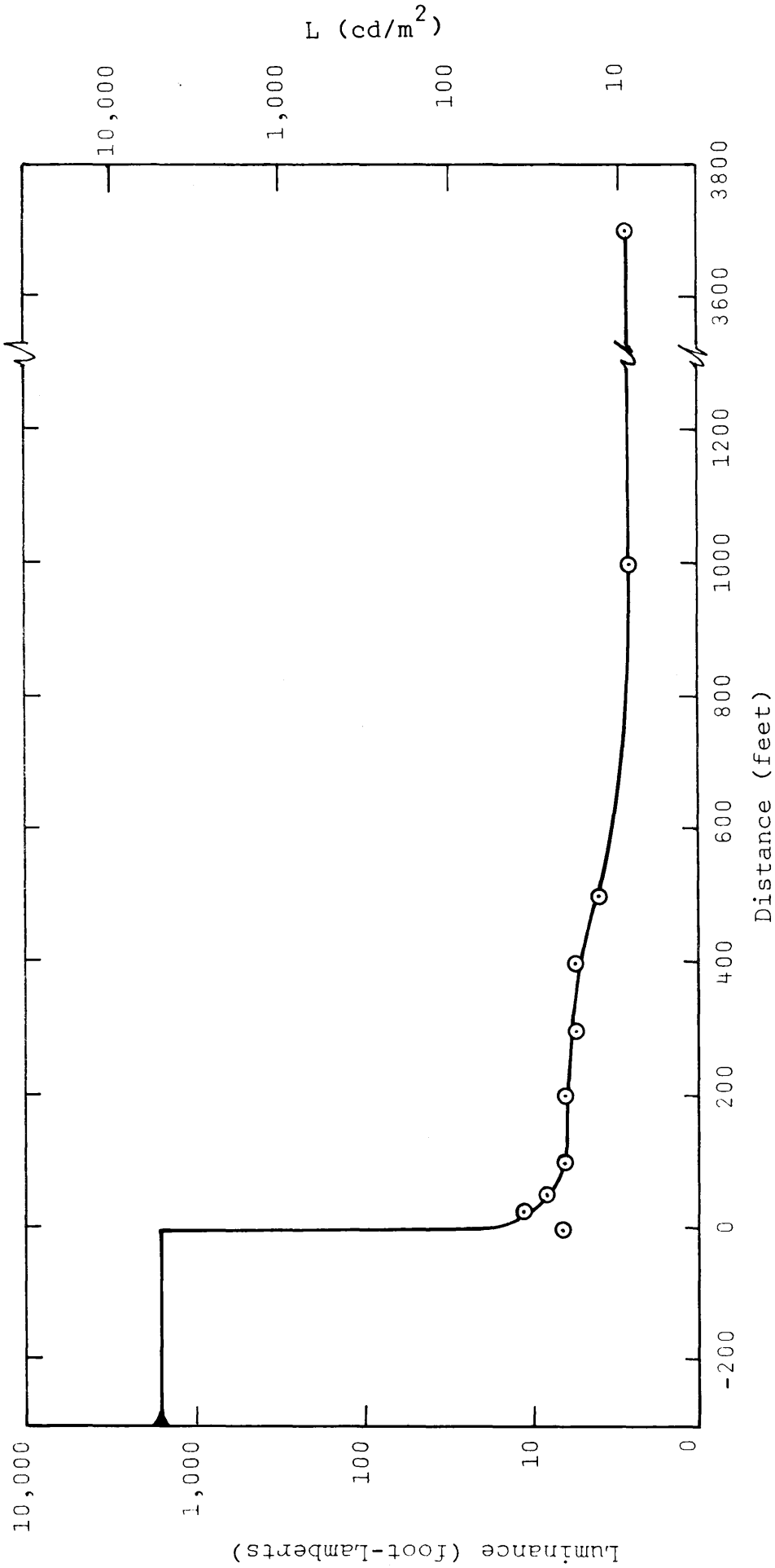


Figure 11. Luminance profile of the north entrance to the Hampton Roads Bridge-Tunnel. Note that the ordinates are logarithmic scales.

Combining the four values obtained within the first 100 ft. of the tunnel yields a value of 8.2 fL (28.1 cd/m²) for the average luminance of the entrance. If this value is compared to the calculated luminance of the averaged background (in this case the walls of the approach or back of a vehicle) at 91 ft. from the portal, the resulting luminance ratio is 178:1, which is considerably larger than the 10:1 ratio in luminance levels recommended by the CIE (1974) and the 25:1 ratio recommended by Ketvirtis (1975).

Given the large ratios of ambient illumination and luminance levels outside the tunnel to those inside the tunnel there should be a significant loss of visibility. Excessive ratios give rise to the black hole effect outside the tunnel and a "black-out" effect (temporary decrease in visibility due to transient adaptation) described in detail by Boynton (1967), Ketvirtis (1975), Narisada (1972), Rinalducci (1972), and Schreuder, (1967, 1972, 1975). In addition, objects in the dark area created by the tunnel entrance are more likely to be hidden by veiling reflections on the windshield (Allen 1970).

User Survey

User survey questionnaires were distributed by the toll collectors to all southbound motorists on Thursday, August 21, 1975, between the hours of 7:00 a.m. and 7:00 p.m. Weather conditions on the day of the survey varied greatly. Between 7:00 a.m. and 9:00 a.m. it was bright but cloudy; from 9:00 a.m. to 10:30 a.m. it was overcast with rain, and by 11:00 a.m. it was hazy but bright, and remained bright throughout the rest of the day.

A total of 9,927 questionnaires were issued, and 2,323 (23.4%) were returned by mail to the Virginia Highway and Transportation Research Council. The largest proportion of questionnaires returned (37.4%) was from the frequent users of the tunnel — those who made 10 or more trips per week through it. The next largest proportion (21.9%) was from the very infrequent user — those who averaged less than once a month.

The questionnaires were numbered so that it could be determined in what hour each was distributed. The number of frequent users peaked at about 8:00 a.m. and again between 4:00 p.m. and 5:00 p.m., i.e., they were commuters traveling to and from work. The very infrequent users seemed to be distributed fairly evenly between the hours of 9:00 a.m. and 5:00 p.m., with a small increase between 11:00 a.m. and 12:00 noon.

In response to the question "Have you ever experienced any difficulty in seeing the cars in front of you?" 45.6% of the respondents indicated "Yes." The distribution of responses to this question was related to the motorists' frequency of use. The most frequent users were more than twice as likely to say "Yes" than were the occasional users. This finding can be accounted for simply by the repeated exposure of the frequent users to the tunnel under varying conditions.

Of the respondents who reported difficulty in seeing cars ahead of them, 83.1% reported that the difficulty occurred in the area of the tunnel entrance. This percentage consists of 36.5% who indicated the problem was greatest just after the tunnel entrance; 34.1% who thought the problem was just before the entrance; and an additional 12.5% who checked both "before" and "after" entrance responses.

Motorists who had experienced difficulty seeing cars did not agree on when this problem was greatest. While 34.8% marked 10:00 a.m. to 2:00 p.m. as the worst time, 33.0% indicated the late afternoon period from 2:00 to 4:00 p.m., and 10.7% checked the 7:00 a.m. to 10:00 a.m. period. As Figure 12 shows, however, the 10:00 a.m. to 2:00 p.m. period is clearly the predominant response for all but the most frequent users. Commuters use the tunnel much more in late afternoon than in midday, and perhaps this accounts for their responses to this question.

In this questionnaire motorists were invited to comment on the tunnel environment and 34.7% of the respondents did so. The more frequent comments were categorized and counted. Many good suggestions and criticisms were received and some of those which do not directly pertain to this study are given in Appendix G.

Of the people who submitted comments, about 17% mentioned sun-related visibility problems. While only one person specifically mentioned "windshield glare," many commented on bright sunny days which cause "glare," "blind spots", or "impossible eye adjustments." The comments describe the high contrast between ambient light and tunnel light. When a car ahead goes into the tunnel, "he becomes momentarily lost because glare outside makes the tunnel seem black until you enter it." A few people noted the glare problem, but dismissed it as not so serious as to make the entrance unsafe. For many other people, however, the inability to see into the tunnel is a very real, albeit momentary, problem. Solutions spontaneously suggested by respondents include some type of sunscreen and painting the walls of the approach darker.

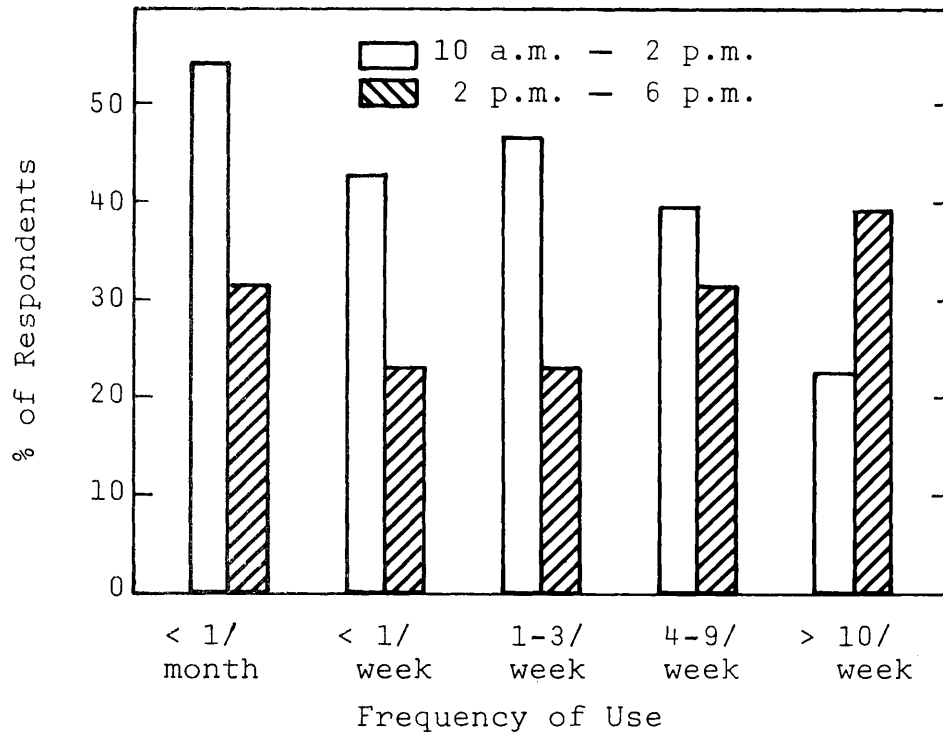


Figure 12. Responses to the question "... when was (the visibility problem) worst?" as a function of the frequency with which respondents use the tunnel.

In addition to the problem of seeing into the tunnel, there seems to be a brief period of reduced visibility once inside the tunnel during which one's eyes adapt to the relative darkness. About 4% of those making comments suggested brighter lights, particularly at the entrance.

In summary, the above data show that a substantial number of motorists have at some time experienced difficulty seeing cars immediately ahead of them. This difficulty occurs primarily around the tunnel entrance during the peak daylight hours.

CONCLUSIONS

It can be concluded from the results of the studies described in the foregoing pages that there is indeed a visibility problem at the Hampton Roads Bridge-Tunnel. The existence of a problem is

particularly evident in the results of the human performance and photometric visibility studies and the survey of motorists using the tunnel. The human performance data indicate that veiling luminance or windshield reflection at the tunnel portal can be an important factor in reducing visibility as suggested by Mintz (1972). The photometric visibility study indicated that there was a higher ratio between the light available outside the tunnel entrance and that of the tunnel interior than has been recommended by the IES (1972), the CIE (1974), Narisada (1972, 1975), or Ketvirtis (1975). In addition, 45.6% of the respondents in the survey reported that they had experienced a severe visibility problem at some time. The majority of these respondents had experienced difficulty in seeing in the vicinity of the tunnel entrance. Opinion was about evenly split between the problem being greater just before or just after the tunnel entrance.

Although there is a definite visibility problem at the north portal, the practical consequences seem to be minimal. There is no obvious effect on safety as judged from the accident reports. Radar and motion picture studies of traffic entering the north portal did, however, indicate a potentially significant problem in the form of reduced traffic flow. It is clear that the visibility problems associated with the black hole effect, and the veiling luminance from reflections on the windshield can act to reduce the speed of vehicles entering the tunnel and thus restrict the flow of traffic. However, other factors may have the same effect: the apparent constriction of the roadway produced by the proximity of the walls of the open approach, the curved descent into the tunnel, the closeness of the walls in the tunnel interior, and the presence of oncoming traffic all probably contribute to the slowdown. The fact that the majority of drivers of the lone and lead vehicles applying their brakes did so at distances greater than 135 ft. suggests that windshield reflections are not the primary cause.

To combat the visibility problems described in his investigation, Mintz (1972) proposed that a sunshield be constructed. His design consisted of a sequence of glass plates of increasing density which would progressively reduce the sunlight in the tunnel approach zone. A model was constructed by Mintz to demonstrate the effectiveness of this method. This kind of sun-screen involves a novel design that may entail considerable engineering and maintenance problems. Other kinds of sunscreens are in use in this and other countries, but Schreuder (1975) has indicated that the use of sunscreens or louvres has not as yet been fully evaluated; some research has found them to be effective and some has not. Westermann (1975) has pointed out that the installations often have a high initial cost and frequently require

continued heavy expenditures for maintenance. Since the visibility problems at the north portal, though at times severe, do not seem to reduce the safety of the tunnel in terms of accidents, the warrant for a sunscreen comes down to a question of efficient traffic flow. With the steadily increasing volume of traffic at the installation, the slowdown at the present north portal could in time become a definite bottleneck. The slowdown is attributable in part to reduced visibility into the tunnel and in part to factors relating to the geometry of the approach. A sunscreen would have no effect on the geometric factors. Use of the second tube, which is wider and eliminates oncoming traffic, will certainly reduce the likelihood of a bottleneck developing. Since the second tube is in most respects like the older one, similar visibility problems will be encountered, but the authors do not think these are severe enough, by themselves, to warrant the expense involved in constructing a sunscreen at this time.

There are, however, some relatively simple and inexpensive steps that can be taken to increase visibility into the tunnel which would likely be justified in terms of increased user comfort and increased speed through the entrance. A variety of techniques have been used or suggested to deal with tunnel visibility problems (Ketvirtis 1975; Westermann 1975; Bijllordt 1975; Muller and Reimenschneider 1975). Some of these include:

1. High entry portals with a flared opening to allow greater spill-in of light at the entrance;
2. an augmented lighting gallery just inside the tunnel entrance;
3. dark colored tunnel facades, approaches, and road surfaces outside the tunnel which act to reduce the contrast between the tunnel interior and the immediate surroundings;
4. light colored walls in the tunnel interior; and
5. light colored road surfaces inside the tunnel.

Modifying the portal at this time would be an expensive project unlikely to produce satisfactory results. Augmenting the existing threshold lighting with high pressure sodium sources (which have been found to be more efficient and economical than other kinds) is a more viable, but still fairly costly, alternative. The authors hesitate to recommend expensive alterations until simpler, less expensive ones have been tried.

Three of the above techniques involve manipulation of the reflectivity of surfaces in and near the tunnel. Some combination of these methods should reduce the black hole and adaptation effects. (Mintz (1972) indicated that the windshield reflections did not appear to be reduced when the tunnel facade in his model was blackened. The dark background thus provided tends to make the reflections more obvious and annoying, though it may reduce their luminance somewhat.)

The concrete supports associated with the tide gates at the tunnel portal are dark gray and thus absorb a considerable amount of light falling on them from the outside. The photometric data in Tables 3 and 4 show that virtually no spill-in can be detected 50 ft. inside the portal at present. If this zone were painted a lighter color, or the tiling on the walls extended to the tunnel entrance, the amount of light spilled into the tunnel would be increased and the contrast between the luminance of the mouth of the tunnel and the immediate surroundings, which causes the black hole effect, would be reduced.

Another modification which would aid the motorist in guiding his vehicle into the tunnel and help him to maintain lane position would be to provide visual cues by edge marking. This simple addition would make the lateral limits of the roadway more visible, and thus give the motorist more confidence when entering the tunnel and allow him to maintain a higher speed.

If the two modifications described above are tried and found to be insufficiently effective, consideration should be given to the use of light colored pavement in the transition zone (Bassett, McCullough, and Hawley 1974). A lighter road surface would increase spill-in of light and would help to reveal vehicles by providing a bright background against which they would be silhouetted.

This technique, suggested to increase visibility at the tunnel entrance, might first be tested on the model constructed by Mintz (1972).

In summary, the investigation found that there is a definite visibility problem at the north portal of the Hampton Roads Bridge-Tunnel complex. The problem is severe enough to have bothered about half of the users of the tunnel at one time or another, but not so severe as to cause difficulty in handling the present volume of traffic. There is a significant slowdown when entering the tunnel from the north. Difficulty seeing into the tunnel probably contributes slightly to this slowdown, but is not the sole cause. Construction of a sunscreen is not at the present time justified on the basis of safety or traffic flow considerations. It is the opinion of the investigators that the existing difficulty seeing into the tunnel could be reduced by extending the reflective tiling used inside the tunnel to the mouth and by edge striping the roadway.

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- Schreuder, D. A. Tunnel lighting in Europe (abridged). HRB Circular 136, August 1972, 28-32.
- Schreuder, D. A. Fundamental visual problems in tunnels. Lighting Research and Technology, 1975, 7, 85-87.
- Thompson, J. A. and Fansler, B. I. Criteria for highway tunnel lighting design. Public Roads, 1968, 35, 77-105.
- Westermann, H. O. Engineering aspects of tunnel lighting. Lighting Research and Technology, 1975, 7, 90-94.

APPENDIX A

ANNOTATED BIBLIOGRAPHY

Part I. Basic References

Reference works which are of general importance to the basic problems of tunnel lighting.

Bassett, G. F., McCullough, V. A., and Hawley, W. L., Mercury Light For a tunnel. Lighting Design and Application, 1974, 4, 40-42.

The lighting characteristics of the Welland Tunnel in Ontario, Canada, are described. Attention is given to the general aspects of the tunnel's design which contribute to driver visibility. A description of the luminaires used, their power supply, and the necessary maintenance also is given.

Brass, J. R., Skootsky, H., and Trospen, G. A. A new approach to highway tunnel lighting. Illuminating Engineering, 1957, 52, 137-149.

An approach to tunnel lighting design is presented which considers wall and ceiling brightness as the most important factors for driver visibility. Basic experimental procedures for determining visibility are given. Recommendations are made for lighting the entrance and central zones of tunnels.

Commission Internationale de l'Eclairage. International recommendations for tunnel lighting. Publication 26, 1973.

General recommendations for the lighting of tunnels are presented. Attention is given to the most troublesome aspects of tunnel lighting design, e.g., how to avoid the "black hole" effect. The admissible value of the ratio between luminances on the open road and the tunnel threshold zone is set at 10:1.

Einhorn, H. D., Simple calculation methods for the lighting of passages and tunnels. Lighting Research and Technology, 1975, 7, 30-34.

Average luminance is used as the basis for a simplified method of determining the lighting requirements of passages. The basic principles demonstrated in this method are combined with the concept of sector flux to produce equations which can be used to determine the appropriate lighting of tunnels.

Illuminating Engineering Society. Lighting of tunnels. Journal of IES, 1972, 247-255.

Recommendations are made for the design of tunnel lighting systems. General illumination design factors are discussed. Specific recommendations are made for both nighttime and daytime lighting of short and long tunnels.

Ketvirtis, A., Illumination design for vehicular tunnels. Paper presented at Highway Research Board, Washington, D. C., 1971. Abridged edition published in Highway Research Circular, 1972, No. 137, 33-43.

In order to design a lighting system which supports the safe and efficient operations of a tunnel, a number of factors must be considered. The functions served by different areas of the tunnel, the tunnel's overall geometrical design, and its traffic characteristics all have an effect on visibility requirements. The greatest design problem lies in attempting to provide a smooth transition from outside luminance levels to tunnel threshold luminance levels. In Europe, sunscreens are often used to provide this transition. Sunscreens, however, are expensive and are affected by weather conditions. Ketvirtis suggests that tunnel lighting systems adopt the luminous gallery method instead of sunscreens.

Ketvirtis, A., Visibility study for long vehicular tunnels. Journal of IES, 1975, 4, 120-128.

According to Ketvirtis, disagreements regarding acceptable tunnel lighting practices are explained, in part, by the wide variety of factors which can affect driver visibility at the tunnel entrance. These factors are discussed, and are shown to preclude strict application of standard tunnel lighting recommendations. Ketvirtis recommends that the lighting requirements of tunnels be determined on an individual basis. The outlines of an appropriate visibility study are given.

Mintz, D. A., Hampton Roads Project, Second Bridge-Tunnel Crossing Approach, Lighting Environment Study, 1972.

A technical report of field observations and laboratory simulations. Field observations at the Hampton Roads Tunnel indicated that loss of visibility at the tunnel entrance is due primarily to windshield reflections. These observations were confirmed by means of a model which simulated the tunnel environment. Various methods of eliminating the observed visibility problems were tested with the model. Conventional methods were not adequate to solve the visibility problems. Model simulations indicated that the installation of a sun shield over the tunnel approach would be the best solution.

Muller, E., and Riemenschneider, W., Tunnel lighting in Switzerland. Lighting Research and Technology, 1975, 7, 99-101.

A brief history of the trends in Swiss tunnel lighting practices from 1964 to the present in various Swiss tunnels are compared.

Narisada, K., Applied research on tunnel entrance lighting in Japan. Lighting Research and Technology, 1975, 7, 87-90.

The basic Japanese recommendations regarding tunnel entrance lighting are presented and compared with the CIE recommendations. Experiments are summarized which demonstrate the influence of various experimental parameters on recommended luminance levels.

Narisada, K., Latest research in tunnel lighting in Japan. Highway Research Circular, August, 1972, Number 137, 9-27.

Problems of driver visibility at the tunnel entrance are discussed in terms of two widely observed phenomena: the "black-out" effect and the "black hole" effect. Previous research concerned with the latter effect, and the economics of alleviating it, are discussed. Japanese research which simulates the "black hole" effect in the laboratory is reported and compared with the earlier research. The Japanese experiments indicate that the luminance level required at the tunnel entrance depends upon the driver's "fixation" point and not simply the average outdoor luminance level.

Narisada, K., and Yoshikama, K., Tunnel entrance lighting — effect of fixation point and other factors on the determination of requirements. Lighting Research and Technology, 1974, 6, 9-18.

Japanese and CIE recommendations for daytime tunnel entrance lighting differ. The Japanese recommend a much lower level of luminance than the CIE. This difference can be traced to the Japanese assumption that the eyes begin to adapt to the lower levels of luminance inside the tunnel at a point far in advance of the CIE's adaptation point. The Japanese call the point on the approach road at which the eyes begin to fixate on the tunnel entrance and, subsequently, begin to adapt to a lower level of luminance, as the "fixation point." Eye movement studies are presented in this article which support the concept of a fixation point.

Rinalducci, E. J., Transitional adaptation in tunnel lighting. Highway Research Circular, August, 1972, Number 137, 1-8.

The phenomenon of transitional adaptation is relevant to problems of driver visibility at the tunnel entrance. Laboratory experiments are described in this article which simulate some of the problems of visibility associated with transitional adaptation. The results of these experiments are expected to assist in the design of appropriate tunnel lighting systems.

Schreuder, D. A., Physiological aspects of the lighting of tunnel entrances. Philips Technical Review, 1966, 27, 76-86.

Induction ("black hole") and adaptation effects are said to account for problems of driver visibility at the tunnel entrance. These two effects do not occur simultaneously, but rather consecutively. Induction is assumed to limit visibility only prior to a hypothetical adaptation point. Experiments are described which attempt to determine tunnel lighting requirements to avoid both effects.

Schreuder, D. A., Road tunnels in the Netherlands. Light and Lighting, 1967, 60, 370-377.

The physical characteristics of seven tunnels in the Netherlands are given. The lighting system adopted in each tunnel is described.

Schreuder, D. A., Trends in European tunnel lighting practice. Illuminating Engineering, 1967, 62, 390-396.

European tunnel lighting recommendations are in basic agreement on the solutions to four major problems: the "black-hole" effect, adaptation time, the flicker effect, and interior levels of luminance. Each of these problems and its solution are discussed in detail.

Schreuder, D. A., Tunnel entrance lighting — a comparison of recommended practice. Lighting Research and Technology, 1971, 3, 274-278.

Discrepancies exist between CIE recommendations regarding tunnel lighting and the recommendations of other research groups, particularly those of the Japanese. The latter propose a much larger admissible value for the ratio between outside ambient luminance and tunnel threshold luminance. According to Schreuder, recommended ratios which exceed the CIE's proposed 10 to 1 ratio are based upon inappropriate assumptions regarding driver behavior and prevailing traffic conditions. Ratios larger than 10 to 1 are appropriate only in exceptional circumstances (e.g., in mountain tunnels where traffic is light).

Schreuder, D. A., Tunnel lighting in Europe. Highway Research Circular, August, 1972, 137, 28-32.

Tunnel lighting practices in Europe are moving toward uniformity. National tunnel lighting codes are in basic agreement with the recommendations of the CIE. The CIE recommendations are briefly outlined here, and the lighting systems adopted in three different types of European tunnels are discussed.

Schreuder, D. A., Practical experience with tunnel lighting installations in the Netherlands. Light and Lighting, 1974, 66, 188-191.

The tunnel lighting recommendations of the Illuminating Engineering Society of the Netherlands (NSVV) are summarized. Five tunnels in which the NSVV recommendations were applied and are discussed. Finally, how valid the NSVV recommendations seem to be in actual practice is discussed.

Schreuder, D. A., Fundamental visual problems in tunnels. Lighting Research and Technology, 1975, 7, 85-87.

The "international standard object" is discussed and justified as an appropriate criterion of visibility. Experiments upon which various tunnel lighting recommendations are based are outlined briefly and shown to be in good agreement. Differences between the CIE recommendations and the recommendations of the Japanese are seen as arising from differing environmental factors found in the regions in which they are applied.

Thompson, J. A., and Fansler, B. I., Criteria for highway tunnel lighting design. Public Roads, 1968, 35, 77-90.

A review of literature relevant to highway tunnel lighting and a survey of the lighting systems used in major U. S. tunnels are presented. Based on the information obtained from the literature review and survey, recommendations are made for lighting underpasses, short tunnels and long tunnels. Guidelines for both daytime and nighttime levels of illumination for each category of tunnel are presented also.

Thompson, J. A., Fansler, B. I., and Ragland, J. S., Tunnel and underpass lighting practice in the U.S.A. Highway Research Circular, August, 1972, 137, 44-47.

The general methods of illumination used in the United States are briefly outlined. It is noted that today the lighting systems of most long U. S. tunnels utilize a single type of luminaire, the fluorescent lamp. The authors suggest that greater use should be made of both sunscreens and combinations of different types of luminaires in order to meet daytime visibility requirement.

Van den Bijllaardt, D., Tunnel lighting practice in the Netherlands. Lighting Research and Technology, 1975, 7, 95-98.

The installation of daylight louvers is no longer a recommended means of lighting tunnel entrances in the Netherlands. Artificial lighting is now the preferred practice. Recent Dutch advances in methods of tunnel lighting and maintenance are reported.

Westermann, H. O., Engineering aspects of tunnel lighting. Lighting Research and Technology, 1975, 7, 90-94.

Daylight louvers have been installed in tunnels in order to provide a smooth transition from outside to inside luminance levels. The disadvantages of this practice are briefly discussed. Detailed consideration is given to the use of artificial lighting as an alternative to daylight louvers.

Part II. Supplementary References

References which are either less general in scope as they apply to the basic problems of tunnel lighting or appear in foreign-language journals. Summaries obtained verbatim from a computer search of references conducted by Virginia Highway and Transportation Research Council.

Berry, G., An investigation into the lighting of road tunnels and underpasses, University of Birmingham, 1969/70.

Summary: The investigation has involved a study of reports on the results of research carried out in the international field in regard to the lighting of road tunnels and underpasses, including inspections of recent schemes in Western Europe and technical details from other countries including Japan, Canada, and U. S. A.

Haukeliveien, Bjorseth H., Lystekinske under sokelser, I forbindelse med tunnelene pa institutt for elektriske anlegg og elektrovarme nth, 7034 Trondheim, (Norway).

Summary: The design of tunnel lighting is investigated on the basis of reducing the supply of electrical energy but maintaining the same degree of luminance. This is to be achieved by applying light colored aggregate in the pavement and light colored walls or a different design of light armature.

Castagnetta, V., Light-colored anti-skid bituminous pavements and their contribution to traffic safety, Riv. Strada. (Italy), Vol. 37, 326, Sept. 68.

Summary: Progress in the last seven years in the development and use of light colored synthetic aggregates in flexible pavements is reviewed. The light-colored aggregates give better light reflection and better visibility, especially in tunnels, with less surface heating.

Cecil, E. F., Subaqueous interstate highway tunnel design and construction, Kentucky Highway Conference Proceedings; 22nd Annual Conf., pp. 30-5. July 71.

Summary: After conducting tunnel studies, Palmer and Baker Engineers, Inc., consultants for the Alabama State Highway Department, completed the design, plans, and specifications for a four-lane, twin-tube tunnel. First, structural design is delineated

for ramps, arch sections, ventilation buildings, twin-tube section, and transition sections. Second, the operations characteristics that are covered in this presentation are ventilation, tunnel lighting, drainage, and pumping, power supply, fire protection, and traffic control. Third, tunnel construction covers contracts that were let and quantities of major items that were needed. Fourth, under the section on special construction considerations, tunnel alignment complications, channel clearances, and floated-in-place tubes are indicated as potential problems in planning.

Cohu, M., Committee for lighting, 17th session Barcelona 7-15 September 1971. (Proceedings), Revue generale des routes et des aerodromes, revue generale des routes; 9 Rue Magellan, Paris 8E; France.

Summary: These proceedings deal with problems concerning public lighting, especially lighting of motorways, tunnels and covered passages. Individual reports are summarized, especially reports dealing with the measurement of the reflecting characteristics of surfacings.

Edwards, J. H., Graham, Dr., The Claremont to Danville road tunnel technology and potential of tunnelling, South African Tunnelling Conf., June 70.

Summary: A description is given of the design and construction to the stage reached in February 1970 of the 1,880 foot long road tunnel from Claremont to Danville in Pretoria. The tunnel runs north to south through the Daspoort system of the Pretoria series. The tunnel centerline was investigated by preliminary drilling, and additional soil tests were conducted after the approach cuttings had been completed. Soil test results are given. The design allows for two traffic lanes and two footwalks, giving a tunnel width at road level of 38 feet. Canopies are provided at each tunnel entrance and a ventilation shaft is provided at mid-length of the tunnel. Light is transitioned into and along the tunnel. Tunnel light values are given. A description is given of the method of construction of the approach cuttings and of driving the tunnel from north to south. Construction has not yet commenced on the southern end of the tunnel.

Janoff, M. S., Lighting in 30th street underpass in I-676, Franklin Institute Research Laboratories; Benjamin Franklin Parkway, Philadelphia, Pa. Study No. C3861.

Summary: This project will evaluate the effect on traffic operations and accidents of changing the lighting in the 30th street underpass on I-676, including new lighting, reflective

walls and resurfacing. IES and AASHTO recommendations for tunnel lighting will be compared and the photometrics of the low-pressure sodium lamps will be measured.

Kalberlah, K., Investigations into the illumination of tunnels and subways, Lichttechnik (Germany), Vol. 22, 7, July 70.

Summary: The distribution of the illumination in tunnel is determined by means of a procedure developed specially for that task, by analogy to the coefficient of utilization method of interior lighting. Formulas are indicated for the optimal wall distance of a fitting mounted on the ceiling and for the optimal angle of the maximum intensity of fitting lines in the corner of the tunnel.

Linarez, Sanchez, A., General problems of tunnel construction, matls. Maquinaria metodos constr. (Spain), N84, August 71.

Summary: This article reviews the economic, social, and technical problems arising during tunnel construction. Tunnels are classified according to use: passenger transport, other uses. Limit values are given for a number of physical, safety, and traffic characteristics needed in preliminary studies and projects: Geological studies, geometric design, ventilation, design, traffic, weather conditions, lighting, and traffic control systems.

Marc, R. C., The underground routine of urban highways. Roads and Road Construction, (Uk) Vol. 49, 578-9, Feb. 71.

Summary: The advantages derived by the community and the road user from the construction of underground urban roads are described with regard to cost, land loss, noise, visual barrier, pedestrian barrier, community division, appearance, driving comfort, access, and view. The depth of tunnels, design of access roads, tunnel shape and construction methods, ventilation, lighting and services are discussed together with the facilities offered by a central city terminal.

Megaw, T. M., Road tunnel construction South African Institution of Civil Engineers, Marshalltown, Transvaal, South Africa, June 1970.

Summary: The three main situations in which road tunnels are used are defined and the development of tunnelling techniques to meet these needs is described. The features particularly characteristic of road tunnels are noted, including requirements for ventilation and lighting. A description follows of the design and construction of the subaqueous second Mersey tunnel now being built.

Morgan, H. D., Haswell, C. K., Pirie, E. S., — Clyde Tunnel Design, construction and tunnel services Inst. Civil Engineers Proc., (Uk) Vol. 30, 2, Feb. 65.

Summary: Part 1 deals with the design and scheme of construction adopted for a road tunnel in particularly variable and difficult ground. Part 2 is concerned with the equipment for lighting, ventilating and other ancillary services. There are twin 2-lane tunnels, downstream from Glasgow, through rock overlain by alluvial deposits. A cast-iron lining was designed and the portals and approaches were of heavy reinforced concrete, the greater part of the approach being below the water table. Ventilation is fully adequate for dilution of carbon monoxide and for visibility, the steep gradients constitute a special factor in ventilation. Lighting is by hot cathode fluorescent tubes with increased level of lighting near the entrances. All services are regulated from a central control room with provision for automatic operation.

Schreuder, D. A., Short tunnels, International lighting review. (Netherlands) Vol. 16, 3. 1965.

Summary: From the lighting point of view a short tunnel is described as one of which the exit can be seen. During the day and with no traffic, from a point at some distance from the tunnel entrance, and of which the exit then occupies a sufficiently large part of the field of vision to make obstacles in the tunnel stand out against it. In reviewing the lighting of short tunnels, the question as to which of these could remain unlit is considered. The form of lighting to be applied for the others is then discussed. A table shows lighting systems recommended for short tunnels.

Schreuder, D. A., Lighting of tunnel entrances taking into account the visual capacity of drivers. Techniques Philips, Dunod, (France), Nov. 68, 6.

Summary: Investigations are made into methods of lighting highway tunnels to enable drivers to drive safely without having to reduce speed excessively. The effects on the vision of drivers approaching and entering long, relatively dark tunnels were examined. Results of these tests were used in the design of the lighting of the Coen tunnel in Amsterdam.

Todres, H. A., Road tunnels — a literature survey, Cncl. Scient. & Indus. Res., South Africa Nat. Inst. Road Res. 1970.

Summary: There is little knowledge available concerning the design and operation of long road tunnels in South Africa. A literature survey has been conducted to determine the state of

knowledge on various aspects and problems. The information is presented under the following general headings: (A) Gradient, (B) ventilation, (C) illumination, (D) traffic capacity, (E) emergency services, (F) miscellaneous factors, (G) engineering geology, (H) tunnel sections.

Underwood, R. T., A review of freeway lighting practice, Paper No. 925, Australian Road Research Board Conv. Proc., 1972.

Summary: Current overseas practice and trends in the lighting of rural and urban freeways is summarized, warrants for the installation of lighting adopted by various authorities are discussed, and the design and levels of lighting and uniformity adopted when freeways are lit are examined. The relevance of overseas practice to Australian conditions is discussed and guidelines for the lighting of freeways are suggested. Freeway lighting experience in Victoria (Australia) is briefly reviewed. AASHTO, California, Michigan, Massachusetts, and Ontario warrants are described, and the British and European practice is outlined. United States, Canadian, British and European observances on the level and uniformity of lighting are set forth. Lighting at interchanges and on freeway bridges, underpasses and tunnels are reviewed and the types of freeway lighting are described. Other aspects covered include transition lighting, poles and pole arrangements, sign lighting (type of poles, pole bases, location of poles and catenary lighting), and the effects of brightly lit illuminating signs. A discussion of this paper and closing remarks by the author are included.

Belchen Tunnel, Switzerland International lighting review (Netherlands) Vol. 22, 2.

Summary: The Belchen tunnel is 3.2 km long and was designed for a maximum capacity of 3,600 vehicles per tube per hour. The transition zones at either end commence with a 30 m. long daylight reduction grid followed by a combination of tubular fluorescent and high pressure sodium lamps mounted in continuous rows along the walls. Lighting in the central zone consists of groups of three tubular fluorescent lamps mounted in a staggered arrangement and spaced at 15.84 m. average illumination ranges from 2,000 lux at the end zones to 40 lux at the center.

Hong Kong Tunnel, International lighting review, Foundation Prometheus Amsterdam (Netherlands), Vol. 24, 4. 1973.

Summary: This article describes the lighting system used in the Hong Kong tunnel. The 1885 m. long tunnel has a daily capacity of 80,000 vehicles. Dimensions of the tunnel are given. One continuous row of twin-lamp luminaires, recessed in the centre of

the tunnel ceiling, give the basic lighting. The luminaires are grouped in sets of 11 and they continually provide smooth visual adaptation, without glare for drivers entering or leaving the tunnel at either end. The maximum average luminance is 265 Lux. The use of threshold, transition and exit zones is described. A 6% reduction in external daytime illumination at the tunnel entrance is achieved by use of a louvered canopy in the threshold zone. The average illuminances in the various zones are automatically adjusted to the outside illuminance by switches and dimmers controlled by photocells. Three phases of outdoor lighting levels can be distinguished. Power is supplied by a diesel generator in an emergency. A ventilation plant supplies 103 m of fresh air/minute/metre of traffic lane. Traffic control and safety systems are listed. Many photographs of the lighting system are included.

Interim Guide for freeway lighting, National Association of Australian State Road Auth., Brickfield Hill, New South Wales, (Australia), 1974.

Summary: This publication which sets out interim guidelines for the lighting of freeways, is intended to be read in conjunction with the Australian standard as 1158, Part I — lighting of urban traffic routes. Warrants for freeway lighting are described which may need to be varied in special or unusual cases. A consideration of design criteria covers such aspects as level of luminance, uniformity of luminance, and transition lighting. Types of lighting sources are listed and various aspects of lighting poles are discussed. Practical installation geometrics are reviewed, as well as alternative arrangements for lighting of the through carriageways. Lighting on freeway bridges, underpasses, and tunnels are outlined. Typical lighting arrangements are listed, as well as current developments in freeway lighting.

Lighting in Amsterdam's IJ-Tunnel. Traffic Engineering and Control, (Uk), Vol. 11, 9, 1970.

Summary: Amsterdam's IJ-tunnel has a threshold zone to eliminate the "Black Hole" effect at the entrance, then a transition zone I (average luminance: 65 cd/sq. m; average horizontal illumination: 1,200 lux), a transition zone II (31 cd/sq. m; 540 lux) and the central zone (13.6 cd/sq. m; 270 lux). The average luminance levels in the various zones are automatically adjusted in accordance with the illumination level outside. Light-sensitive detector cells monitor traffic flow, and immediately inform central control of congestion or stalled vehicles.

Switzerland: Lighting for the Belchen tunnel. Tunnels and tunnelling, (Uk), Vol. 4, 1/4, 1972.

Summary: A description is given of the lighting system employed in the Belchen road tunnel in Switzerland. The tunnel has a 30 m transition zone for driver adaptation and a zone of about 125 m with combined fluorescent and high pressure sodium lamps, giving a gradually reduced level of illumination from 2,000 to 500 lux. Single lamp fittings give an illumination of 150 lux up to 300 m into the tunnel. The central zone has an illumination of 40 lux. All the latest safety devices for the control of lighting and ventilation systems have been incorporated in the design.

1969 World survey of current research and development of roads and road transport, Bureau of Public Roads (US), 1970.

Summary: Research and development studies in progress during CY 1969 or recently completed on roads and road transport are listed by country showing research agency, study title, and objective. This research includes information for 14 countries not previously surveyed, complete surveys for 9 countries, and updating information for 22 countries. The new countries surveyed are Algeria, Costa Rica, El Salvador, Ghana, Guatemala, Honduras, Ivory Coast, Liberia, Morocco, Nicaragua, Niger, Panama, Rhodesia and Tunisia. The report also includes reports on in-depth studies of the current status of research and development on lighting of road tunnels and underpasses, computer produced perspective views, phasing of vertical and horizontal alignment, effect of speed limits on road safety, end-product contracts, and joint development and multiple use of right-of-way.

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APPENDIX B

QUESTIONNAIRE

This questionnaire is part of an effort by the Virginia Highway and Transportation Research Council and the University of Virginia to identify the needs of the motorist using the present Hampton Roads Bridge Tunnel so that maximum safety and visibility can be built into the new tunnel. Please fill out this questionnaire after you have crossed the Bridge Tunnel and drop it into any mailbox. If you are a visitor to the Peninsula area, leave it at the desk of your motel to be mailed. In either case, postage is prepaid for its return. Your cooperation in completing this form will be appreciated.

(1) How often do you use the Hampton Roads Bridge Tunnel? (Check one)

10 or more times a week

1 to 3 times a week

4 to 9 times a week

Less than once a week

Less than once a month

(2) Have you ever experienced any difficulty in seeing the cars in front of you while using the Bridge Tunnel?

Yes

No

(3) If you did experience difficulty in seeing, where was it worst? (Check one or more)

Far outside the tunnel Just before the tunnel entrance Just after the tunnel entrance Far inside the tunnel

(4) If you did experience difficulty, when was it worst? (Check one)

Early morning (7 am - 10 am)

Late afternoon/early evening (2 pm - 6 pm)

Mid-morning/early afternoon (10 am - 2 pm)

Late evening (6 pm - 10 pm)

Thank you for your cooperation. Please feel free to list below any other comments you have about the tunnel environment

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APPENDIX C

SPECIFICATIONS OF THE FIRST AND SECOND TUBES

Table C-1

Specifications for the First Hampton Roads
Bridge-Tunnel Crossing*

Tunnel:

Length; 7,479 feet portal to portal
 Roadway Width; 23 feet
 Overhead Clearance; 13 feet 6 inches
 Maximum grade; 4%
 Roadway 105 feet below sea level at lowest point
 Maximum channel depth below sea level; 60 feet
 Ventilation; Eight supply fans and eight exhaust fans with
 each fan having a maximum capacity of 213,000 cubic
 foot per min. CO₂ content usually kept at two parts
 in 10,000 or less.
 Lighting; Continuous fluorescent lighting system in tunnel
 and 20,000 lumen mercury-vapor lamps on approach bridges.
 Twenty-four fc were available for the first 225 feet,
 12 fc for the next 225 feet, and 8 fc for the next
 225 feet on the remainder of the tunnel.

Approach Bridges:

Length of North Approach Bridge; 3,250 feet
 Length of South Approach Bridge; 6,110 feet
 Bridge Runway width; 30 feet
 Total Length of Bridges and Tunnels: 3.5 miles
 Speed Limit: 45 mph
 40 mph in tunnel
 Open Approach: 600 feet

*Information obtained from folder issued by the Division of Toll Facilities, Hampton, Virginia, and Thompson and Fansler (1968).

Table C-2

Specifications for the Second Hampton Roads
Bridge-Tunnel Crossing*

Tunnel:

Length; 7,315 feet portal to portal
Roadway Width; 26 feet
Overhead Clearance; 16 feet 6 inches
Maximum Grades; 4%
Roadway 108 feet below sea level at lowest point
Maximum depth of channel below sea level; 60 feet
Ventilation; Eight supply fans and eight exhaust fans with
each fan having a maximum capacity of 200,000 cubic
feet per minute. CO content is to be 2 parts of CO
per 10,000 parts of air with two lanes of uni-directional
traffic in the tunnel at a design traffic flow of 1,200
vehicles per hour per lane.

Lighting:

Continuous flourescent lighting system in tunnel with two
rows of fixtures on each side of roadway and extending
into tunnel for a distance of about 450 feet, with a
single row thereafter. (No illumination values were
given.)

Approach Bridges:

Length of North Approach Bridge; 3,226 feet
Length of South Approach Bridge; 5,925 feet
Bridge Runway width; 40 feet

*Information obtained from the Division of Toll Facilities,
Hampton, Va.

APPENDIX D

ADDITIONAL ACCIDENT DATA

The figures in this section illustrate the monthly variations in traffic volume and accident rate at the Hampton Roads Bridge-Tunnel.

In the search for a pattern in the accident data that would be indicative of a sun-related visibility problem, it was hypothesized that accidents would be more frequent in the summer, when the sun is higher in the sky. The 181 accident reports for calendar years 1972, 1973, and 1974 were tabulated by the months in which the accident occurred (Figure D-1). Inspection of the figure confirms that there were indeed more accidents in the summer months. The increased number of accidents is, however, most likely a reflection of the larger volume of traffic carried at this time (see Figure D-2). It is true that there is a slight increase in the accident rate as well (Figure D-3), but this is not judged large enough to serve as evidence of unusual visibility conditions, as the accident rate also increases as a function of volume in normal circumstances.

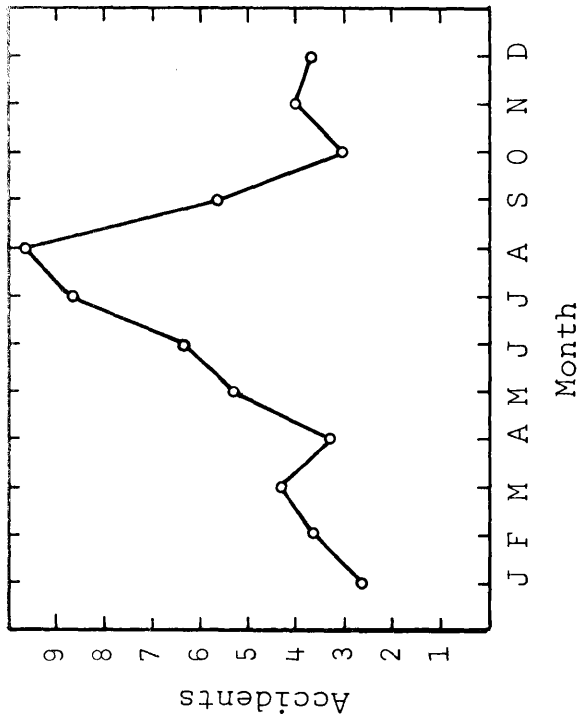


Figure D-1. Mean number of accidents per month, for calendar years 1972, 1973, and 1974.

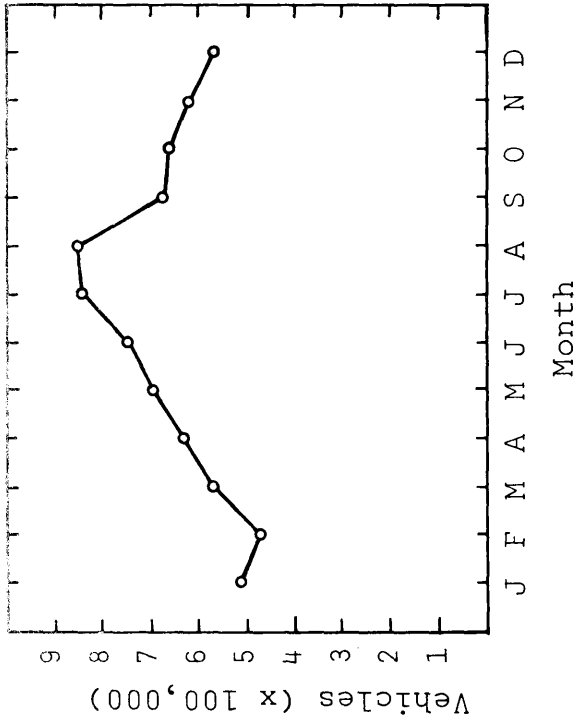


Figure D-2. Monthly volume of traffic at the tunnel. (Averaged over 1972, 1973, and 1974.)

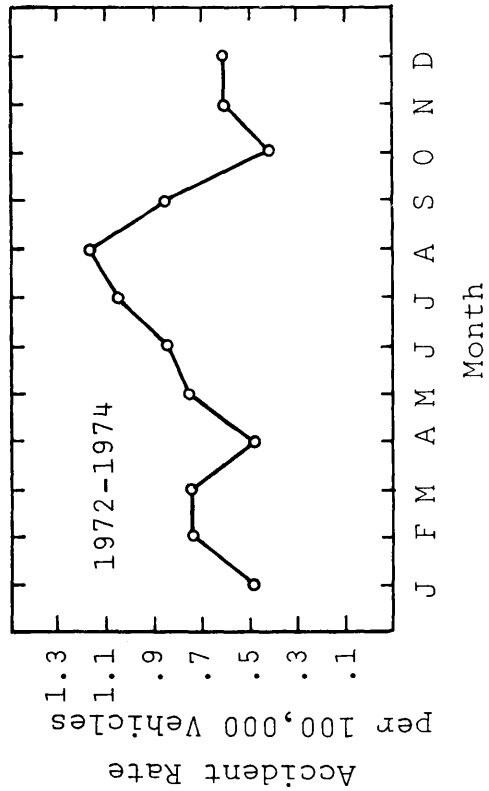


Figure D-3. Monthly accident rates at the tunnel. (Averaged over 1972, 1973, and 1974.)

APPENDIX E

CLASSIFICATION SYSTEM USED IN BRAKING ANALYSES

The following classification system was adopted for viewing films of braking patterns at the Hampton Roads Bridge-Tunnel:

0-Type: Refers to a "lone" vehicle. There must be a distance equal to or exceeding 160 feet between it and any other vehicle(s).

1-Type: Refers to a "lead" vehicle. Criteria for this type require a minimum distance of 160 feet from any vehicle(s) preceding the 1-Type and a distance of less than 160 feet for following vehicles.

2A-Type: Refers to the second vehicle in a cluster of two vehicles. There must be a distance of less than 160 feet between the 2A vehicle and the preceding (1-Type) vehicle, and a distance exceeding 160 feet from following vehicles.

2B-Type: Refers to the second vehicle in a cluster of three or more vehicles. Criteria for this type, require a distance of less than 160 feet between the 2B vehicle and the preceding (1-Type) vehicle, and a distance less than 160 feet to the following vehicle.

3A-Type: Refers to the last vehicle in a cluster of three or more vehicles. The criteria require a distance of less than 160 feet to the preceding vehicle and greater than 160 feet to the following vehicle(s).

3B-Type: Refers to a vehicle position of third or greater, but not last, in a line of traffic. There must be a distance of less than 160 feet to the preceding vehicle and less than 160 feet to the following vehicle.

Figure E-1 shows the relative number of motorists in each vehicle category who brake either before entry to the tunnel (from 145 feet outside to the portal) or immediately afterward (from the portal to 50 feet inside). This figure shows a fairly consistent pattern of braking for all vehicle types (except the 3B-Type), which indicates that 63% to 70% of all motorists brake at some point prior to or immediately following the tunnel entrance.

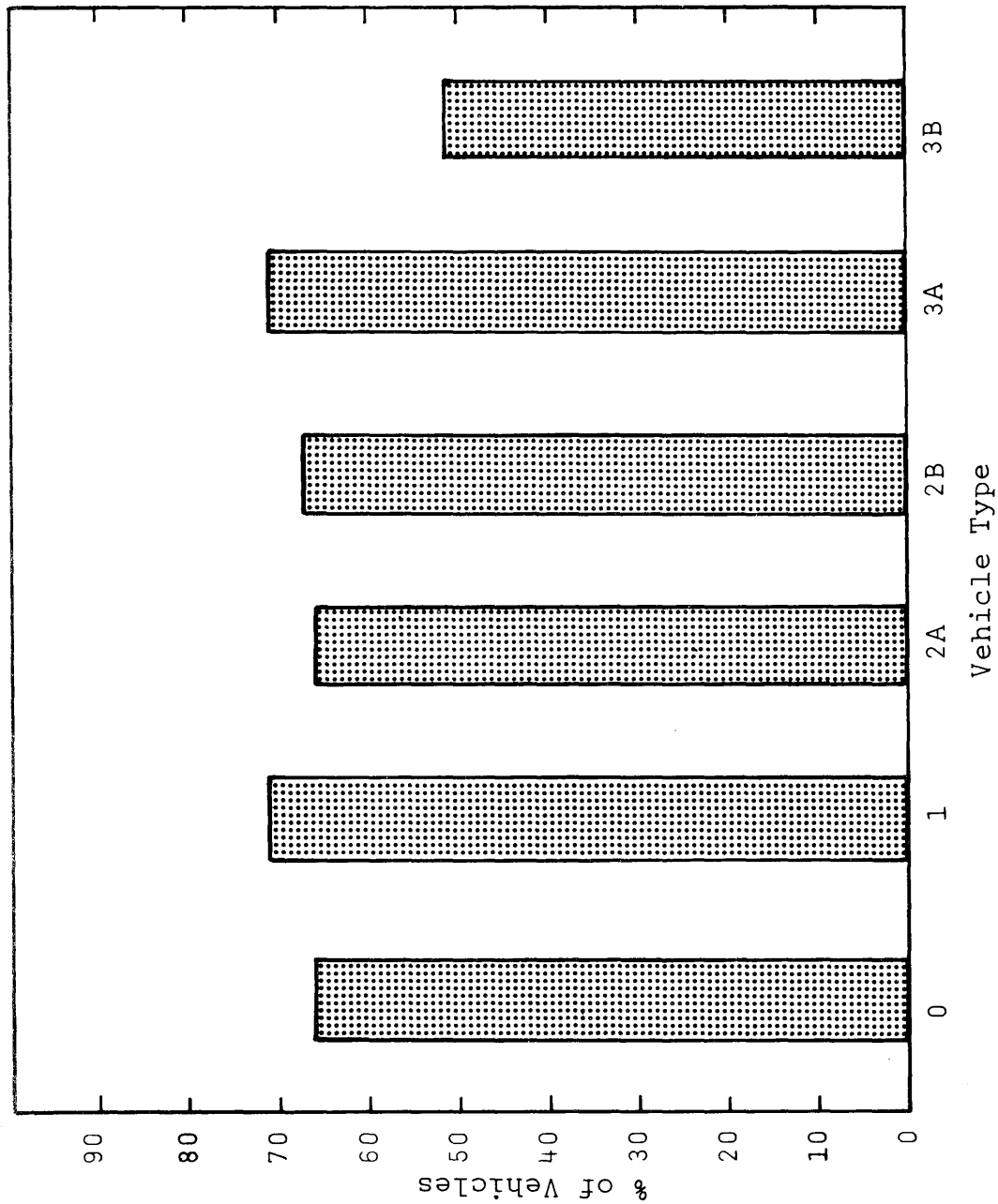


Figure E-1. Proportion of vehicles braked at the north entrance to the Hampton Roads Bridge-Tunnel.

APPENDIX F

PHOTOMETRIC CALCULATIONS

Ketvirtis (1975) calculates the "working outdoor illumination" (E_{01}) as 2/3 of the maximum illumination. The working luminance (L_{01}) for these conditions is calculated by multiplying the illumination level by the coefficient of reflectance (P), which is assumed to be 25%. A reflectance of 25% is taken to be an average figure which might vary with the nature of the object viewed. Ketvirtis found the maximum illumination level in the Toronto area to be about 12,000 fc in the summer. Measurements of illumination made at the Hampton Roads Bridge-Tunnel in September were 9,513 fc at the top of the tunnel (area located between the old and new tubes), 8,936 at a point on the open approach 600 ft. from the tunnel portal, and 8,763 at a point 91 ft. in front of the tunnel portal. Using the maximum illumination level measured at the tunnel, the "working luminance" is determined as follows:

$$\begin{aligned} E_{01} &= 9,513 \text{ fc} \times 2/3 \\ &= 6,342 \text{ fc} \quad (68,240 \text{ Lux}) \end{aligned}$$

The working luminance is calculated as

$$\begin{aligned} L_{01} &= E_{01} \times P \\ &= 6,342 \times 0.25 \\ &= 1,586 \text{ fL} \quad (5.430 \text{ cd/m}^2) \end{aligned}$$

In addition, using the methods suggested by Ketvirtis (1975), one can calculate the lengths of the total supplementary lighting zone and the threshold zone for the Hampton Roads Bridge-Tunnel. The length of the threshold zone just inside the tunnel should be related to the safe stopping sight distance. The length of the total supplementary zone (where additional lighting is required to prevent the black hole effect and visibility loss) is related to the pupillary response. The pupil of the eye increases in size with time in the dark to allow more light to enter the eye. In addition, transient adaptation must also play a role here. Ketvirtis indicates that the total length of the supplementary zone can be calculated as

$$L_s = (V_s \times t_a) - d_a$$

Where

$$\begin{aligned} V_s &= \text{speed (ft/sec.)} \\ t_a &= \text{adaptation time (8 sec.)} \\ d_a &= \text{adaptation point} \end{aligned}$$

The adaptation point, according to Schreuder (1975), is that point at which the state of adaptation of the visual system of the driver begins to change as a result of the appearance of the dark tunnel portal. It can also be defined as that point at which the tunnel portal height subtends a suitable angle such as 25° .

$$\begin{aligned} L_s &= (V_s \times t_a) - d_a \\ &= (58.7 \text{ ft/sec.} \times 8 \text{ sec.}) - 20.3 \text{ ft.} \\ &= 449.27 \text{ ft.} = 449 \text{ ft.} \end{aligned}$$

Where

$$\begin{aligned} d_a &= (H - h) \cot \Psi \\ &= (13.5 \text{ ft.} - 4 \text{ ft.}) 2.14 \\ &= 20.3 \text{ ft.} \end{aligned}$$

Where

$$\begin{aligned} H &= \text{portal height (13.5 ft.)} \\ h &= \text{height of driver's eye above pavement (4 ft.)} \\ \Psi &= \text{angle between horizontal line of vision and} \\ &\quad \text{highest point of tunnel opening (} 25^\circ \text{)} \end{aligned}$$

The length of the threshold zone can be determined as follows:

$$\begin{aligned} L_{tr} &= \frac{a}{h - a} \times ds \\ &= \frac{1}{4 - 1} \times 236 \text{ ft.} \\ &= 78.7 = 79 \text{ ft.} \end{aligned}$$

where

- a = hazardous object height (1 ft.)
- h = height of driver's eye above the pavement
- ds = safe stopping sight distance
(236 ft. at 40 mph; from Glennon, 1970)

The greatest amount of light should be provided in that part of the supplementary zone known as the threshold zone (79 ft. in the present case). Illumination and luminance values in the Hampton Roads Bridge-Tunnel were averaged over the first 100 ft. from the portal as it is close to the calculated 79 ft. A gradual reduction in lighting from the end of the threshold zone to the end of the overall supplementary zone (370 ft.) should also be provided. This zone is sometimes called the transition zone, as it provides a transition in lighting from the threshold zone to the tunnel interior.

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APPENDIX G

MISCELLANEOUS COMMENTS OF TUNNEL USERS

"The Hampton Roads Bridge Tunnel has been from its conception, one of the most outstanding works of highway and 'seaway' construction ever devised by men!" Another motorist described it as "a horrible daily experience." These are typical of the wide range of comments and suggestions that were received in the survey study. Many of the constructive suggestions apply only to the Hampton Roads tunnel, but many are general enough to apply to other projects.

Over 10% of those who made comments mentioned the traffic congestion and backed-up traffic that occurs at certain times of the day. Many felt that congestion, rather than visibility, is the problem of greatest concern to the tunnel users. "Hurry and finish the new tube!" was a frequent comment.

Some people suggested opening special toll booths for only those people with commuter tickets. Other people suggested simply opening more toll booths during peak hours. It was pointed out that if the northbound toll booths were south of the tunnel, traffic would not back up into the tunnel. Another idea was to collect from one lane only a round trip toll. The most popular suggestion was to eliminate the toll completely. Several owners of half-ton pickup trucks objected to being denied commuter tickets.

Until one gets to the toll booths, there are no signs indicating the amount of the toll. The "dim lights" sign on the approach was considered ambiguous by many; some suggested a flashing sign to urge all motorists to use parking lights.

There were quite a few compliments on the tunnel personnel. The toll collectors and guards were described as friendly, courteous, well-trained, etc. The only complaint people mentioned was being waved on in the tunnel when traffic is bumper-to-bumper. Drivers feel as though they are being encouraged to tailgate and some find the guards' waving to be distracting. Drivers who slow down at the tunnel entrance and continue through at a slow pace were a frequent source of complaint. Suggestions for improving traffic flow included increasing the speed limit and posting "Minimum speed 40" signs rather than the "Keep up speed" signs now in use. A few suggested issuing warnings to those who drive too slowly.

About 11% of those commenting cited the use and misuse of vehicle lights in the tunnel. The main problem is that motorists who use headlights tend to blind oncoming drivers. Yet many

motorists thought that being able to see taillights of the car ahead helped them in their driving. Taillights and brake lights are visible through the glare of the entrance and prevent the vehicle from being lost from view to those behind it. The general feeling seemed to be that in the tunnel parking lights and only parking lights should be required at all hours of the day and night.

One person suggested that the white stripes "painted on the wall entering the tunnel from the Hampton side have helped to break the glare." These stripes were the reflective tape used as temporary distance markers in the braking study.

A few complaints were received about the noise level, but this problem seems minor compared to the problem of exhaust fumes, which elicited comments from 12% of the respondents.

Radio reception in the tunnel was a feature that was enjoyed and appreciated by many motorists.

The overall response to the Hampton Roads Bridge-Tunnel was generally positive. For most, the tunnel runs very well. Visitors to the area reported they enjoyed their trip through the tunnel. Commuters who daily hit traffic at its worst are eager for the parallel tunnel to open; they hope that the new tube will be the solution to their problem of traffic congestion.