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FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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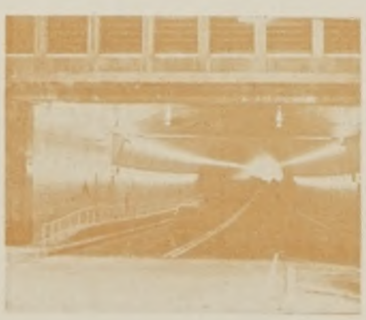

COVER

Lighting in one tube of the twin-tube tunnel under Wheeling Hill, Wheeling, W. Va. Lighting criteria for proper tunnel lighting is discussed in the first article of this issue.

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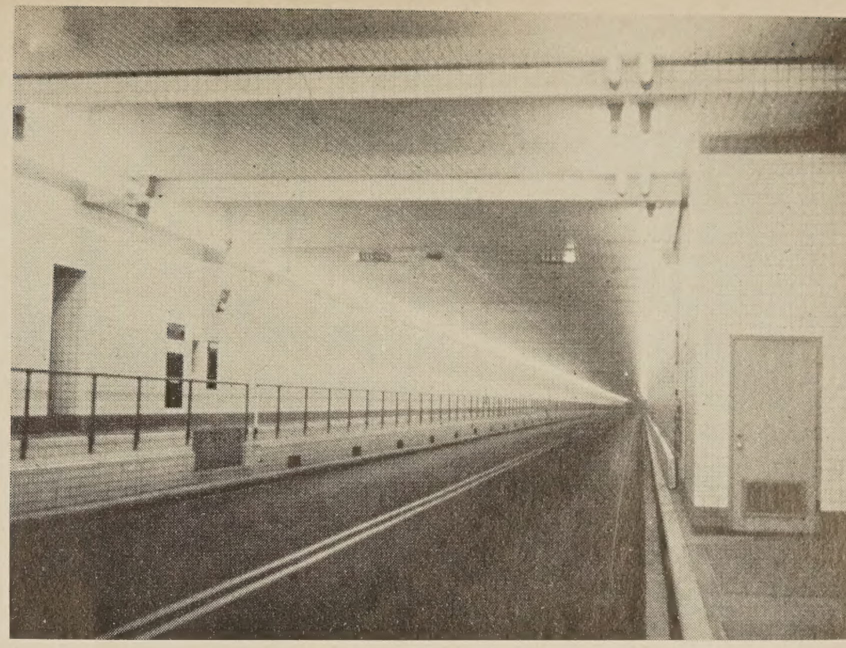
Criteria for Highway Tunnel Lighting Design



Tunnel lighting in Thimble Shoal Tunnel, Chesapeake Bay Bridge and Tunnel District, Norfolk, Va.

3Y THE OFFICE OF
:NGINEERING AND OPERATIONS
3UREAU OF PUBLIC ROADS

Reported by [1] JAMES A. THOMPSON, Regional Traffic Operations Engineer, Region 5, and BENDER I. FANSLER, Electrical Engineer, Office of Traffic Operations, Engineering Division

Modern highways designed to accommodate high-speed, high-volume vehicular traffic incorporate in their construction numerous tunnels and underpasses. Many of these structures require fixed lighting to provide adequate visibility for the road user. Information obtained during a national survey of the lighting system in most of the major tunnels throughout the United States is presented in this article, and the authors discuss the important lighting features noted during the survey.

Suggestions are offered for determining which tunnels and underpasses should be lighted; factors which must be considered by the designer when selecting lighting criteria for a specific project are outlined; and guidelines for both day and night levels of illumination in these facilities are summarized.

Introduction

THE INCREASING use of the automobile today, the higher standards of highway esign, and the projected expansion of the Vation's highway construction programs are reating a substantial increase in the number f underpasses and tunnels both in urban and ural areas. In urban areas, the increase is ecessitated by esthetic considerations in ighway construction, urban planning philosophies, and the use of air rights above the highway for building construction; in rural areas, is brought about by improved highway esign standards and construction methods.

The increased number of tunnels and underasses, together with higher vehicle operating peeds, has increased the need for proper ghting of these structures. The attention eing given highway safety emphasizes this eed, not only for the safety of vehicle occuants and pedestrians but also to insure the fficient use of the highways.

How to distinguish an underpass from a unnel and when to provide lighting for strucures between 75 feet and 1,000 feet long are uestions that need clarification. It is likely hat any guidelines or standards for tunnel ghting may not be universally applicable nd that each of the structures should be dividually evaluated.

Once a structure is defined as a tunnel, such factors as length, cross-section, lining, traffic volume, alinement and grades, location, and outside field-of-view brightness immediately adjacent to the portal should be considered in the design of the lighting. But so many combinations of variables can exist that no two tunnels are alike, and even though tunnel lighting guides are available (*1, 2, 3*),[2] an onsite evaluation of existing lighting systems, to determine fundamental objectives and operational experience, is a necessary prerequisite to an evaluation of tunnel lighting.

In this article, a library study of literature on highway tunnel lighting and a field investigation of existing tunnels are summarized. The three major objectives of the research were (1) to identify published materials related to the lighting of tunnels, (2) to summarize the survey of existing tunnel lighting installations, and (3) to distinguish between a tunnel and an underpass for lighting purposes and formulate guidelines for illumination, based on pertinent research and the field investigation.

For the first of these objectives, studies were conducted in Washington, D.C., at the Library of Congress, the library of the Catholic University of America, and the professional library of the Bureau of Public Roads. Night Visibility Bulletins of the Highway Research Information Service and reports of the Highway Research Board were reviewed, in addition to industry bulletins, publications, and equipment specifications on tunnel and underpass lighting solicited from manufacturers.

For the second objective, information was obtained directly from officials responsible for

[1] Messrs. Thompson and Fansler were formerly in the ffice of Engineering and Operations, Highway Standards nd Design Division.

[2] Italic numbers in parentheses refer to the bibliography listed on p. 105.

the design, operation, and maintenance of the major tunnels throughout the United States. A comprehensive questionnaire, submitted to the officials, consisted of nine parts:

- Tunnel physical data
- Portals and approaches
- Traffic conditions
- Electrical system
- Lighting system—continuous burning
- Supplemental daytime entrance (adaptation) lighting
- Maintenance procedures
- Cost information
- Miscellaneous

The questionnaire was mailed before the tunnel was officially visited for an on-site (day and night) inspection of tunnel lighting, operation, and maintenance, and for interviews with design, operation, and maintenance personnel to obtain their evaluations of the lighting installations. In general, complete information was furnished in all but the cost item of the questionnaire. In many of the tunnels, the initial cost of the lighting was included with other work and was not available. A summary of the tunnel lighting survey is given in table 1.

For the third objective the published literature, questionnaires, field inspections, and interviews were analyzed to identify criteria for determining the difference between an underpass and a tunnel for lighting purposes, and to determine criteria for proper highway tunnel lighting design.

Lighting terminology for a tunnel is shown in figure 1.

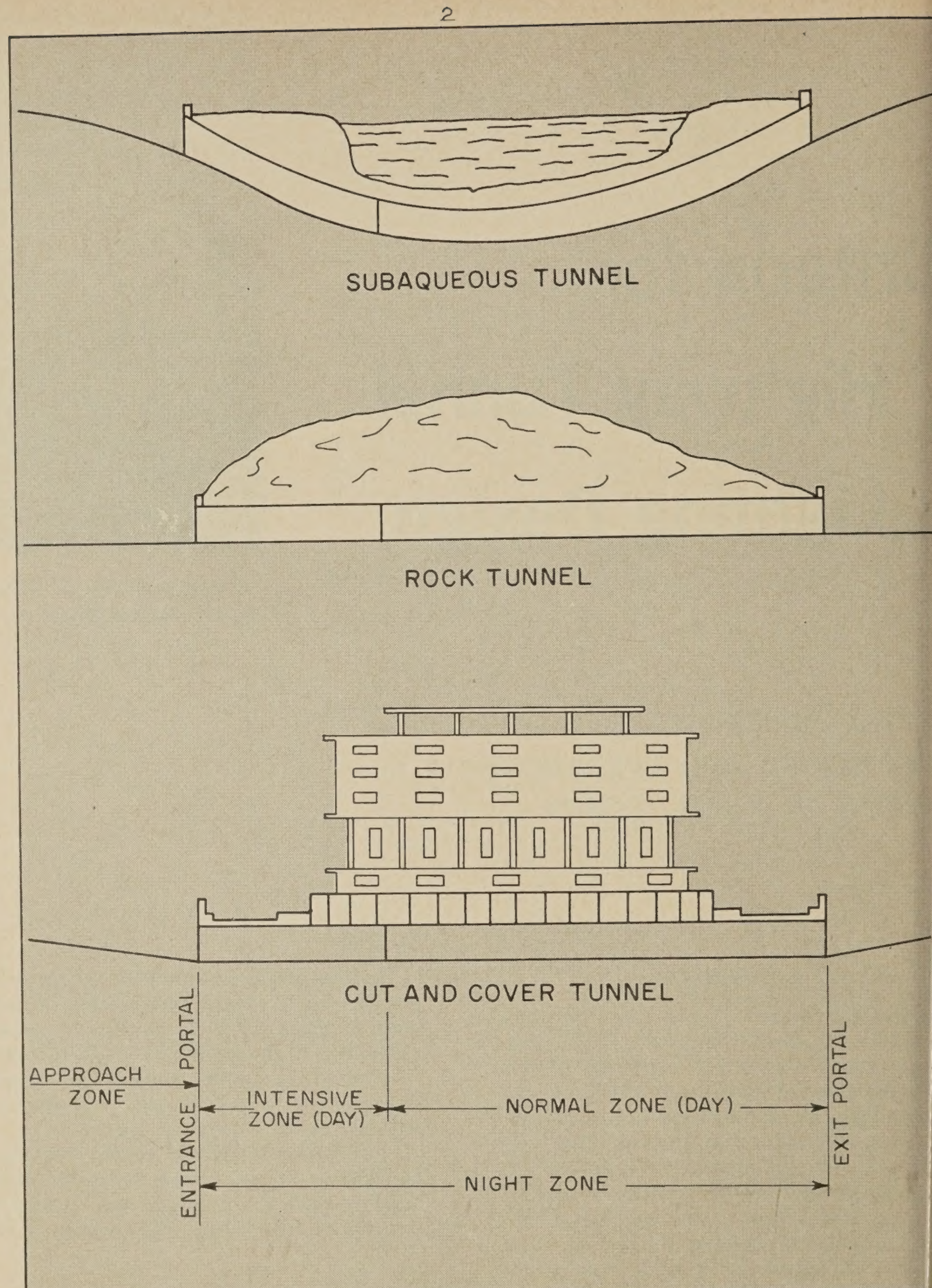


Figure 1.—Tunnel lighting terminology.

Background

Good visibility is a prerequisite to safe traffic operation in a highway tunnel. The lighting in a highway tunnel has too often been designed on the basis of insufficient guidance and opinion rather than on a factual basis. Upon completion of the nationwide tunnel lighting survey, the general observation of day and night lighting levels indicated an excess of nighttime lighting and a deficiency of daytime entrance-zone lighting. When either of these conditions exists, highway safety and highway utility are not being served to the best interest of the road user. Examples of well designed night lighting and of well designed daytime lighting were observed, but a combination of well designed day and night lighting was not found in any one tunnel. In many tunnels inadequate day lighting existed because the same type of equipment was being used both for night and day conditions. With the lighting equipment available at present, it may be impractical to use the same equipment for both day and night conditions because of the difference in the lighting requirements.

Many illuminating engineers are convinced that the foremost shortcoming in the field of tunnel lighting is the lack of basic research to isolate visibility requirements, and the instrumentation to check these requirements. Others believe that new research would result, largely in the rediscovery of many old truths; they are convinced that to reveal and discredit many ideas, allegedly motivated by commercial interest, would be rewarding. This group does not agree that there is a lack of basic research and that the gap between available research and needed information is small. The research reported here revealed that little attention has been devoted to the lighting of tunnels, and that technical advances and research on the subject have not been recognized, or remain unknown to those who are responsible for the tunnel lighting design. Evaluations of tunnel lighting by such individuals often reveal that the criteria used and the judgments exercised in design and operation continue to be clouded with personal, and frequently inept, opinion. Therefore, analysis of available information, and its dissemination to those responsible for making final design decisions, is essential to the proper consideration of sound engineering judgment and fiscal aspects.

Tunnel lighting design should account for the most important aspects of lighting—the road user's ability to see. Eye adaptation is a phenomenon that requires understanding to evaluate this ability. Eye adaptation is much faster when the eye transfers from a dark to bright environment than when it transfers from bright to dark environments. Accordingly, supplemental daytime entrance lighting is critical, whereas supplemental daytime exit lighting is not. At night, the entrance lighting becomes less critical, but attention should be given to exit lighting because of the ıdaptation of the driver's eye from light in the unnel to the darker environment outside the unnel.

During the day, the entrance of the tunnel equires sufficient lighting to prevent the effect of entering a *dark hole*, the most serious demand on eye adaptation. The exit of the unnel appears as a *light hole* in the daytime nd presents fewer problems. At night, the *lark hole* may be at the exit and the *light hole* t the entrance—a situation created by too nuch light in the tunnel. The survey of existng tunnel lighting showed this condition to e the rule rather than the exception.

Research and technical advancements have ot made momentous strides, but significant ontributions that provide ways to greatly nprove tunnel lighting have been made.

In the tunnel lighting guides (*2*, *3*), it is ecommended that daytime entrance lighting e provided for 15-second eye-adaptation time rom the instant that the road user enters the unnel. Based on studies of California tunels, this adaptation period exceeds road user equirements (*4*). With the 6-foot-lambert vall brightness of the Park Presidio Tunnel n San Francisco, full iris and partial retinal daptation times varied among individuals, ut no more than 2 seconds were required for atisfactory adaptation in this tunnel. At the Posey Tunnel in San Francisco, which had a ow interior brightness ranging from 0.03 to .5 footlamberts, satisfactory adaptation ocurred on a bright day within 3 or 4 seconds fter the tunnel was entered, although visiility remained relatively poor. It was conluded from these studies that long stages of aytime adaptation lighting are wasteful, hat visibility of obstacles within the tunnel s poorest before the tunnel is entered, and hat daytime entrance lighting is needed to rovide better visibility before entering.

An understanding of certain characteristics f the human eye is important to establish riteria for tunnel lighting design. It is ometimes thought that changes in pupil size re important in allowing the eye to work fficiently over a wide range of light intenties, but, actually, the pupil area changes ver a range of brightness of only about 16 o 1, whereas the eye works efficiently over a ange of about 100,000 to 1 (*5*). In a 1943 tudy, it was established that the response f the small foveal area of the eye's retina ccounts for approximately 90 percent of the daptation to a uniform field (*6*). As shown n figure 2, the fovea is a depression at the ack of the retina, the point at which the ision is most acute, corresponding to approxmately the central 2 degrees of the human isual field. Complete foveal vision adaptaon requires about 7 minutes; complete eripheral (or retinal) vision adaptation connues for an hour or more (*5*). The adaptaon time for tunnel lighting may be considrably shorter than the time necessary to reach he final state of adaptation.

In a 1916 study, it was established that, n normal eyes, the pupil contracts autoatically to protect the retina from excessive rightness, and expands to admit light to the etina when it is required (*7*). On sudden exposure to a bright light, the diameter of the pupil varies from about 2 to 8 millimeters, contracting in about 1 second. On a sudden reduction of full brightness, the pupil dilates to about 5 millimeters in about 2 seconds, and then continues to expand slowly to its limit.

In a 1920 study (*8*) concerning the rate of change of pupil size for instantaneous changes in image brightness, it was shown that only a fraction of a second is required for the pupil to expand—increase its area 2½ times—after a scene was changed from 1,000 footlamberts to 30 footlamberts.

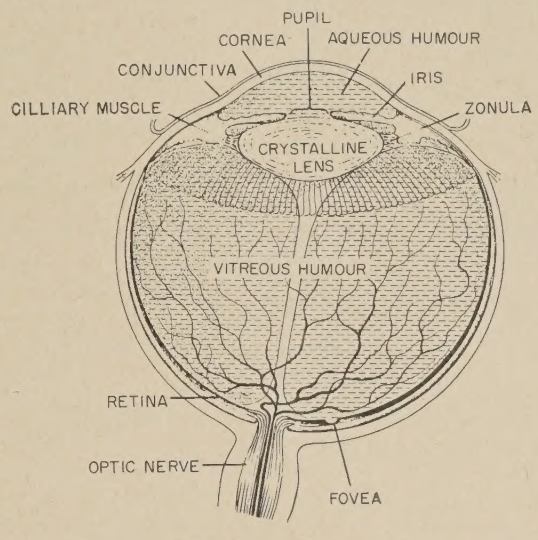


Figure 2.—The human eye.

Complete adaptation is not necessary for good visibility. Partial adaptation is the objective, and there is sufficient evidence to support a lighting design that provides an adaptation time of only 4 seconds, which even exceeds the minimal road user requirements. Visibility must be provided for the road user outside the tunnel, or just about to enter, to see a stalled vehicle or smaller object inside the tunnel. However, the principal problem is not the rate of adaptation, which takes place very quickly, but rather the adaptation level of a road user approaching the tunnel entrance (*4*, *9*). The problem of adaptation level is aggravated by the effects of atmospheric scatter of the aerosals (haze) between the road user and the tunnel portal. In bright sunlight this haze, composed of dust and vehicle exhaust, can produce an apparent brightness at the portal of above 100 footlamberts and is a hindrance to visibility (*9*).

The visibility required for the road user to see objects within the tunnel as he approaches the entrance can be achieved by only two methods: (1) by reducing the adaptation level of the road user; and (2) by greatly increasing the brightness of the background within the tunnel against which objects can be seen (*9*).

Roadway brightness has less effect on the road user's visibility than wall and ceiling brightness, except in wide tunnels (*10*). Generally, roadway brightness can be assigned a secondary consideration in the lighting design because with sufficient wall and ceiling brightness, adequate roadway brightness will automatically follow (*4*).

Because the tunnel walls and ceiling constitute a background to silhouette a vehicle to the road user outside the tunnel, or just about to enter it, a high level of illumination is required to provide high brightness of these surfaces. If the tunnel is straight and level, this intensive lighting zone must extend far enough into the tunnel to provide a background for vehicles, perhaps beyond what is normally required. If the tunnel has curved horizontal or vertical alinement near the entrance, the intensive lighting design is much simpler.

One of the worst conditions for tunnel lighting may occur when the tunnel portal faces the south—a condition for which there is little hope of achieving sufficient tunnel wall and ceiling brightness by conventional lighting systems of reasonable magnitude (*11*). This condition can be improved considerably by keeping the reflection of the portal and surrounding area low, thus reducing the brightness level in the motorist's field of view. Also, the brightness in the road user's field of view can be reduced by roadway louvers or screens located outside the tunnel entrance.

In summary, the visual requirements of the road user are most critical when he is still outside and immediately entering the tunnel, not after he has entered it. When he leaves the tunnel, the visual requirement isn't acute. The entrance problem is basically range of adaptation, not rate of adaptation. There are two possible ways to overcome this problem: Either provide enough brightness on the inside of the tunnel, or design the approach to the tunnel so that the brightness level in the road user's field of view is reduced. In good design, both methods should be evaluated so that they can be considered in combination.

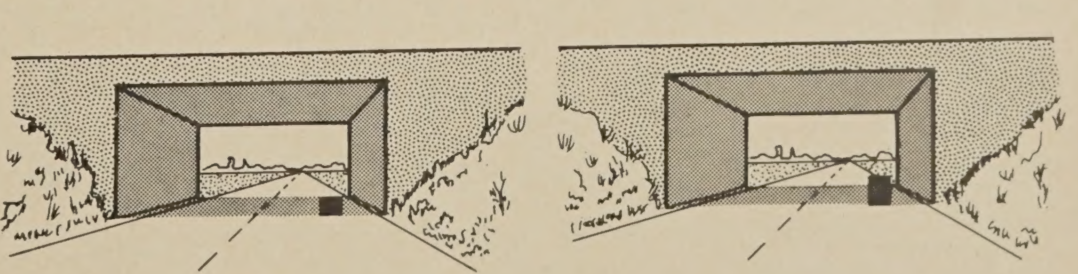


Figure 3.—Underpass dark-frame and obstacle visibility.

Table 1.—Summary of tunnel lighting survey

Name	Location	Physical data: Length	Year built	Type pavement	Tubes: No.	Width: ft.	Width: in.	Operation
		ft.				*ft.*	*in.*	
John F. Fitzgerald Expressway.[2]	Boston, Mass	2,335	1958	Portland cement concrete	2	40	0	1-way
Wm. F. Callahan, Jr	do	5,047	1961	Asphaltic concrete	1	26	9	do
Prudential Passageway[2]	do	1,980	1965	Portland cement concrete	2	49	0	do
Lincoln Tunnel (3d tube)	New York, N.Y	8,013	1959	Asphaltic concrete	1 (of 3)	26	4	do
Holland Tunnel	do	8,557	1927		2	25	0	do
George Washington Bridge Lower Level	do	600 eastbound; 800 westbound.	1962		2	42	0	do
Fort Pitt	Pittsburgh, Pa	3,550	1960	Brick	2	29	4	do
Allegheny No. 2 (New)	Pennsylvania Turnpike	6,070	1964	Asphaltic concrete	1	31	9	
Hampton Roads	Norfolk, Va	7,479	1957	do	1	27	0	2-way
Norfolk-Portsmouth No. 2 (Midtown)	do	4,194	1962	do	1	28	10	do
Thimble Shoal Tunnel	Chesapeake Bay Crossing, Norfolk, Va.	5,738	1964	do	1	28	9	do
Baytown Tunnel	Baytown, Harris County, Tex	3,009		Portland cement concrete	1	26	10	do
State Highway No. 183 Tunnel	SW International Airport, Fort Worth, Tex.	813	1964	do	2	48	0	1-way
Caldecott Tunnel No. 3 (New)	Oakland, Calif	3, 371	1964	do	1	34	6	do
Webster St. Tube	Almeda-Oakland, Calif	3,340	1962	Asphaltic concrete	1	32	9	do
Waldo Tunnel Route No. 101	Marin County, Calif	1,000	1955	do	2	46 (new) 46 (old)	6 8	do
Park Presidio Tunnel	San Francisco, Calif	1,300		Portland cement concrete	1	49	0	2-way
Bothell Tunnel	Seattle, Wash	390	1963	do	2	32	0	1-way
Roanoke Tunnel	do	662	1963	do	1	25	0	do

Name	Location	Night lighting (normal day zone): Year lighting installed	Lamp data: Type	Current	Luminaire: Data	Location	Spacing
				Milliamperes			
John F. Fitzgerald Express-way.[2]	Boston, Mass	1959	Fluorescent 72-in. T8 Slimline.	120	Lamp in pyrex tube	Ceiling near each wall.	1 row continuous on each side.
Wm. F. Callahan, Jr	do	1961	do	150	do	Walls approx. 12 ft. above roadway.	do
Prudential Passageway [2]	do	1965	Fluorescent 96-in. T12/HO.	800	8-ft. 3-lamp internal reflector.	Wall, 15 ft. above roadway.	do
Lincoln Tunnel (3d tube)	New York, N.Y	1959	Fluorescent [4] 72-in. T12 Slimline.	325-600	Lamp in pyrex tube	Wall near ceiling	do
Holland Tunnel	do	1963 [5] (Relighted)	Fluorescent 96-in. T12 Slimline.	430	do	1 row on ceiling over safety walk and other on upper wall surface.	do
George Washington Bridge Lower Level	do	1962	Fluorescent 72-in. T12 Slimline.	350	do	Wall approx. 1 ft. below ceiling.	do
Fort Pitt	Pittsburgh, Pa	1960	do	200	do	Ceiling near wall	do
Allegheny No. 2 (New)	Pennsylvania Turnpike	1964	Fluorescent 96-in. T12/HO.	1, 000	Internal reflector 1 HO lamp operated in each 8-ft. luminaire.	Wall near ceiling	do
Hampton Roads	Norfolk, Va	1957	Fluorescent 72-in. T8 Slimline.	180	Lamp in pyrex tube	Wall 12 ft. below ceiling.	do
Norfolk-Portsmouth No. 2 (Midtown).	do	1962	do		do	Wall near ceiling	do
Thimble Shoal Tunnel	Chesapeake Bay Crossing, Norfolk, Va.	1964	do	Approximately 125	do	Wall just below ceiling.	do
Baytown Tunnel	Baytown, Harris County, Tex.	1953	Fluorescent 72-in. T12 Slimline.	200	Single lamp 6-ft. luminaire internal reflector.	Center of arch ceiling.	2 rows continuous
State Highway No. 183 Tunnel	SW International Airport, Fort Worth, Tex.	1964	Fluorescent	1, 000	2 lamps with reflector (only 1 lamp at night).	Ceiling at junction of each wall.	do
Caldecott Tunnel No. 3 (New)	Oakland, Calif	1964	Fluorescent 96-in. T12 RS/XHO [13] (high temperature).	60	3 lamps with reflector, deflectors (only 1 lamp used).	On each side near ceiling.	do
Webster St. Tube	Almeda-Oakland, Calif	1962	do	60	do	do	do
Waldo Tunnel Route No. 101	Marin County, Calif	1955	Fluorescent 72-in. T8 Slimline.	120	3-lamp luminaires with reflector (only 1 lamp used).	On each side of both bores.	do
Park Presidio Tunnel	San Francisco, Calif	1955 (Relighted)	do	120	do	On each side near ceiling.	do
Bothell Tunnel	Seattle, Wash	1963	Fluorescent 96-in. T12 Slimline.	425	3-lamp luminaire with internal reflector.	On each wall near ceiling.	Continuous each s Spacing 24 ft. at night.
Roanoke Tunnel	do	1963	do	430	3 lamps with internal reflector (1 lamp in each 3d luminaire used).	On each side near ceiling.	do

[1] ADT=Average Daily Traffic.
[2] Entrance and exit ramps within tunnel. Lane changes permitted.
[3] Circuitry is arranged so lighting levels can be controlled. All lights now being operated during day and night. Operation being studied to determine most effective conditions.
[4] Operated 600 ma. day and night.
[5] Original lighting incandescent. New lighting used old wall boxes.
[6] Lane changes permitted.
[7] No intensive lighting on westbound tube.

Physical data—Continued

Traffic lanes each tube			Ceiling					Finish		Direction portal faces	Volume	Speed
No.	Width		Ht.		Shape	Portal	Taper	Ceiling	Walls			
	ft.	*in.*	*ft.*	*in.*		*ft.*	*ft.*				*ADT* [1]	*m.p.h.*
3	12	5	14	3	Flat			Concrete	Ivory and yellow tile	N-S	100,000	30-55
3	10	9	13	6	do			Yellow tile	Yellow tile	SW	23,000	20-35
4	11	0	14	0	do			Painted concrete	Painted concrete	E-W		55
2	10	9	13	0	do	29	130	White tile	White tile	S	27,000	35
2	10	0	13	6	do			Concrete	do	W-NE	60,000	35
[5] 3	12	0	18	0	do	28	75	White tile	Yellow tile	E-W	23,000	45-55
2	12	0	12	0				do	White tile	NE-SW	61,000	45
2	13	0	13	0				Painted concrete [9]	do	E	30,000	50
2	11	6	11	6				White metal panels	do	SE-NW	10,000	40-45
2	11	0	11	0				do	do	E-W	11,000	35-45
2	12	0	14	0	Flat	[10] 19	17	Ivory tile	Ivory tile	NE-SW	3,000 to 7,000	45
2	11	0	19 17	18 1	Arched			Tile	Tile	NE-SW	+12,350	15-35
3	[11] 12	0	21 15	7 9	do			Painted concrete	Painted concrete	E-W		70
2	14	0	18	4	Flat			Green tile	Green tile	NE	26,000	55
2	12	0	15	0	do			do	do	NE	17,550	35
[6] 3	12	0	29	0	Arched			Yellow tile (new); concrete (old).	Yellow tile	N-S	35,000	50
[6] 4	11	0	31	0	do			Concrete	Painted concrete	N-S	54,000	45
[6] [14] 2	12	0	16 (max.) 4 (min.)	4 10				Yellow tile	Yellow tile	NE-SW	14,000	30-35
1	14	0	16 (max.) 14 (min.)	5 11				do	do	N	8,800	35-40

Night lighting—Continued		Daytime entrance lighting (intensive zone)						
Roadway illumination	Approach roadway illumination	Length	Lamp data		Luminaire			Roadway illumination
			Type	Current	Data	Location	Spacing	
Average ft.-c		*ft.*		*Milliamperes*				*Average ft.-c*
.5	400-w. mercury; 0.9-1.0 ft.-c.	Approximately 650.	Fluorescent 72-in. T8 Slimline.	300	Lamp in pyrex tube	Ceiling near wall	2 rows continuous each side.	9.0
	400-w. mercury; 1.0 ft.-c.	1,700	do	450	do	Side walls	1 row continuous each side.	
Approximately 40.	400-w. mercury 1.2 ft.-c.						[3]	Approximately 40.
.0	1-2 ft.-c	800	Fluorescent [4] 72-in. T12 Slimline.	600	Lamp in pyrex tube	Wall near ceiling	1 row continuous each side.	6.0
.0-6.0	Mercury 2-3 ft.-c	250	Mercury 400 w		R-60 reflector lamps	Recessed in each wall and over roadway.	Approximately 16 ft	70
.0	Mercury 3.5-3.7 ft.-c.	250 [7] east-bound only.	do		Refractor type	Recessed in ceiling 3 ft. 6 in. from wall.	First 150 ft.—5-ft. centers. Next 100 ft.—10-ft. centers.	75 (first 150 ft.); 45 (next 100 ft.).
	400-w. mercury		Fluorescent 72-in. T12 Slimline.			[8]		
0	400-w. mercury; 1.8 ft.-c.	1,800	2 96-in. fluorescent PG 17 (first 900 ft.); 2 96-in. T12/HO (next 900 ft.).	1,000	2 lamps, internal reflector.	Wall near ceiling	1 row continuous each side.	60 (first 900 ft.); 40 (next 900 ft.).
.0-5.0	400-w. mercury; 1.0 ft.-c.	675	Fluorescent 72-in. T8 Slimline.	180-300			2 rows continuous each side.	24 (first 225 ft.); 12 (next 225 ft.); 8 (next 225 ft.).
	400-w. mercury	430	do				do	
Approximately 8-9.	Fluorescent 6.0 ft.-c.	1,459	do	125-450	Lamp in pyrex tube	Wall near ceiling	do	Variable manually.
-8.4	400-w. mercury; 1.0 ft.-c.	325	do	400	Single lamp with internal reflector.	Center of ceiling	6 rows continuous	
12.0	Fluorescent 3.0	550	Fluorescent	1,000	2 lamps with reflector.	Ceiling near wall	do [12]	
Walls—5.0; roadway—3.0.	400-W. mercury; 1.0 ft.-c.	304	Fluorescent 96-in. T12 RS/XHO High temperature.	1,400	3 lamps with reflector and deflectors.	Each side	1 row continuous	Roadway—60; walls—90.
do	11,600-lumen fluorescent.	340	do	1,400	3 lamps with reflector and deflectors.	Each side near ceiling.	do	Do.
Walls—3.0; roadway—5.0.	10,000-lumen incandescent; 0.5 ft.-c.	1,000	Fluorescent 72-in. T12 RS/HO, 2 lamps.	1,000	3 lamps with reflector.	do	2 rows continuous	Roadway—30; walls—20.
Walls—1.5; roadway—2.5.	175-w. mercury; 0.2 ft.-c.	1,300	do	1,000	do	do	do	
3.0	Mercury 1.0 ft.-c	150	Fluorescent 96-in. T12 RS/HO, 2 lamps.	800	do	Each wall near ceiling.	do	Roadway—75-30; walls—50-34.
-0	Mercury 0.75 ft.-c	140	Fluorescent 96-in. T12.	800	3 lamps	do	do	Roadway—95-75 (in zone 1); 65-60 (in zone 2).

[8] Lamp output changed by manual variation of current through lamps.

[9] Dull brick on face at portal.

[10] NE portal has metal sun shields above approach road for distance of 500 ft.

[11] 8-ft. shoulder on right, 4-ft. shoulder on left.

[12] First 225 ft.—3 rows each side=65; next 225 ft.—2 rows each side=40; balance—1 row each side=25.

[13] Control circuit changes operation of one lamp in each luminaire as follows: Intensive zone: Daytime 1,400 ma., Night 60 ma; Normal day zone: Daytime 600 ma., night 60 ma.

[14] Inside lane part of reversible roadway.

Definitions of Terms

Adaptation.—The process by which the retina of the eye becomes accustomed to more or less light than it was exposed to during an immediately preceding period. It changes the sensitivity of the photoreceptors to light.

Brightness (Luminance).—The luminous flux per unit of projected area, per unit solid angle, either leaving a surface at a given point in a given direction or arriving at a given point from a given direction; the luminous intensity of a surface in a given direction per unit of projected area of the surface as viewed from that direction.

Footcandle.—The illumination on a surface 1 square foot in area on which is distributed a light output of 1 lumen. It equals 1 lumen per square foot.

Footlambert.—The unit of photometric brightness (luminance). A theoretically perfect surface reflecting light at the rate of 1 lumen per square foot would have a brightness of 1 footlambert.

Glare.—The sensation produced by brightnesses within the visual field that are sufficiently more intense than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility.

Lamp.—The light source employed.

Lamp Lumen Depreciation Factor.—The multiplier to be used in illumination calculations to relate the initial rated output of light sources to the anticipated minimum rated output based on the relamping program to be used.

Luminaire Dirt Depreciation Factor.—The multiplier to be used in illumination calculations to relate the initial illumination provided by clean, new luminaires to the reduced illumination provided because of dirt collection on the luminaires at the time it is anticipated that cleaning will be required.

Louver.—A series of baffles used to shield a source from view at certain angles or to absorb unwanted light.

Lumen.—The unit of measure of the quantity of light. The amount of light that falls on an area of 1 square foot, every point of which is 1 foot from a source of 1 candela (candle).

Luminaire.—A complete lighting device consisting of a light source together with its direct appurtenances.

Maintenance Factor.—The product of the lamp lumen depreciation factor and the luminaire dirt depreciation factor.

Matte Surface.—A surface from which the reflection is predominantly diffuse, with or without a negligible specular component.

Reflectance.—The ratio of the flux reflected by a surface or medium to the incident flux. This general term may be restricted by the use of one or more of the following adjectives: regular (specular), diffuse, spectral.

Spacing.—The distance, in feet, between successive luminaires measured along the center line of the roadway.

Visual Task.—Those details and objects that must be seen for the performance of a given activity, including the immediate background of the details or objects.

Survey of Existing Lighting Installations

Underpasses

Lighting requirements of a tunnel are different from those of an underpass; and the criteria for lighting will determine whether it will be classified as a tunnel or an underpass. Consequently, to establish that a structure is a tunnel or an underpass is a prerequisite to determining the criteria for highway tunnel lighting design.

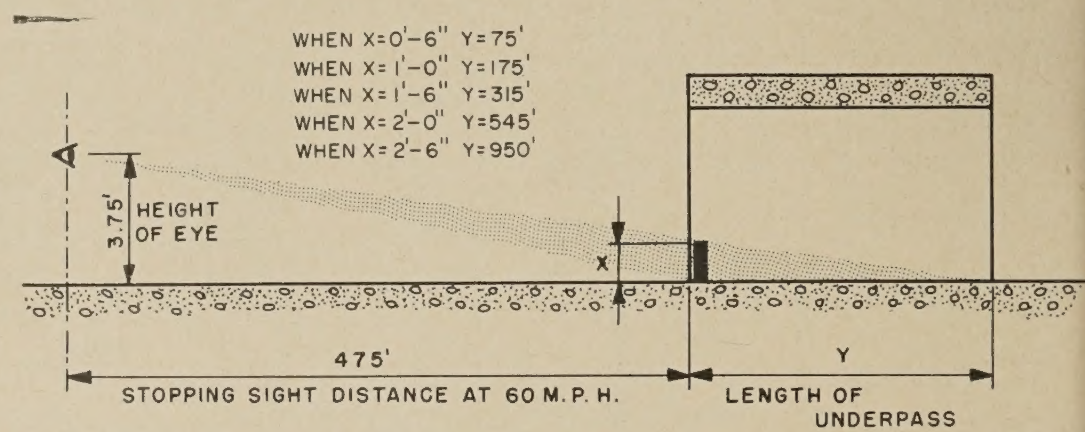


Figure 4.—Vertical dimensions for dark frame (x) across roadway for corresponding underpass lengths (y).

Unlike the lighting on a highway where warrants and justifications are considered and evaluated to determine the need, the lighting in a tunnel is as important a requirement as the ventilation or pavement surface. Daytime lighting is not required in an underpass and the warrants for night lighting would be included in the warrants for that particular section of highway of which the underpass is a part. Daytime and night lighting are required in all tunnels.

Underpasses were included in the study reported here to properly identify them so that they can be distinguished from tunnels. Several factors, including length, height, width, alinement, and grade, must be considered in determining whether a structure is an underpass or a tunnel. In daytime, as a driver approaches an underpass on a straight and level roadway, it will appear in the field of vision as a *dark frame.* After entering the underpass, the central part of the field of vision is taken up by the brightness of the exit, so that the lower brightness of the walls and ceiling has insignificant adaptation stimuli (*6*). Visibility of an object in the *dark frame* of the underpass, as shown in figure 3, is limited because the outside brightness through the underpass exit—the light center of the *dark frame*—controls the adaptation stimuli. Problems such as the influence of flicker and wall brightness, which are important in tunnels, are less important in underpasses.

Obstructions in the underpass can be seen if they are high enough to silhouette against the bright environment of the exit. If the vertical dimension of the *dark frame* across the roadway is less than the height of the smallest object that must be seen, the object will be silhouetted against the exit brightness and be visible. In figure 4 is shown the vertical dimension for the *dark frame* across the roadway and the corresponding underpass lengths, with driver's eye at a height of 3.75 feet and at a distance of 475 feet (stopping sight distance at 60 m.p.h.) from the underpass portal. The figures in the illustration apply to an underpass located on a straight and level roadway.

Because of the daylight penetration from both portals, an underpass on a straight and level roadway can be as much as 75 feet lo[ng] and not require lighting during the day f[or] an obstacle height of 6 inches. As the leng[th] of the structure is increased, the later[al] dimensions of the frame created by the wa[lls] influence the silhouetting of objects with[in] the structure. Silhouetting can be enhanc[ed] by lining the structure wall with a lig[ht-]colored material to reduce the *dark fra[me]* formed by the walls.

Lighting requirements for a long underp[ass] on a straight and level roadway, one so lo[ng] that the exit provides too small a part of [the] field of vision to serve as an effective ba[ck]ground, can frequently be resolved by lin[ing] the wall with a light-colored matte-fin[ish] material to better utilize natural light pe[ne]tration. For such a structure, artificial li[ght] must be intense enough to compete with [the] natural daylight from either end of [the] structure. Illumination to produce the requi[re]d brightness may be economically impracti[cal], and in many structures impossible to achi[eve] (*10*). A substantially lower level of illu[mi]nation is frequently installed in this typ[e of]

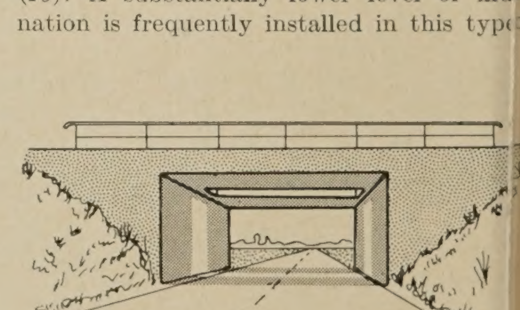


Figure 5.—Effect of ceiling opening appr[oxi]mately midway of structure.

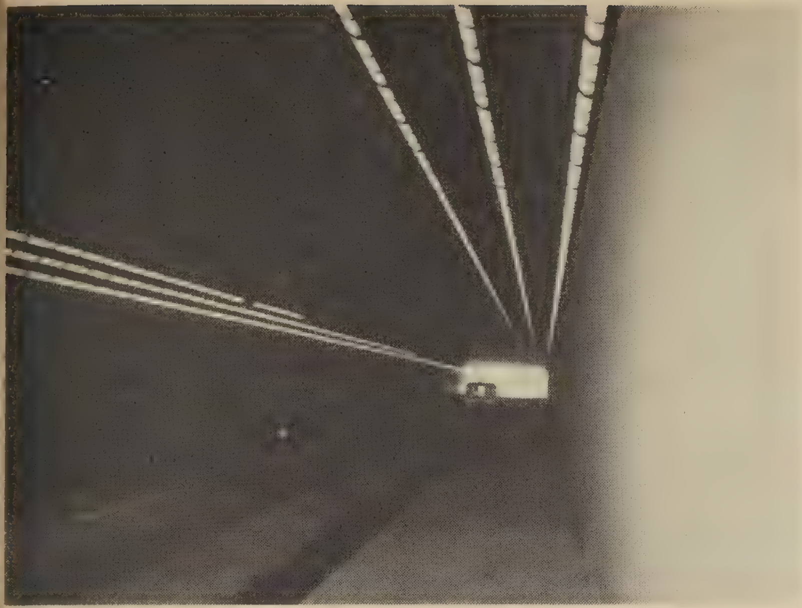


Figure 6.—Southwest International Airport Tunnel, Fort Worth, Tex.—daytime, all lights on.

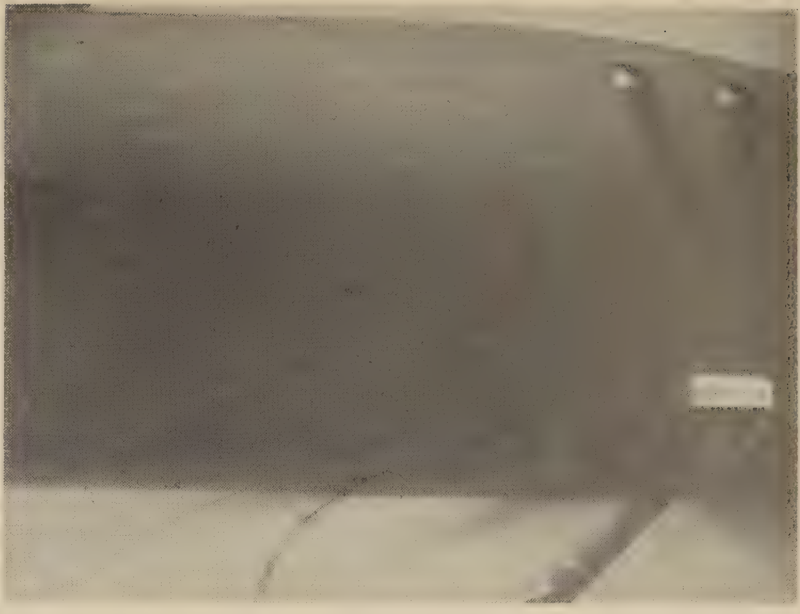


Figure 7.—Southwest International Airport Tunnel, Fort Worth, Tex.—daytime, all lights off.

structure and produces little, if any, additional visibility.

Visibility in a relatively long, straight, and level underpass can be improved by providing an opening in the ceiling about midway through the structure to permit daylight penetration, as shown in figure 5. A ceiling opening may eliminate the need for an artificial daytime lighting system.

In effect, the open ceiling provides two structures instead of one, and may satisfy the requirement for lighting during the day.

Walls and ceilings lined with a light-color matte-finish material will enhance the natural light penetration into the structure. A design with a funneled-up ceiling height at the portal will permit more effective daylight penetration. A white or light-colored pavement surface inside the structure,[3] and a black or dark-colored pavement surface outside the structure, combined with a low reflectance finish on the face of the portal, will improve the visibility without artificial lighting.

If the underpass is not on a straight and level roadway, the silhouette effect may be reduced or become nonexistent, causing relatively short structures to require daytime lighting. However, in this report, an underpass is considered to be a structure that does not require lighting during the day, and a tunnel is considered to be a structure that requires artificial lighting during the day.

Short Tunnels

A tunnel is defined as short when no more than 5 seconds are required to travel through it at the speed limit or design speed. For example, if the posted speed is 55 m.p.h., a tunnel no longer than 400 feet is considered a short tunnel.

No tunnel is long enough to allow the retina of the eye to completely adapt to nighttime light levels during the day (*4*, *5*). Unlike iris (or pupil) adaptation, which occurs in 3 or 4 seconds, complete retinal adaptation to a dark environment takes as long as an hour.

Physical design of the tunnel approach, and exit roadway may invite special lighting problems that could require extending the length of daytime entrance lighting to 6 or 7 seconds' traveltime. The same factors that are used to determine the difference between an underpass and a tunnel may also be used to determine lighting requirements that vary from standard guidelines. This is particularly true of short tunnels. Resolving that a structure is a tunnel rather than an underpass may be indefinite, and consequently, the lighting requirements may be nebulous. It is in this vague area that an in-depth evaluation is required prior to making design decisions.

Factors to be considered are length; cross-section dimensions; lining; traffic volume and speeds; location; roadway alinement on the approach, in the structure, and on the exit roadway; type of approach and exit roadway (depressed or elevated); and the direction the portal faces. A thorough evaluation of all pertinent factors should precede preliminary design.

The Southwest International Airport Tunnel on State Highway 183 in Fort Worth, Tex. (figs. 6 and 7), may have been appropriately classified as an underpass. This structure is located on a straight, level, depressed roadway with rounded back slopes that open the roadway, even at the structure portals, so as to negate the depressed features. It serves as a grade separation between Highway 183 below and the Southwest International Airport north-south runway above. As it is located within the airport, roadway lighting outside the structure is restricted to 14 fluorescent luminaires mounted 20 feet high to transition

Figure 8.—Virginia-New Hampshire Avenue Tunnel, Washington, D.C.—northbound from portal, daytime.

[3] Master's thesis, Hristaki Sofokidis (see acknowledgments).

Figure 9.—E Street Tunnel, Washington, D.C.—westbound approach, daytime.

Figure 10.—E Street Tunnel, Washington, D.C.—interior nea westbound exit, daytime.

from the lighted structure to the dark highway at night. The portal facades are painted gray to reduce their brightness during the day.

A relatively high level of night lighting of the type in the Southwest International Airport Tunnel exists in many of the tunnels in this country. The cost of operating lighting at higher then necessary levels is not justified for tunnel visibility and the high light levels at night are frequently the cause of hazardous conditions at the tunnel exit.

A reevaluation could classify the Southwest International Airport Tunnel as an underpass rather than a tunnel. Sufficient artificial lighting to provide enough brightness to compete with the natural daylight penetration from both ends of the structure is impractical. Very little, if any, additional visibility is provided by the 65-footcandle daytime en trance lighting. Based on observations on bright day with the daytime artificial lightin turned off, reclassification of the structure a an underpass should be seriously considere Because of its location, the expense of daytim lighting may not be justified.

An investigation of the lighting reveale that a 12-footcandle, nighttime illumination

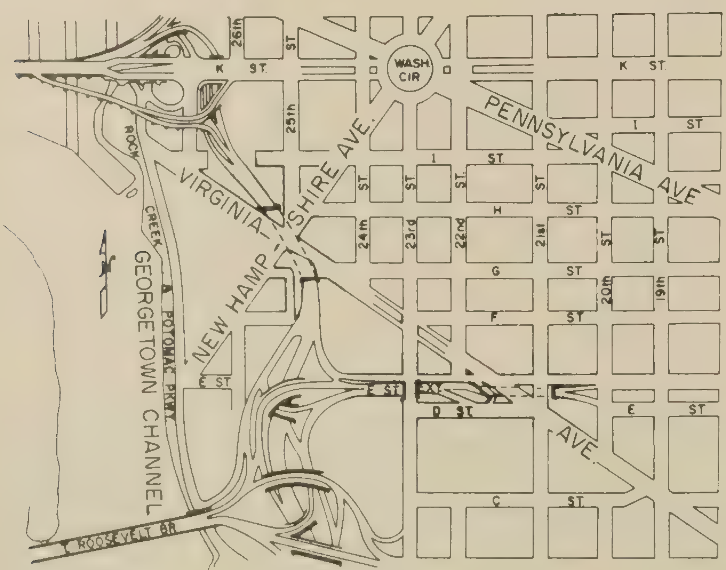
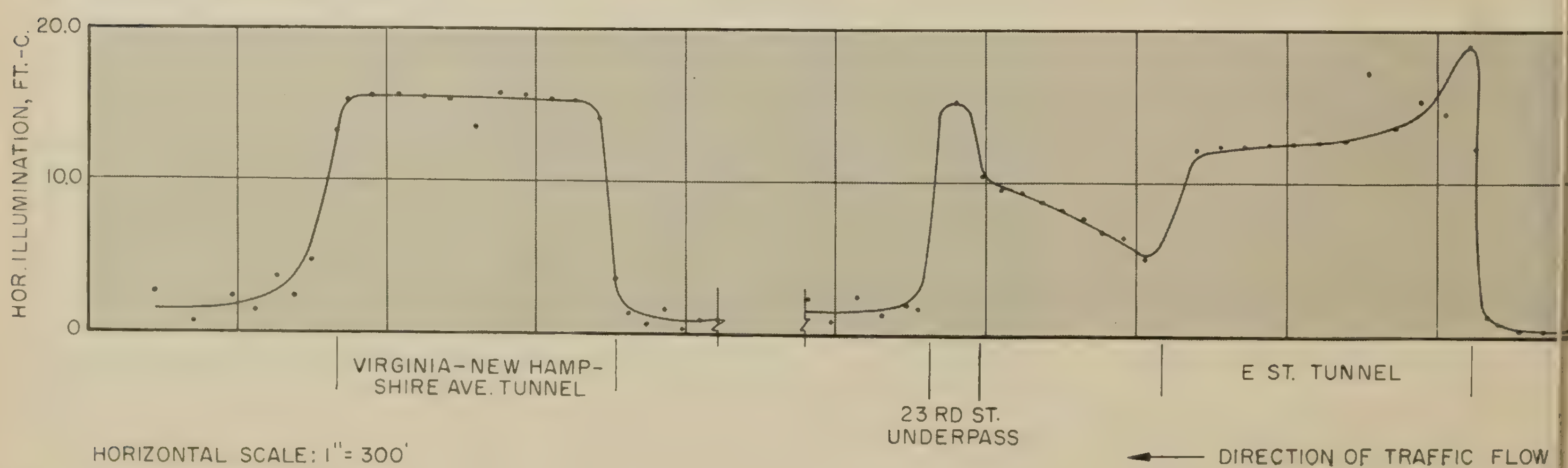


Figure 11.—Light profile at night for E Street, 23d Street, and Virginia-New Hampshire Avenue structures.



more than necessary and that a one-third reduction may still leave it in excess of the desirable level. Because the adjacent roadway lighting is restricted, the contrasting dark and light environments may require minimum lighting to avoid a hazardous condition on leaving the tunnel.

Photographs of the Virginia-New Hampshire Avenue and E Street tunnels in Washington, D.C., are shown in figures 8–10, and the physical and lighting characteristics of these structures are given in figure 11 and in tables 2 and 3. According to the light profiles in figure 11, there is an undesirable variation of roadway and tunnel (or underpass) illumination in both structures. The higher levels of night lighting in the structures tend to negate the lighting on the roadways beyond the exits. To the westbound road user of the E Street structure, this situation is critical beyond the 23d Street underpass because a major fork in the roadway necessitates a motorist's decision about 200 feet west of the underpass. Such night driving situations can be avoided by an artificial lighting environment in the underpass that is similar to the lighting on the exit roadway. Decreasing the structure lighting, as opposed to increasing the roadway lighting, is the most desirable way of correcting the condition.

Table 2.—Measured illumination in Virginia–New Hampshire Avenue Tunnel, Washington, D.C.

Tunnel station [1]	Roadway, horizontal illumination								Wall, vertical illumination		
	Line A [1] Lights on		Line B [1]			Line C [1]					
			Lights on		Lights off	Lights on		Lights off	Lights on		Lights off
	Day	Night	Day	Night	Day	Day	Night	Day	Day	Night	Day
	ft.-c.	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*
0+00	------	------	------	------	------	------	------	------	------	------	------
0+28	168	14.0	169	14.0	37.4	154	16.6	42.5	121	11.1	42.0
0+78	144	15.8	155	15.2	23.0	151	17.3	42.5	114	13.1	8.6
1+28	142	15.6	155	15.3	3.8	146	17.2	9.2	110	13.2	2.8
1+78	128	15.2	144	15.5	1.7	135	17.4	2.8	105	13.2	1.2
2+28	142	16.6	154	15.6	0.6	142	16.6	1.1	108	13.2	0.7
2+78	130	[2] 12.9	149	[2] 13.3	0.2	142	16.4	0.6	102	[2] 12.8	0.7
3+28	140	16.4	144	15.2	0.4	137	16.2	0.4	105	13.2	0.7
3+78	139	15.6	144	15.5	0.3	137	16.8	0.9	106	13.5	0.7
4+28	147	16.6	160	15.6	0.9	146	16.8	0.8	111	13.5	1.5
4+78	137	16.4	155	15.5	1.6	146	16.3	1.3	113	13.6	2.5
5+28	160	16.1	160	15.1	15.8	155	16.0	14.0	120	13.2	11.3
5+57	------	------	------	------	------	------	------	------	------	------	------

[1] Tunnel stations and lines are shown in figure 12.
[2] Ventilation opening in ceiling near this point.

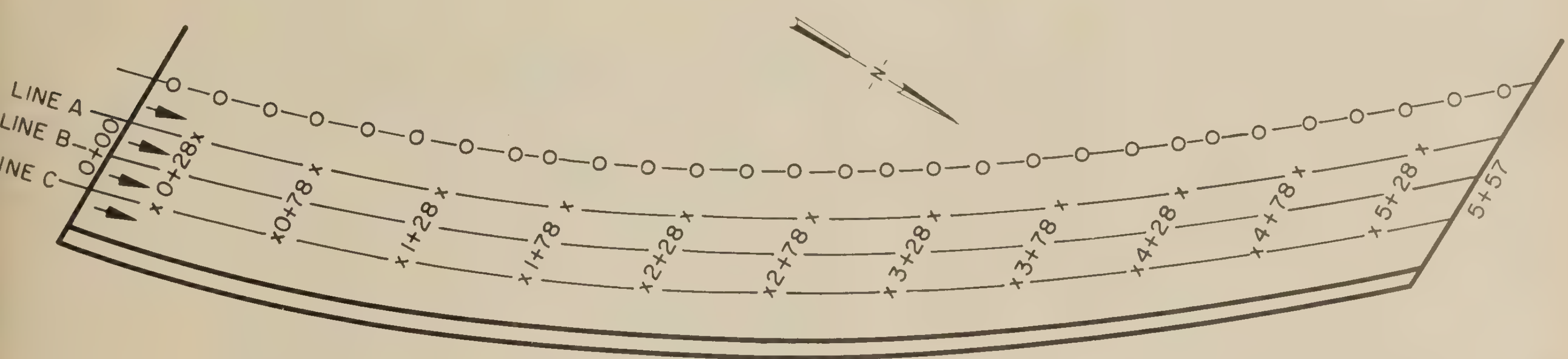


Figure 12.—Station numbers and lines used for measuring illumination in Virginia-New Hampshire Avenue Tunnel, Washington, D.C.

Table 3.—Measured illumination in E Street Tunnel, Washington, D.C.

Tunnel station [1]	Roadway, horizontal illumination			Wall, vertical illumination	
	Lights on		Lights off	Lights on	
	Day	Night	Day	Day	Night
	ft.-c.	*ft.-c.*	*ft.-c.*	*ft.-c.*	*ft.-c.*
0+00	------	------	------	------	------
0+15	209	------	209	31.0	9.2
0+65	43	12.0	18	24.0	9.7
1+15	29	12.4	2.5	22.0	9.5
1+65	28	12.4	[2] 3.5	22.0	9.5
2+15	25	12.4	0.4	20.0	9.5
2+65	24	12.5	0.6	18.0	9.5
3+15	24	12.8	0.3	18.0	9.5
3+65	24	12.8	------	25.0	11.3
4+15	36	17.2	------	28.0	10.1
4+65	39	13.7	------	30.0	10.6
5+15	43	15.3	------	32.1	10.7
5+65	52	14.5	------	73.5	11.8
6+15	200	19.0	------	------	------
6+20	------	------	------	------	------

[1] Tunnel stations are shown in figure 13.
[2] Ventilation opening in ceiling near this point.

It is highly desirable to maintain a constant and continuous lighting environment for the road user at night on all sections of the highway including tunnels and underpasses. Illumination in structures and on adjacent roadways should vary no more than 3 to 1 and preferably no more than 2 to 1.

The daytime lighting in the Virginia-New Hampshire structure may be a good example of economically impractical lighting that provides artificial illumination of sufficient brightness to compete with the natural daylight from the ends of the structure. Visibility in the tunnel is improved very little by the artificial lighting system, which provides as much as 150 footcandles on the roadway and 100 footcandles on the walls. A comparison of conditions with and without artificial lighting showed that natural light penetration provided reasonable visibility and that the requirement for daytime lighting is questionable. The cross-section area of the tunnel enhances natural daylight penetration. Artificial daytime lighting probably would not have been considered had the structure been on a straight and level roadway; even with the existing curvature in the structure, the need for daytime lighting is questionable.

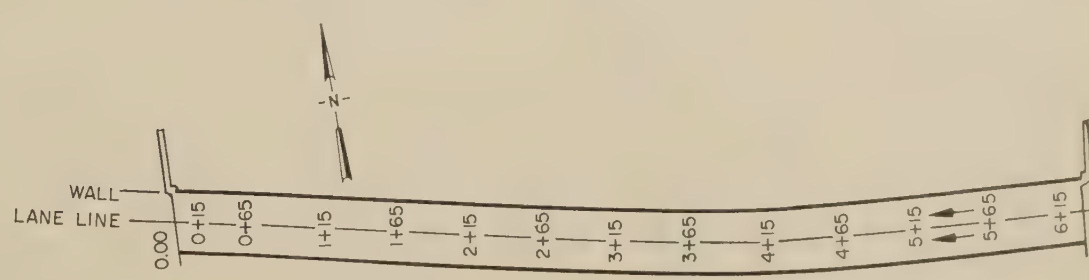


Figure 13.—Station numbers used for measuring illumination in E Street Tunnel, Washington, D.C.

Figure 14.—George Washington Bridge Lower-Level Tunnel—near entrance, dusk.

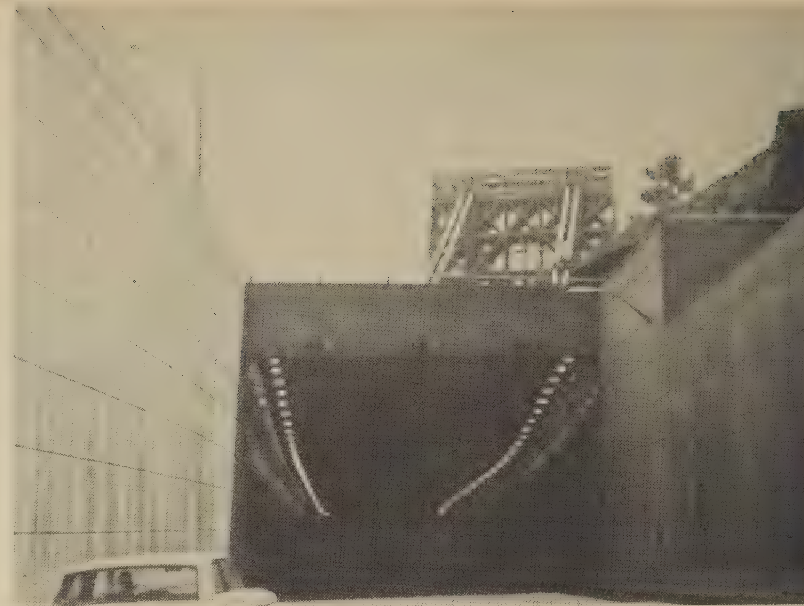


Figure 15.—George Washington Bridge Lower-Level Tunnel—approach, daytime.

Figure 16.—George Washington Bridge Lower-Level Tunnel—near entrance, nighttime.

The George Washington Bridge Lower Level Tunnel lighting design provides a new concept that merits special attention.[4] This tunnel (figs. 14–16) uses continuous fluorescent lighting for night lighting and for the normal day zone. Supplemental daytime entrance zone lighting is accomplished with mercury luminaires. For the night and the normal day (interior) zone lighting, 6-foot, 350-milliampere slimline fluorescent lamps are wired so that two lamps are connected in series with a choke across a 1,000-volt, three-phase supply. The supply voltage can be reduced to 800 volts or raised to 1,200 volts to vary the lighting intensity. In addition, entrance (intensive) zone lighting, consisting of 400-watt clear mercury luminaires, spaced 5 feet on center for the first 150 feet, and 10 feet on center for the next 100 feet, is provided for the eastbound tunnel. These luminaires are recessed into the tunnel ceiling and are close to and directed toward the walls to produce 100 footcandles on the walls in the first zone and 65 footcandles in the second zone.

The mixing of fluorescent and mercury lamps, with the yellow tile tunnel lining, produces pleasing and effective lighting in the daytime. While the validity of transitioning the intensive zone may be questioned, the road user is provided with one of the best examples of tunnel entrance lighting in the United States.

Long Tunnels

A long tunnel is generally considered to be one that is longer than 1,000 feet, but because of physical or geometric design, some may be less than 1,000 feet in length. A long tunnel has physical, pschological, technical, and economic aspects that are different from those o short tunnels and underpasses.

The long tunnel requires two daytime light ing systems—one for the intensive zone (day time entrance lighting) and another for th normal day zone (daytime interior lighting Adaptation level of the road user approachin the tunnel entrance and rate of adaptatio may be identical for long and short tunnels therefore, intensive zone lighting require ments may be the same for both types of tu nels. Beyond the intensive zone is the norma day zone which is referred to as the interio Daytime lighting of the interior is a separat consideration, and design requirements de pend to a great extent on quality and type lighting in the intensive zone. The intensiv zone should allow the road user to adapt hin self to the change of brightness in the tunne If an adaptation of 5 seconds' traveltime satisfied by the intensive zone, normal d

[4] Paper by Henry W. Wenson, Jr., and H. S. Lewis (see acknowledgments).

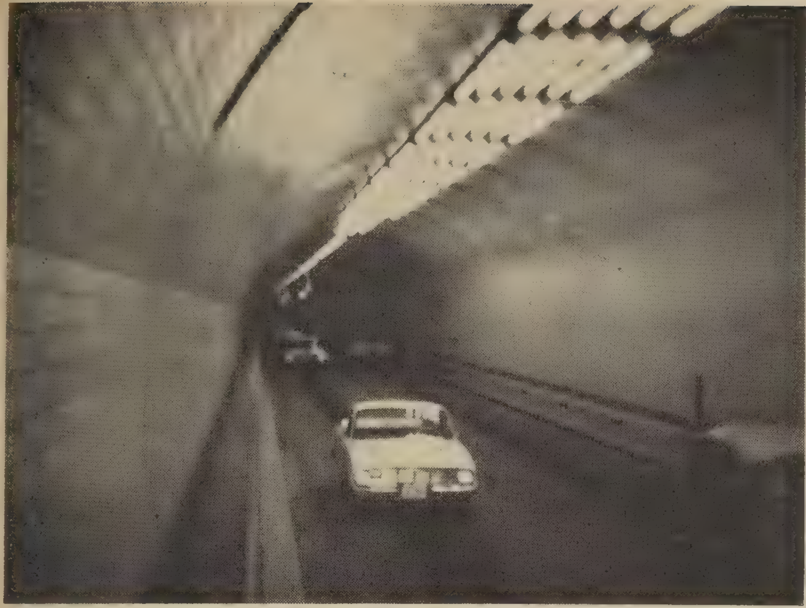


Figure 17.—Baytown Tunnel, Houston, Tex.—entrance zone, daytime.

Figure 18.—Baytown Tunnel, Houston, Tex.—near exit, nighttime.

zone lighting may be designed as a separate lighting system.

As intensive zone lighting cannot be designed for complete retinal adaptation, it is necessary to have a higher level of illumination in the interior during the day than at night (*4*). Night lighting and normal day lighting for the interior are often the same not only because design problems can be simplified by one system but also because available lighting equipment may lack design flexibility. As shown in table 1, the normal day zone (and night lighting) illumination ranges from 2.5 to 40 footcandles, which are roadway values. Wall illumination was furnished for a few tunnels and ranged from 1.5 to 5 footcandles.

The primary objective in all except wide tunnels is to provide lighting on walls, and, to a lesser extent, on the ceiling. Uniform brightness is best achieved with a light-colored matte-finish surface. Although several of the older tunnels and a few of the newer ones have painted walls and ceilings, the additional cost of tile or porcelain-enamel panels may be justified on the basis of performance and maintenance.

The interiors of existing long tunnels are lighted by four basic types of lighting equipment. The first type, in some of the older tunnels, consisted of incandescent equipment that was recessed in the tunnel walls during initial construction, providing intermittent flush windows which can be easily cleaned. This lighting system is not recommended because it is inflexible and relatively less effective.

A second type, the fluorescent luminaire with internal reflector, is placed either on the walls or in the angle between the ceiling and the wall and is one way of adding new lighting to an old tunnel. This type of luminaire has been installed in some recently completed tunnels. It does offer flexibility for future new lighting, but must be watertight, bugtight, and dusttight for efficient lighting and maintenance.

A third type, the fluorescent luminaire with reflector-deflector, was developed by the California Division of Highways.[5] This luminaire is similar to the internal reflector, except it has reflector louvers to direct the light to the walls and ceiling, and delivers only indirect light to the roadway.

The fourth type consists of a fluorescent lamp inside a protecting Pyrex glass tube, mounted a few inches from the tunnel wall or ceiling. Compared with the others, this type of luminaire is easier to make watertight and is being used in several newly constructed tunnels.

Continuous fluorescent equipment is the best interior lighting for preventing undesirable flicker. It is difficult, and often impossible, to provide both sufficient brightness for intensive zone lighting and reduced brightness for interior or night lighting using the same equipment without additional luminaires, even though variation in voltage or current is possible in some lighting systems. For this reason, it seems undesirable to restrict the design choice to the same type of equipment for both intensive and interior zone requirements. Where lower lighting levels are required, as for interior and night lighting, fluorescent lighting is desirable and is the type most commonly used.

The most difficult section of the vehicular tunnel to illuminate is the entrance section. The lighting of this section is one of the few problems in illuminating engineering in which both day and night levels of lighting are common considerations. This critical lighting problem demands maximum analysis and evaluation, and an understanding of several professional fields. It is evident that entrance lighting has been a problem in many tunnels in this country, and it is equally evident that the problem has not been properly solved. The underdesign of the daytime entrance lighting occurs as often as the overdesign of the night lighting.

In some daytime entrance lighting designs, illumination of the roadway has been given major importance when roadway brightness should have been incidental to wall brightness. The most common occurrence, however, is simply insufficient lighting. Responses from interviews with those responsible for the designs ranged from a complete misunderstanding of the entrance lighting problem to an acute awareness of it. Weakness in tunnel entrance lighting practices stemmed from two primary practices: (1) Attempting to use the same luminaire or type of luminaire to satisfy three lighting conditions, and (2) designing for eye adaptation within the tunnel without recognizing the fact that difficulty is experienced by the driver not when he has entered the tunnel, but when he is still outside of it.

While outside the tunnel, the driver is adapted almost to full daylight brightness and is trying to look into the much darker tunnel interior. The Texas Highway Department's evaluation of the daytime entrance lighting in the Baytown Tunnel (figs. 17 and 18) under the Houston Ship Channel in Harris County, Tex., is typical of prevailing conditions in many other tunnels—satisfactory on a cloudy day, and unsatisfactory on a bright day. Better designed daytime entrance lighting is needed for this tunnel. Night lighting is provided by two rows of luminaires that produce about 8 footcandles on the roadway in the tunnel. Roadway illumination outside the tunnel is about 1 footcandle. When one row of the luminaires was turned off, the visibility in the tunnel was not impaired, but the transition from the tunnel interior to the outside roadway was greatly improved. This same condition was observed in evaluations of many tunnels in which it is indicated that the night lighting in a tunnel should be kept to a minimum and should always be considered in relation to the lighting on the roadway outside the tunnel. This does not imply that the roadway lighting should be increased, but that the tunnel lighting should be reduced

[5] Reported by Harold Skootsky and John R. Brass (see acknowledgments).

so that the ratio of roadway lighting inside the tunnel to the roadway lighting outside the tunnel should not exceed 3 to 1 and preferably 2 to 1.

Visibility was judged as satisfactory when vehicles were clearly seen as silhouettes against the tunnel walls or ceiling. Very low, but uniform, wall and ceiling brightness will provide this visibility. Tiling or paneling of walls and ceiling enhance lighting uniformity and decrease the illumination requirements.

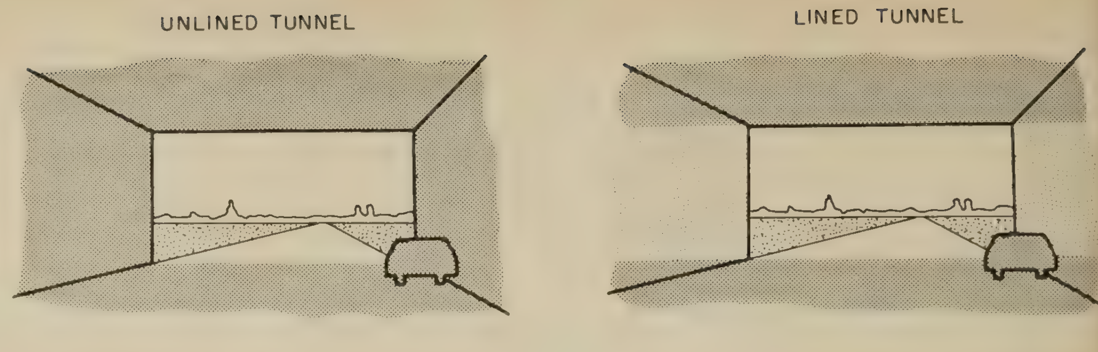


Figure 19.—Effect of natural light penetration on walls at the tunnel exit.

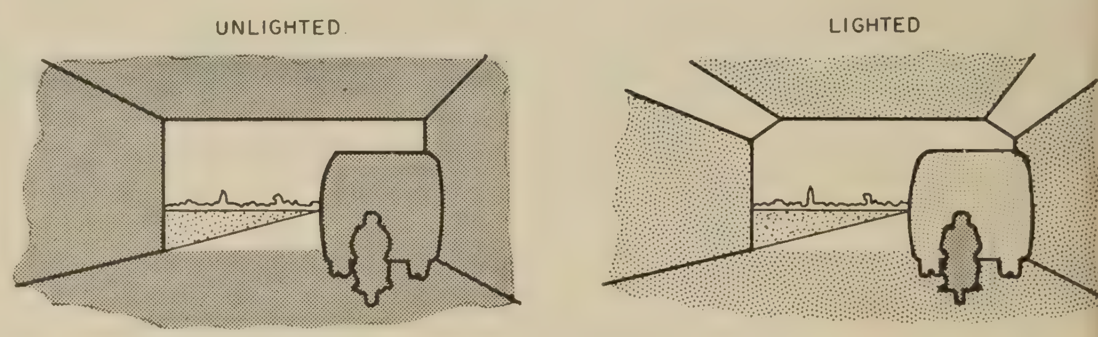


Figure 20.—Effect of normal day zone lighting at the tunnel exit.

Conclusions

Daytime entrance lighting

During daytime operation, tunnel entrances should have a supplemental lighting system to satisfy the visual requirements and adaptation of the road user as he approaches the tunnel, as he enters the tunnel, and after he enters it. Adaptation over the ranges experienced in entering a tunnel occurs very quickly; therefore, the basic requirement of the entrance lighting is to provide the range of adaptation and not the rate.

Many types and combinations of luminaires have been used to meet these demands because the prevailing characteristics are rarely identical for any two tunnels. Tunnel inspection in the United States showed that there are few good examples of lighting, several examples of fair lighting, and many examples of poor lighting. None was completely in accord with the Illuminating Engineering Society's 1957 report entitled *Lighting Traffic Tunnels and Underpasses*. However, this fact alone would not necessarily deem them unsatisfactory, as this report is outdated and is now being revised.

Using equipment that is available, innovation and good engineering can provide a product that will satisfy the need for three lighting systems: (1) Daytime entrance; (2) normal day zone; and (3) night.

If one piece of hardware will not accomplish all three needs, then more than one should be used. Therein lies the solution to many of the existing problems of tunnel lighting. Economic considerations should prevail only after the minimum functional requirements are achieved.

Although the majority of entrance lighting has been provided with additional fluorescent luminaires similar to those used for normal day zone and night lighting, the high brightness desired may best be accomplished with other types of luminaires. Economy, which is always an engineering factor, may be achieved by investing more in the entrance lighting and less in the night lighting.

Exit lighting

During the day, the tunnel exit appears as a *light hole* to the road user. Obstacles on the roadway will stand out as a silhouette against the exit and thus be clearly visible. This silhouette visibility at the exit can be further enhanced by the additional natural light penetration into the tunnel produced by tile- or panel-lined walls at the exit, as shown in figure 19. Thus, no visibility problem exists as long as the tunnel exit is clear.

When the exit is not clear, there may be a different visibility requirement. When a small object is following a larger one, as shown in figure 20, the smaller object would not be obvious and, depending on its color, may not be visible. This situation is improved by the normal day zone lighting, and is sufficient justification to extend the normal day zone lighting to the exit portal. Supplemental exit lighting is rarely required at the tunnel exit.

The most common difficulty at the tunnel exit occurs at night, when the roadway outside the tunnel has no lighting or a lower level of illumination than inside the tunnel, and the exit appears as a *dark hole* to the road user. Excessive lighting inside the tunnel is the common cause of this situation. Many tunnels have the same system for night lighting as for normal day lighting. Inasmuch as the normal day lighting system must provide substantially more brightness than is required for the night lighting, a single lighting system, with no provision for varying the amount of illumination, cannot satisfy both requirements. At night, lighting in excess of the optimum is detrimental and may create a hazardous condition at the exit. The conditions for road user visibility are not met if the normal day lighting in the tunnel remains the same at night. The California State Highway Department designed a luminaire with control circuits to change lamp operation for daytime, and nighttime conditions. Two 1,400-ma. lamps and one 600-ma. lamp are for daytime operation and one 60-ma. lamp is used at night. Actually, the lamp that is operated at 600 ma. during the day is operated at 60 ma. at night. This luminaire satisfies the day and night lighting requirements for the tunnel interior but does not furnish sufficient illumination for mos daytime entrance lighting needs.

Flicker

Discontinuous lighting in long tunnels re sults in nonuniform brightness of the interio and produces a recurrent flicker which dis comforts the road user. It also reduces vis ibility by producing phychological harassmen in the form of moving shadows within th driver's vehicle, and troublesome reflection that appear to crawl over other vehicles and to some extent, camouflage them. This pho nomena, which is the result of periodic brigh ness changes, is dependent on the repetitio frequency. When the frequency is increase to 50 to 80 cycles per second, called th flicker-fusion frequency, the periodic charact of the lighting can no longer be distinguishe

In the United States, flicker causes fe problems because most tunnel interiors a illuminated by continuous lines of lightin Fluorescent luminaires installed in continuo rows eliminate flicker. Even though the e plates, fittings, etc., interrupt the continuo lighting, they are not of sufficient length cause objectionable flicker. Continuous ligh ing must be installed parallel to the roadwa the mounting of a linear source lateral across the ceiling of a tunnel can be glari and cause flicker.

Continuous fluorescent tunnel lighting sy tems are recommended for night lighting a interior day lighting.

Maintenance

Reliability of tunnel lighting is vital beca it is used continuously, 24 hours a day. T lighting depends on many factors that shou

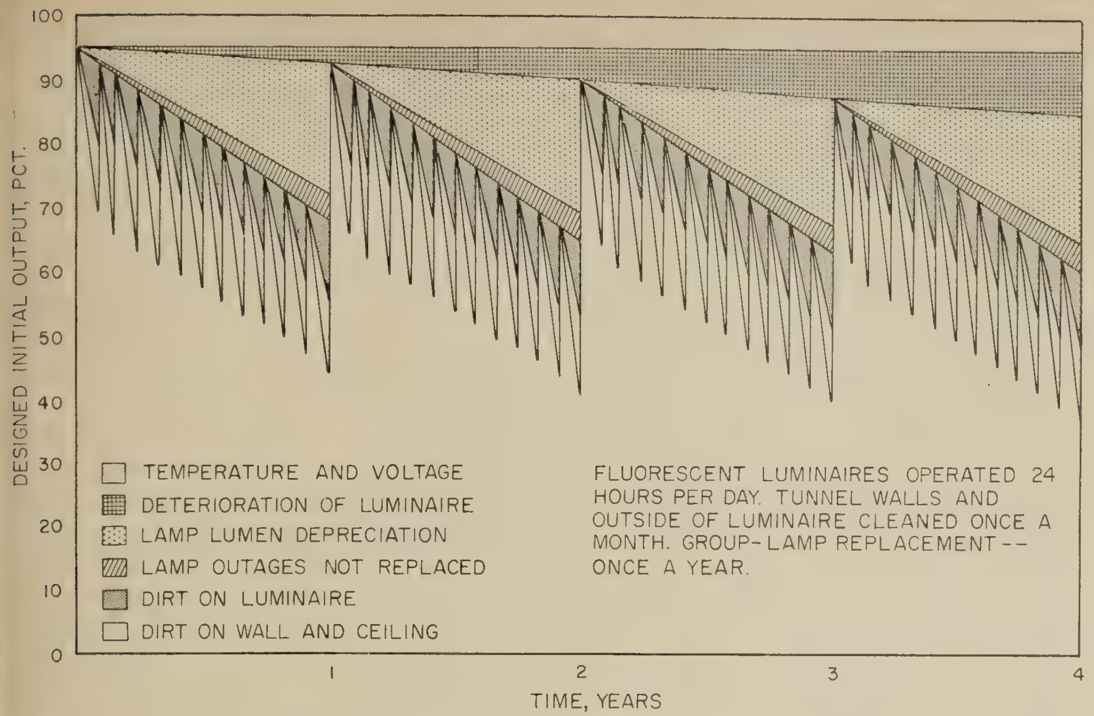


Figure 21.—Effect of a preventive maintenance program—six causes of light loss for a tunnel interior lighting system.

be recognized and accounted for at the design stage. Maintenance of the lighting is a most important factor, and the proposed maintenance program must be reflected in the initial design or realistic results cannot be forecast (fig. 21). Poorly maintained tunnels discredit the responsible agency, and present ineffective lighting with its associated hazards.

The maintenance required depends on the location, type, and volume of traffic; type and capacity of the ventilation system; tunnel cross section and shape; ceiling and wall finish; operating speeds in the tunnel; type and location of luminaires; grades and alinement within the tunnel; and the electrical system and supply. Even momentary failure of the lighting is dangerous, and adequate standby equipment and supplies are necessary. There is much more equipment in a tunnel than in a corresponding length of ordinary roadway, and tunnel maintenance is a large undertaking.

A tunnel must have sufficiently high initial illumination to compensate for the many factors that will reduce it. The most important factor, with the exception of the luminaries is the surface treatment of the walls and ceiling. Reducing the reflection factor of these surfaces may be more detrimental to lighting effectiveness than any other single factor. Vehicular tunnels must be finished with an interior surface that will not deteriorate as time progresses and as chemicals attack it, that will not readily soil, and that can be easily cleaned. These attributes are characteristics of a light-colored matte-finish tile or porcelain-enamel panel with an initial reflectance of 70 percent or higher. The temptation to use a less costly finish should be resisted because the cost of cleaning and repainting, plus the loss of reflectance, will result in much higher maintenance costs and require more initial illumination.

Luminaires should be sealed to prevent the entry of dust and water when the tunnel is being cleaned by a high-pressure spray. They should be designed to permit quick and easy internal cleaning. The materials used should be resistant to alkaline deposits, to concentrated exhaust fumes, and especially to harsh cleaning solutions that must be used to thoroughly clean the tunnel walls and ceiling.

More frequent tunnel cleaning is required when traffic volumes are high and there is a large percentage of truck traffic. Cleaning also is required more often when the vehicular speeds are slow and ascending grades exist within the tunnel, as exhaust fume deposits are a major cause of tunnel dirt.

Because exhaust fumes are a major cause of tunnel dirt, design of the ventilation system is a factor to be considered in the design of the lighting as well as in maintenance programs.

Regardless of the difficulties, lamps should be replaced on a group replacement program, which not only will help preserve the light output at the desired level, but also provide for a balanced maintenance workload. The magnitude of relamping will generally require group replacement by sections. To replace lamps on a burnout basis is usually false economy from the standpoint of lighting output and equipment maintenance costs. Fluorescent ballasts and lamp holders can be damaged by very old lamps that develop rectification and sputtering. Even though some lamps will burn for years, eventually their light output will be reduced to a point beyond which it is economical to keep them in service. Design for a specific level of illumination is impossible when lamps are replaced on a burnout basis only.

The inside of the luminaire will require cleaning more often than the frequency of lamp replacement, but maintenance schedules still should prescribe cleaning each time a lamp is replaced.

Some tunnels need cleaning weekly, whereas others may not require cleaning for several weeks. Locations in northern sections of the country, where freezing conditions may exist continuously for several weeks or months, make cleaning operations difficult and frequently impractical. These are factors that must be recognized, evaluated, and accounted for in the design of the lighting system. Designs

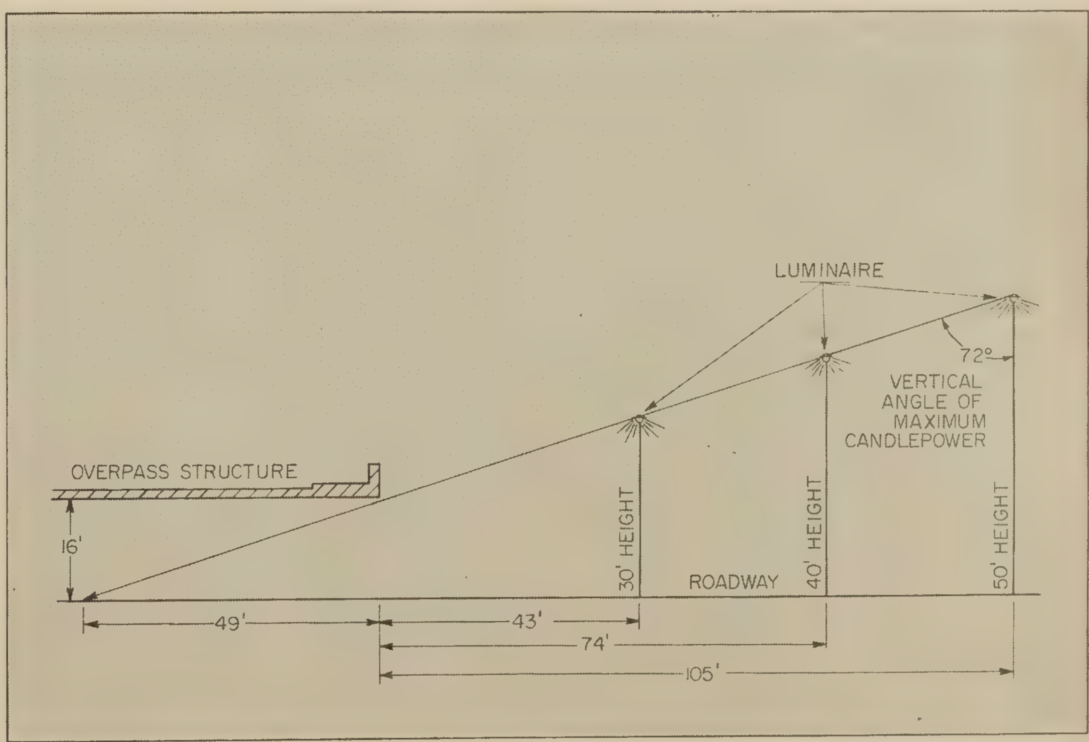


Figure 22.—Location of roadway lighting luminaires adjacent to underpass portals for maximum penetration.

that do not include provisions for maintenance are incomplete and ineffective.

Entrance roadways

Nighttime roadway lighting adjacent to the tunnel entrance is not required for visibility but may be provided without detrimental effect. The criteria for roadway lighting should be the same as though no tunnel existed. When the roadway is continuously lighted, no change should be required because of the tunnel.

Special designs have been successfully used, and are recommended when practical, to reduce the daytime brightness of areas outside the portal and enhance the visibility of the road user. A low reflectance finish on the face of the portal, dark pavement surface, and heavy tree foliage shading the roadway and portal area will reduce the adaptation level of the driver.

Light transition louvers have been used on the approach roadway to reduce the brightness ratio between the tunnel interior and the exterior environment (*12*). A few installations have been judged favorably, and many illuminating engineers believe more use should be made of louvers, which shade the roadway ahead of the entrance and provide a light transition between the bright daylight of the exterior and the darker tunnel entrance.

Exit roadways

There is no need for special treatment at the exit roadway during the day. With properly designed night tunnel lighting and roadway lighting adjacent to the tunnel exit, there should be no problem at night. However, when the lighting in the tunnel exceeds the requirements for visibility, the additional expense of designing higher-than-necessary roadway illumination to provide transition from the excessively bright tunnel interior to the relatively dark exterior roadway should not be condoned. The night lighting should be much less than the normal day lighting to avoid creating potentially hazardous conditions and unnecessary expense, yet provide the road user with optimum visibility.

Guide Values for Lighting

Underpasses

Underpasses, up to 75 feet in length, may be adequately lighted from roadway luminaires outside the underpass. Lighting poles should be located near each portal, as shown in figure 22, so that the maximum amount of light can penetrate the underpass. When supplemental underpass lighting is required, the roadway lighting in the underpass should be the same as that on the approach and exit roadway. In urban areas, additional illumination may be required for pedestrians and for the policing of underpasses. For these applications, the underpass lighting should be no more than three times the lighting on the roadway outside the underpass.

Lighting is not necessary in an underpass during the day, except for pedestrians and policing, and then only in long underpasses.

Short tunnels

Short tunnels require two lighting systems, one for daytime and one for nighttime.

Daytime entrance lighting.—The entire length of the tunnel should be designed for sufficient wall and ceiling brightness to silhouette an obstacle for the road user outside the tunnel. The required lighting will vary with prevailing conditions, but should generally average between 30 and 60 footcandles maintained on the walls. All values of wall and ceiling illumination are based on a reflectance factor of at least 70 percent for wall surfaces. When reflectance is less than 70 percent, designed illumination should be increased to compensate for the lower reflectance. (See table 4.)

Table 4.—Guidelines for maintained illumination on wall

Lighting system	Underpass	Short tunnel	Long tunnel
	ft.-c	*ft.-c*	*ft.-c*
Day entrance	--------	30–60	30–60
Day interior	--------	------	5–10
Night	[1]	0.7–2.0	0.7–2.0

[1] Should be same as approach roadway lighting.

When more than one row of fluorescent luminaires is required to light each wall, other types of luminaries to provide the additional illumination should be considered.

Night lighting.—Lighting at night must be designed to avoid flicker and glare, and illumination should be the same throughout the entire length of the tunnel. The ratio of the roadway lighting inside the tunnel to that of the roadway outside the tunnel should not be greater than 3:1 and preferably should not exceed 2:1. Wall and ceiling illumination in tunnels during the night should be maintained between 0.7 and 2.0 footcandles. Fluorescent luminaires are recommended for night lighting to provide continuous, uniform, low brightness lighting on the walls and ceiling.

Long tunnels

Three lighting systems are required for long tunnels, one for daytime entrance, one for normal day zone (interior), and one for night.

Daytime entrance lighting.—Requirements for daytime entrance lighting in long tunnels are identical to those for short tunnels. The length of daytime entrance lighting should provide for at least 5 seconds' traveltime in the tunnel, or provide a safe stopping distance. An additional length of intensive zone lighting may be required in a straight and level tunnel to provide sufficient background brightness to silhouette an obstacle in the tunnel. The effectiveness and economy of all types of luminaires should be considered, evaluated, and compared before selecting the type of luminaire to perform the daytime lighting task in the tunnel entrance.

Normal day zone (interior) lighting.—Interior lighting must be free from flicker and glare. A high-reflectance tunnel lining is recommended to produce adequate wall and ceiling brightness in tunnels during the day and night. The interior lighting should maintain between 5 and 10 footcandles on the walls. Fluorescent luminaires extended to the tunnel exit are recommended to provide interior lighting.

Night Lighting.—The night lighting requirements for long tunnels are identical to those for short tunnels.

Tunnel lining

The interior walls and ceiling of the tunnel are essential adjuncts of the lighting system. Wall and ceiling brightness and uniformity depend on the reflectance quality of the surfaces. The surfaces should be of a material that will not deteriorate with age and chemical attack, will not readily soil, and can be easily cleaned. Although special paints are available for use on tunnel interiors, a more permanent light color matte (nonspecular) finish surface, with a reflectance of 70 percent or greater, is recommended. When a surface material has less than 70 percent reflectance, the designed lighting should be increased to provide equivalent wall and ceiling brightness.

The roadway surface even though it is more subject to dirt and discoloration can affect the tunnel lighting. Consideration of lighting effectiveness would indicate preference for a light color pavement. An asphalt roadway surfacing would be desirable for decreasing noise, however, maintenance and economical considerations would probably be the deciding factors in the choice of roadway material.

Wide tunnels

In lighting tunnels up to about 50 feet wide, wall brightness is the principal objective; in wider tunnels, roadway lighting may become equal in importance. The objective of providing background brightness for silhouette vision may not be completely achieved in a wide tunnel from wall brightness alone. In these tunnels it may be impractical to provide sufficient background brightness; therefore, entrance lighting, preferably by ceiling mounted luminaires, must also provide direct discernment or object glint for the approaching road user.

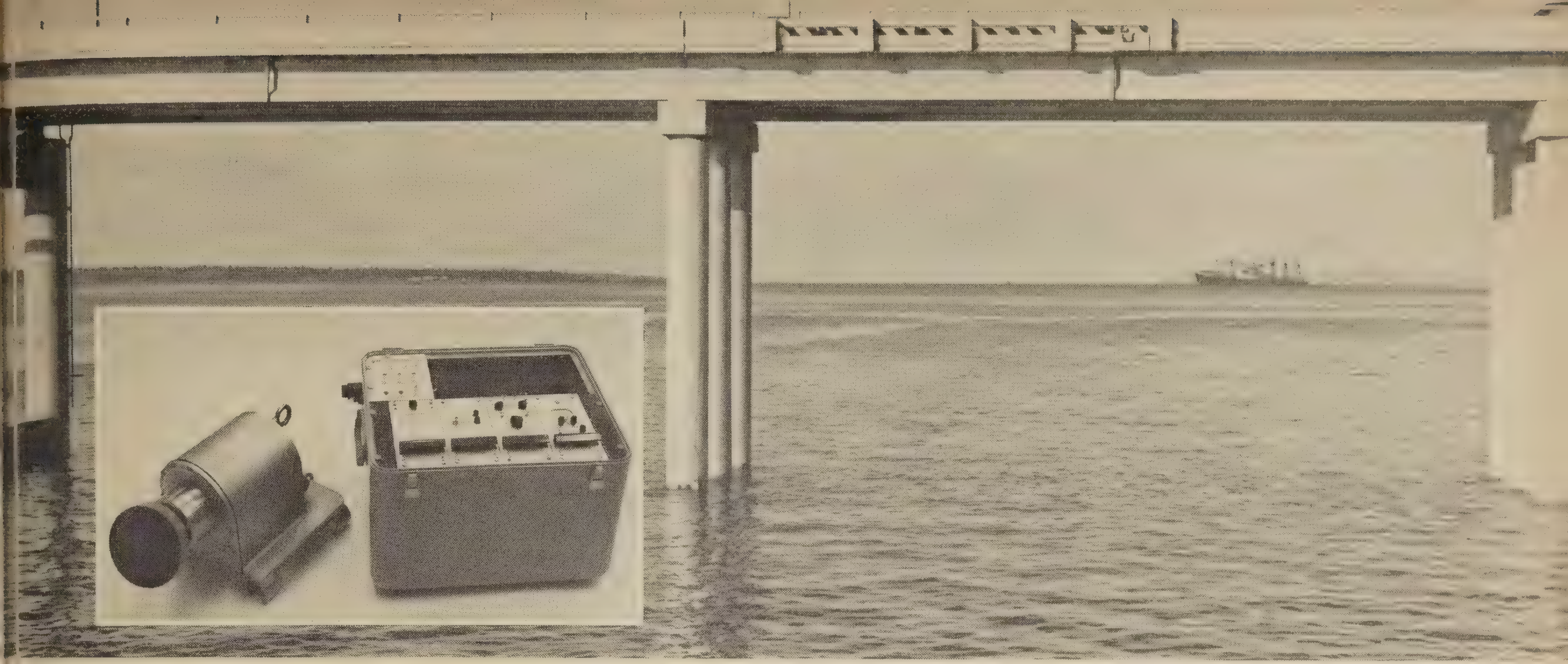
Some roadways, because of the specular nature of their surfaces and their reflectance at the grazing angles of incidence, *mirror* the wall and ceiling brightness. This *mirror* characteristic may reduce the amount of overhead illumination required.

The levels of illumination in a wide tunnel should be similar to those in any other tunnel. Luminaires providing wall and ceiling brightness in tunnels up to about 50 feet wide usually produce adequate roadway brightness. In wider tunnels, wall lighting may leave a dark center in the roadway—a condition that may be alleviated by additional lighting.

Maintenance

Tunnel maintenance cannot be allowed to *just happen*—it must be planned. To assure satisfactory lighting results, the designer must have knowledge of the proposed maintenance program. Physical maintenance is the only way to continue the effectiveness of any light

(*Continued on p. 105*)



Youngs Bay Bridge, Astoria, Oregon, site at which newly developed scour meter was tested.

Ultrasonic Instrument for Determining Local Scour at Bridge Piers

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

Reported by MURRAY L. CORRY,[1] Highway Engineer, Office of Engineering and Operations and WILLIAM SAGER, Research Engineer, Automation Industries, Inc.

The ultrasonic scour meter described in this article was developed to determine the magnitude of local scour around bridge piers. The instrument automatically obtains sufficient depth data to map the stream bottom around the upstream face of a pier. Although the instrument was designed to fill a research need, a simplified version could also be adapted to maintenance and inspection operations.

Introduction

IN 1894, Engels published the results of a model study in which he investigated local scour around bridge piers and the effectiveness of riprap in attenuating such channel degradation. Since that time, numerous other model studies have been undertaken to define the mechanics of this localized scour process, resulting in a large body of data that adequately describes the local scour phenomenon in scale models and, with the application of model-prototype similitude relations, could be used to predict local scour in a real environment. To determine these model-prototype similitude relationships, scour and related hydraulic and geometric data must be obtained around full scale structures for comparison with the model results.

The instrument described in this article was designed to obtain the local scour portion of these data. It is an electroacoustical device for determining, as a function of time, the changing streambed elevation around bridge piers. The device, called an *ultrasonic scour meter,* was developed in a research program sponsored by the Office of Research and Development, Bureau of Public Roads.

Electroacoustical Systems

Usually, any electroacoustical system designed for underwater operation requires the following elements:

- A signal generator that sends an electrical pulse to a transmitter.
- A signal transmitter (transducer), located in the water, to convert the electrical pulse into a mechanical vibration, resulting in the propagation of a pressure wave through the water.
- The media (water) in which the pressure wave is transmitted and the reflected echo retransmitted.
- A receiver (transducer), also located in the water, to detect the reflected pressure wave and convert the received mechanical energy to an electrical pulse. Often, one transducer serves as both a receiver and transmitter.
- An electronic amplifier to upgrade the pulse to a usable amplitude.
- A computer that measures the time lapse between transmission and reception and converts this information into distance between transmitter and reflector.

The basic configuration of the ultrasonic scour meter follows this general design concept (fig. 1). It consists of a transducer that serves both as a transmitter and receiver, and an electronic unit that generates the signal or pulse, amplifies the return pulse, and computes a voltage proportional to the distance between the transmitter (transducer) and the stream bottom. The unique feature of the

[1] During the research program, Mr. Corry was in the Office of Research and Development.

instrument is its ability to automatically obtain sufficient data to map the stream bottom near the upstream face of a bridge pier. This multipoint depth data is acquired by a mechnical unit that moves the transducer through a preset positioning sequence similar to that shown in figure 2.

Initially, a depth reading is obtained while the transducer is positioned straight down (0° vertical and minus 120° horizontal). Next, a vertical positioning gear moves the transducer to the 4° vertical position where motion is delayed for 1 second while a depth indication is obtained. A horizontal positioning gear then moves the transducer to the −90° horizontal position where motion is again delayed 1 second to obtain a depth reading. The sequence is continued through the −60°, −30°, 0°, +30°, +60°, +90°, and +120° horizontal positions, after which the transducer is returned to the original −120° position. Immediately upon return of the horizontal mechanism to the −120° position, the vertical drive moves the vertical gear to the 8° position. The horizontal sequence is then repeated, and the vertical mechanism moves the transducer to the 18° position. This sequencing continues through the vertical angles of 28°, 43°, and 61°. After completing the horizontal sequence at the 61° vertical position, the vertical drive returns the vertical gear to the 0° position in preparation for the next sequence.

In operation, the mechanical unit is positioned on the bridge pier below the water surface and is connected to the electronic unit on the bridge by waterproof cables.

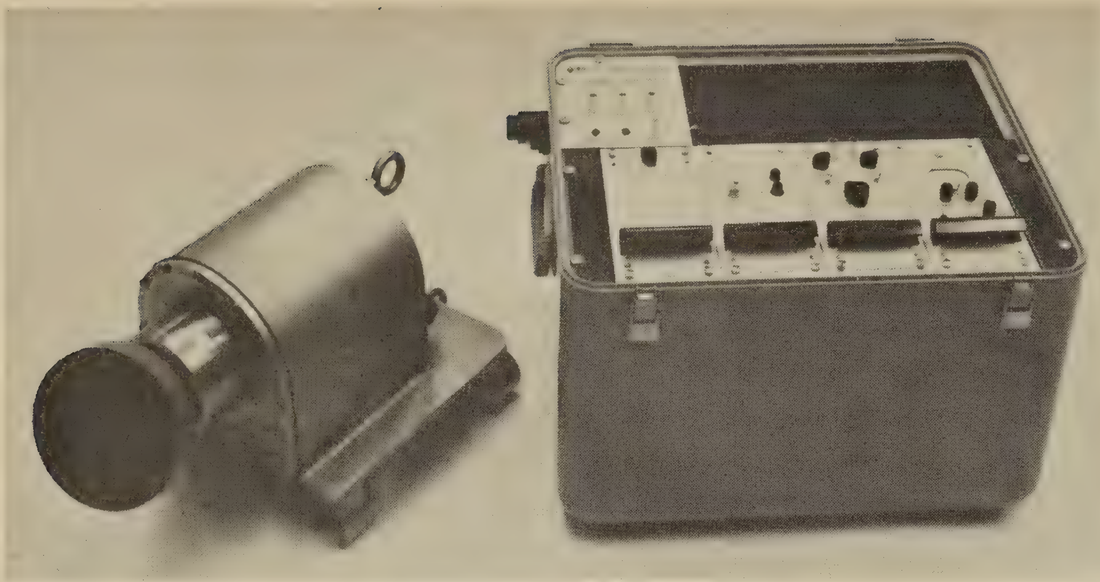


Figure 1.—Ultrasonic scour meter.

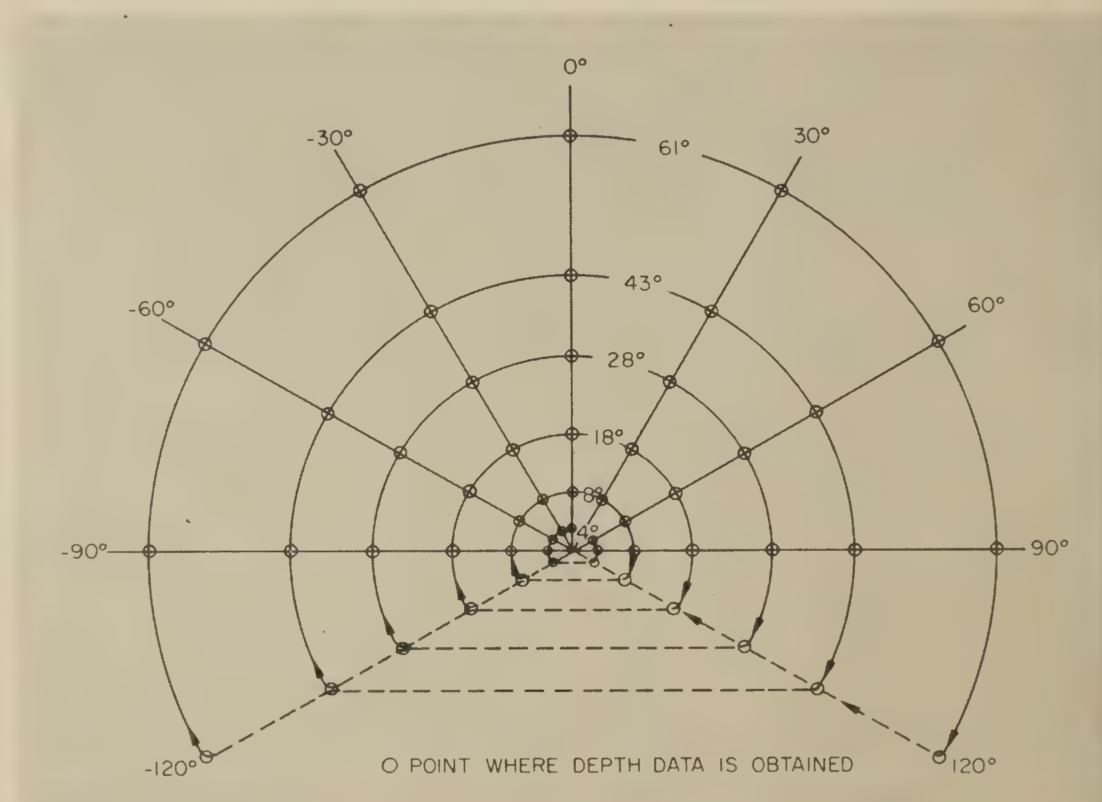


Figure 2.—Bottom mapping sequence.

Field Test

The scour meter was tested under field conditions at a highway bridge over Youngs Bay, Oregon, in December 1966. Because of the tidal action, this site had two flood, or scour, periods daily.

The instrument was positioned normal to the bridge alinement, and guidelines were strung from the instrumented pier to the piers on each side and to a railroad trestle approximately 150 feet away (fig. 3). Distance from the instrumented pier was indicated on each line. Check measurements were obtained by lead-line soundings at the pier and from a boat following the guidelines. An ultrasonic device with an accuracy comparable to that expected from the test instrument was used as the check instrument in the boat. Depth measurements were obtained by the two instruments at approximately the same time; that is, the test instrument mapped the scour hole while the ultrasonic device on the boat obtained a continuous depth record along the 0° and ±90° sounding ranges.

Both instruments recorded the shortest distance from the transducers to the streambed within the transmitted energy beams. Therefore, the depths recorded were functions of the transducer positions relative to the channel bottom. Accordingly, with an upward sloping channel bed, the test instrument should have always recorded a greater depth than that shown by the check instrument. The test results proved this to be true for most of the measurements obtained within the limits of the scour hole (angles less than 45°); but outside the limits of the scour hole (angles more than 45°), the reverse situation was encountered—the check instrument recorded the greater depth. (See figs. 4 and 5.) Outside the scoured area the discrepancies were probably due to the large angle between the transducer face of the test instrument an[d] the streambed, which could have resulted in [a] high energy loss and a corresponding reduc[-]tion in accuracy.

Although the tests were more qualitativ[e] than quantitative, they did indicate th[e] feasibility of using such a device to map scou[r] hole areas. However, because of the difficulti[es] encountered with the larger vertical angle[s] care should be exercised in interpreting th[e] data for vertical angles larger than 45°.

The mapping capability of the test instru[-]ment is illustrated in figure 6. The contou[r] map shown was derived from data obtaine[d] during one test sequence.

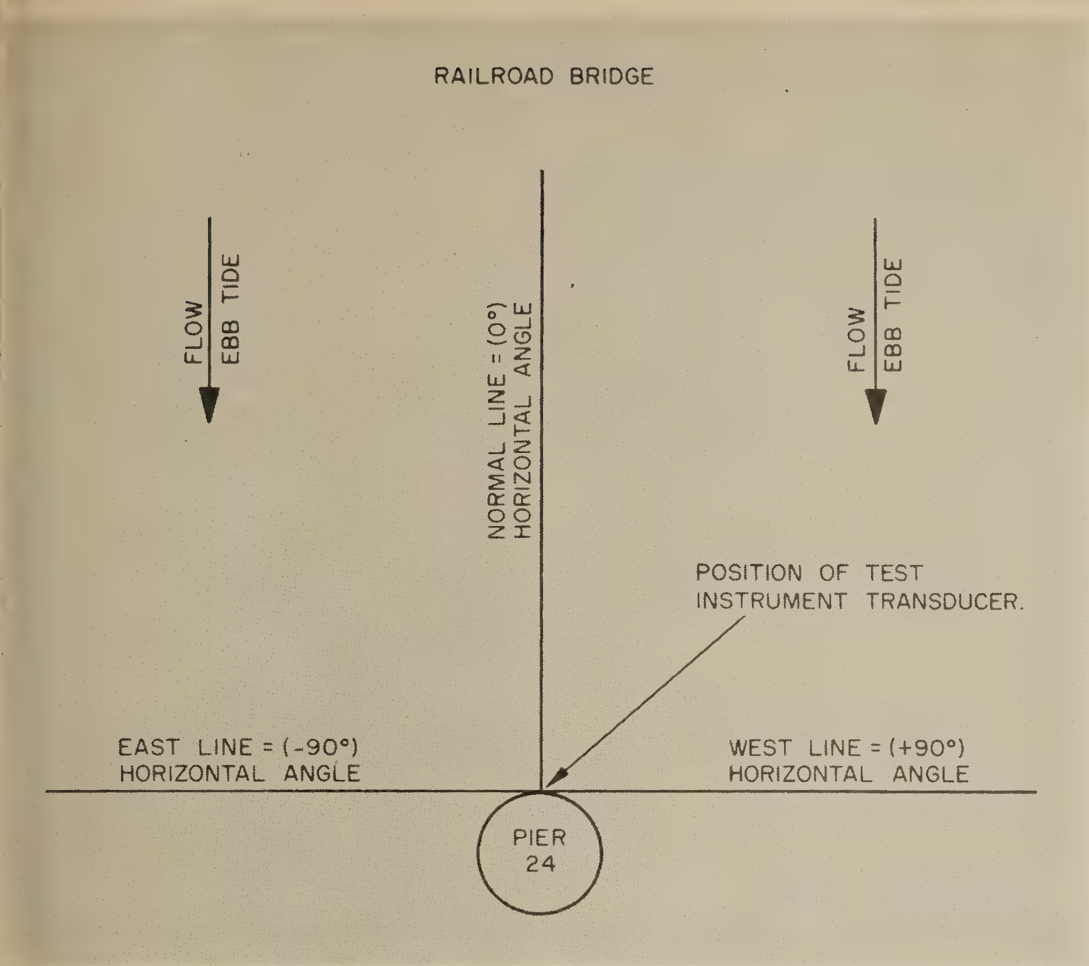


Figure 3.—Plan view of sounding lines at test location.

Instrument Development

The development program was divided into wo phases—a feasibility-study phase and a lesign, construction, and testing phase. Hylraulic mechanical, electronic, and transducer roblems and capabilities were investigated luring the feasibility study.

'easibility study

Results of the hydraulic portion of the easibility study indicated that no detrimental ffects should be experienced from turbulence, emperature gradients, air bubbles, and sediaent conditions usually encountered around iers. However, swift streams may carry ediment particles of sufficient size or concenration to make detection of the bottom ifficult. Measurements of ultrasonic-signal ttenuation due to suspended sediment inicated that concentrations larger than 20,000 .p.m. will greatly reduce the effective range f any pulse-echo instrument. Measured twoay attenuation figures for a 200-kilo Hertz kHz) ultrasonic beam, using bentonite as the ash load, were 0.136, 0.336, and 1.55 decibels er foot at 10,000, 20,000, and 30,000 p.p.m. oncentrations, respectively. These correspond o power losses of 3%, 8%, and 30% per foot.

From theoretical calculations for the transucer design a computer program was devised o plot the transducer directivity functions. Transducer diameters from 3 to 9 inches were plotted using a 200 kHz driving frequency. Subsequent pattern measurements, using a large tank and three transducers 2, 7, and 10 inches in diameter, indicated good agreement with the calculated values. Figure 7 is a plot of the measured directivity of the 7-inch unit.

Instrument design

Instrument design was controlled by the results of the feasibility study and by the data requirements. The design specifications required: (1) that the instrument consist of an electronic package containing transmitter and receiver modules and a mechanical unit containing the transducer and transducer positioning mechanism; (2) that the electronic package be transistorized and designed for battery operation; (3) that the electronic design provide all necessary functions for a pulse-echo system capable of ranging in increments to a distance of 150 feet with an absolute accuracy of ±0.50 foot and with a relative accuracy (linearity) of ±1%; (4) that the mechanical unit automatically move the transducer through a predetermined position sequence and transmit to a recorder the radial distance from the transducer to the bottom and to the position identification; (5) that the 6-inch piezoelectric transducer transmit a beam of ultrasonic energy not exceeding 3° in width (see fig. 6); (6) that the mechanical unit be designed for submersion to a depth of 25 feet; and (7) that a rail, permanently attached to a bridge pier, be provided to lower and raise the mechanical unit.

The requirement for a maximum range of 150 feet necessitated an ultrasonic frequency low enough to avoid excessive water losses, and the requirement of a maximum beam width of 3 degrees with a maximum transducer diameter of 6 inches limited the frequency of operation to a minimum of 200 kHz. This frequency was found suitable for the 150-foot range requirements and was used in all subsequent testing and design.

Mechanical unit

The mechanical unit contains the transducer, the drive mechanism, and the automatic sequencing circuits. Because this unit operates under water, its case was designed to resist the impact of water-borne debris and

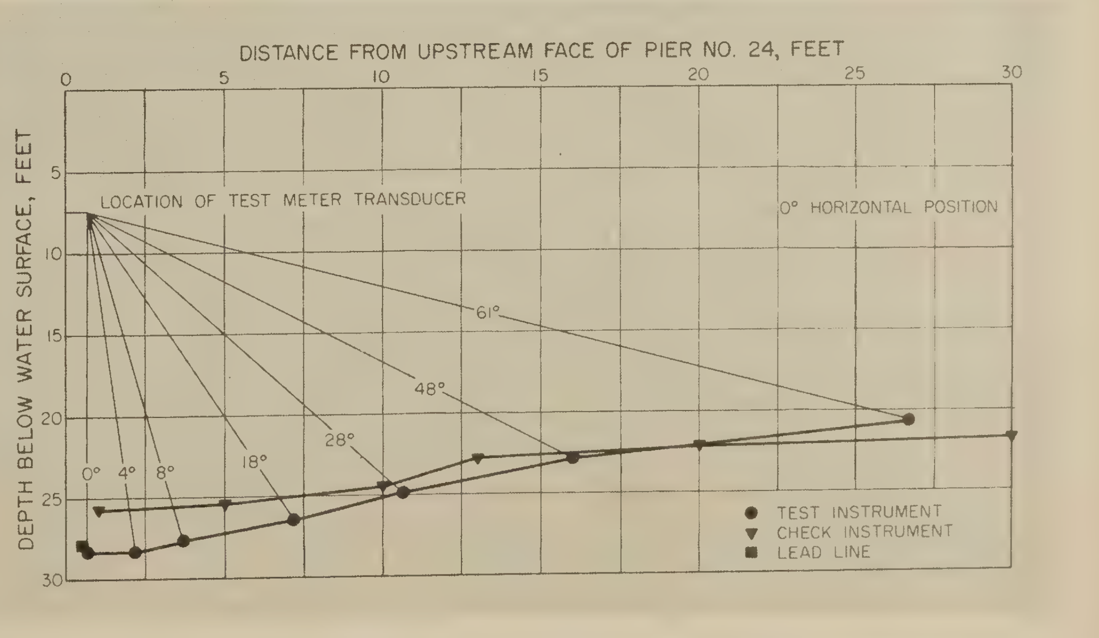


Figure 4.—Depths recorded during test run No. 3.

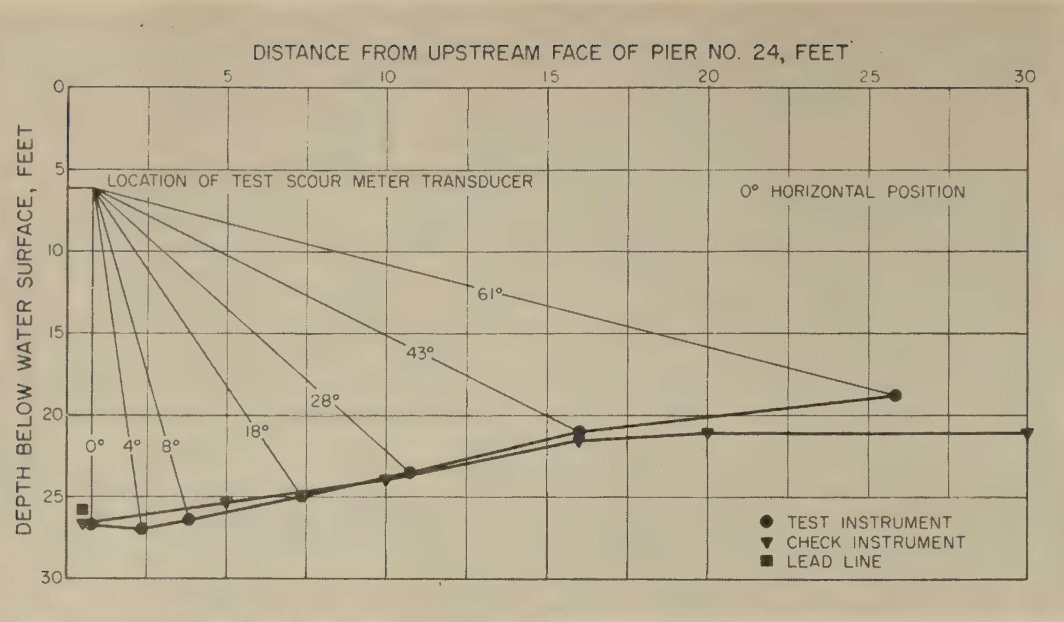


Figure 5.—Depths recorded during test run No. 5.

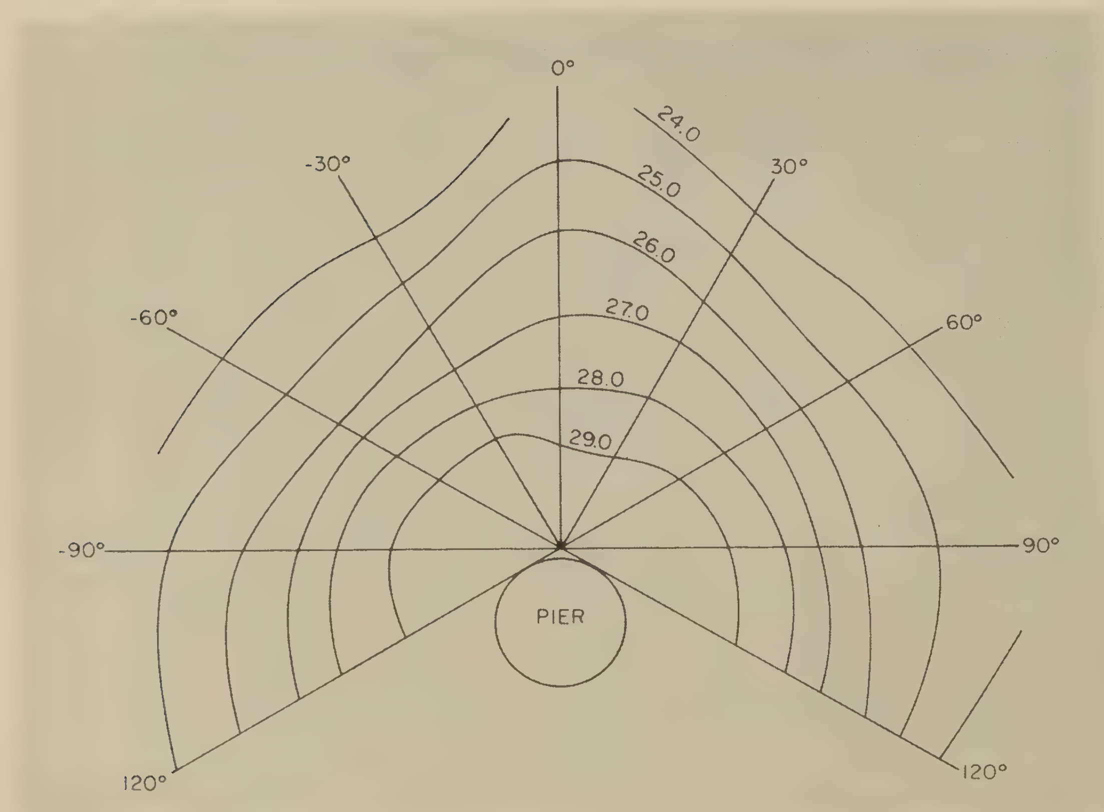


Figure 6.—Scour map depth contours (number of feet below water surface).

was constructed of ⅜-inch thick stainless steel with guide loops welded on the back for installing the unit on permanent pier rails. Figure 8 is a photograph of the unit mounted on the pier rails. Complete, the unit weighs 85 pounds in air and about 30 pounds in water.

The sequencing and position indicating circuits are all contained in the mechanical unit. Automatic sequencing is accomplished by 6 relays, 12 microswitches, 20 diodes, and an RC timing network. Position information is provided by 9 diodes, 10 resistors, and a 10-turn potentiometer. The drive mechanism consists of horizontal and vertical drive gear assemblies and two 24-v.d.c. drive motors. The horizontal drive operates in one direction only and covers the full 360° movement. Microswitches, mounted just outside the circumference of the horizontal gear are activated by a cam on the gear to provide horizontal position information as well as automatic sequencing signals. The vertical drive operates in both directions over a 61° gear segment. The vertical drive mechanism, vertical position indicating potentiometer, and vertical sequencing cams and microswitches are all mounted on the horizontal gear. The 6-inch diameter transducer is connected to the vertical drive gear by a shaft that protrudes from the bottom of the unit.

Vertical position is provided by a voltage at the arm of the potentiometer coupled to the vertical drive mechanism. Horizontal position is indicated only when the horizontal gear is stationary at one of the incremental horizontal positions. Each discrete horizontal position connects to a point on a voltage divider network to provide a different voltage. The separate horizontal and vertical voltages are transmitted to the control panel of the electronic unit through the interconnecting cable. The two position-indicating voltages are then added to provide a distinctive position indication. Recorded radial distance and position data are shown in figure 9.

Electronic unit

The electronic unit is housed in a watertight case and comprises a power module, transmitter module, receiver/computer module, display/test module, and a control panel for the mechanical unit. A complete block diagram of the instrument is shown in figure 9.

The power module contains two 24-volt batteries and recharging circuits. Starting with fully charged batteries, the electronic unit may be operated for 24 hours if the positioning mechanism is not operated. Operating the positioning mechanism of the mechanical unit once every 10 minutes reduces the operating time to 8 hours.

The transmitter module contains a voltage regulator printed circuit board and a transmitter panel control board. The voltage regulator board provides regulated voltage, plus and minus 15 volts, for the operational amplifiers in the computer circuit and connects to the power switch on the front panel. The transmitter circuit consists of a unijunction oscillator, a clock flip-flop, a gated 200 kHz oscillator, a voltage amplifier, a power amplifier, and an output transformer. Th

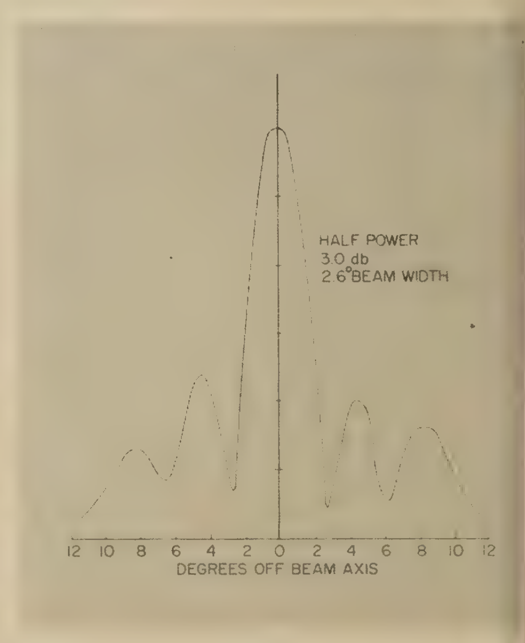


Figure 7.—Directivity pattern of 7-in transducer.

output voltage to the transducer is approximately 100 volts peak-to-peak.

The clock repetition rate is controlled by the position of the range switch on the front panel of the receiver computer module. The rate is changed from a maximum of 30 pulses

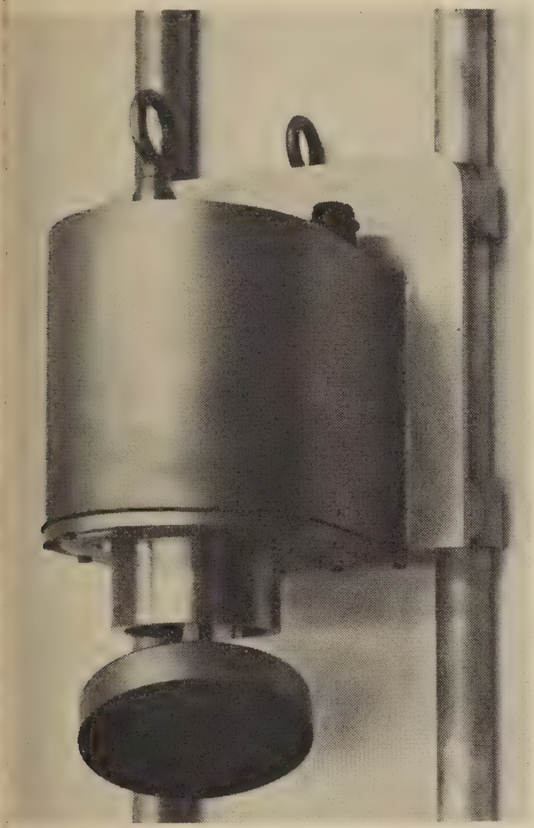


Figure 8.—Mechanical unit mounted on pier track.

per second for the 100-foot position, to 6 pulses per second for the 150-foot position. The design requires that the round-trip time for a signal pulse be less than one-half the clock period. The round-trip time for this instrument is approximately 62 milliseconds, and the one-half clock period is approximately 80 milliseconds.

The receiver/computer module contains the receiver printed circuit board, the computer printed circuit board, and the operating controls. The receiver circuit consists of an RF section, detector, and video amplifier. Included on the receiver panel control board is a gating circuit that makes it possible to eliminate all received signals originating at a distance less than the desired target distance. This circuit enables the operator to eliminate a large part of any undesirable output. The output of the receiver panel control board is a pulse which is equal in duration to the time required for the ultrasonic signal to travel from the transducer to the target and back again. The pulse is generated by a bestable multivibrator, which is turned *on* by the transmitted pulse and turned *off* by the first echo received through the receiver and gate circuits.

The computer consists of a ramp generator and a sample-hold circuit with appropriate switching and resetting circuits. The pulse from the receiver is clipped to a constant amplitude by a voltage reference diode and coupled to the ramp generator input. During the time that the pulse is present, the output voltage at the operational amplifier increases linearly. When the pulse ends, the voltage at the ramp generator output remains constant until the end of the first half of the clock square wave. The second half of the clock square wave resets the ramp generator and holds it in the reset condition until the start of the next clock cycle. Immediately after the input pulse ends, a sample pulse is generated. This sample pulse is approximately 2 milliseconds in length and connects the ramp generator output to the sample-hold input for the duration of the pulse. During the short time that the sample pulse is on the sample-hold, the output voltage is the same as the ramp generator voltage at the input. Between sampling pulses, the sample-hold circuit holds the last voltage value seen at its input during the sampling pulse time.

The output of the sample-hold operational amplifier is the output of the instrument. Thus, the output is basically a d.c. signal that changes only when the distance to the target changes. An important feature of the instrument is that if the return signal is momentarily lost (because of sediment, etc.), the output signal will drop toward zero rather than indicate full scale.

The display/test module contains a 2-inch oscilloscope; a d.c. to a.c. inverter to provide power for the oscilloscope; signal connections from the clock, transmitter, receiver, and computer boards; and a switch for the oscilloscope display. Although the module was intended to be used during normal operation, it was found that the high voltage inverter square wave caused too much interference when the sensitivity control was turned to a practical level. However, the test function of the module is useful for troubleshooting and checking the operation of the critical circuits. The transmitter pulse, clock square wave, time pulse, and ramp generator output signals

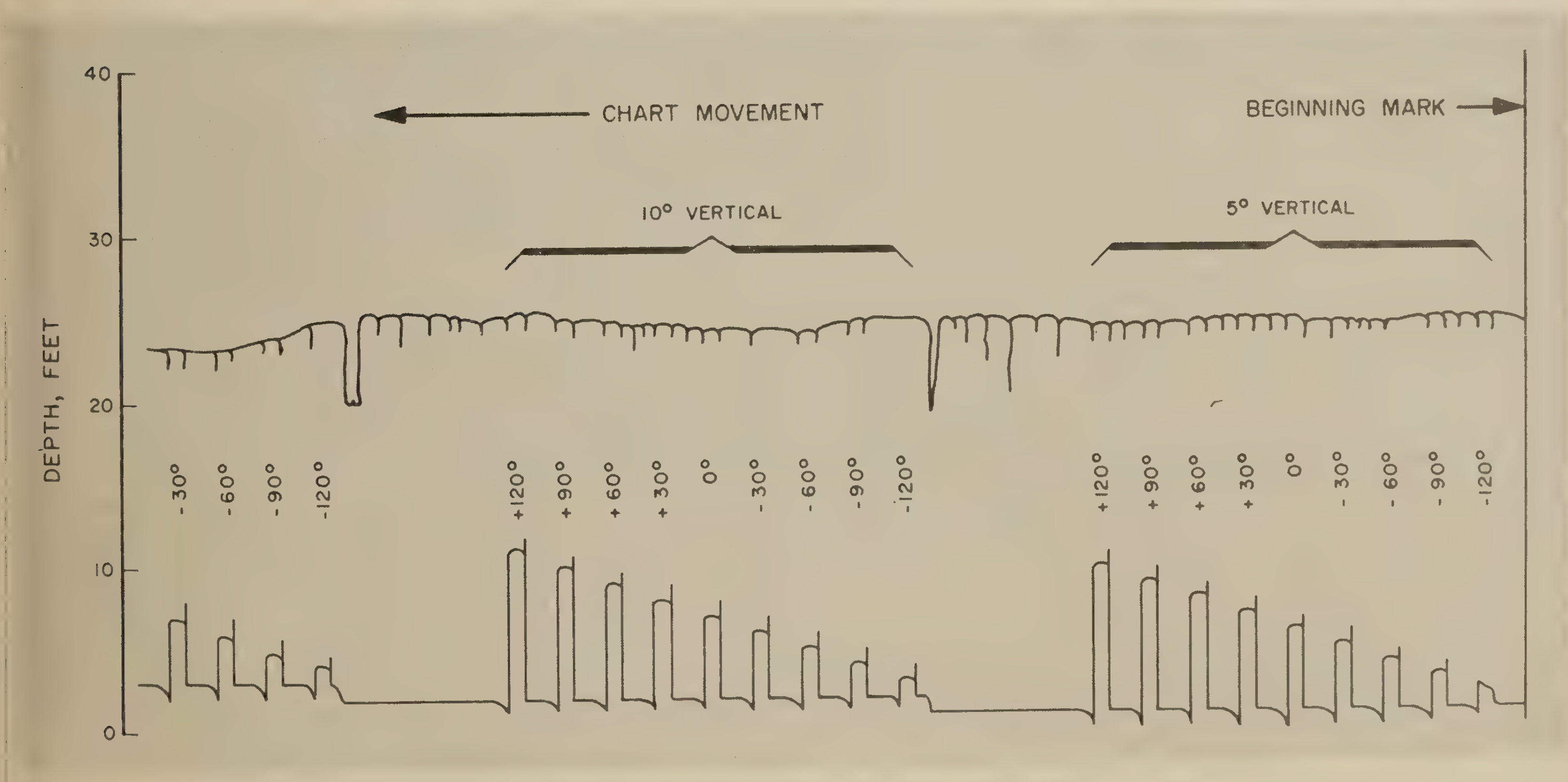


Figure 9.—Block diagram of complete ultrasonic scour meter.

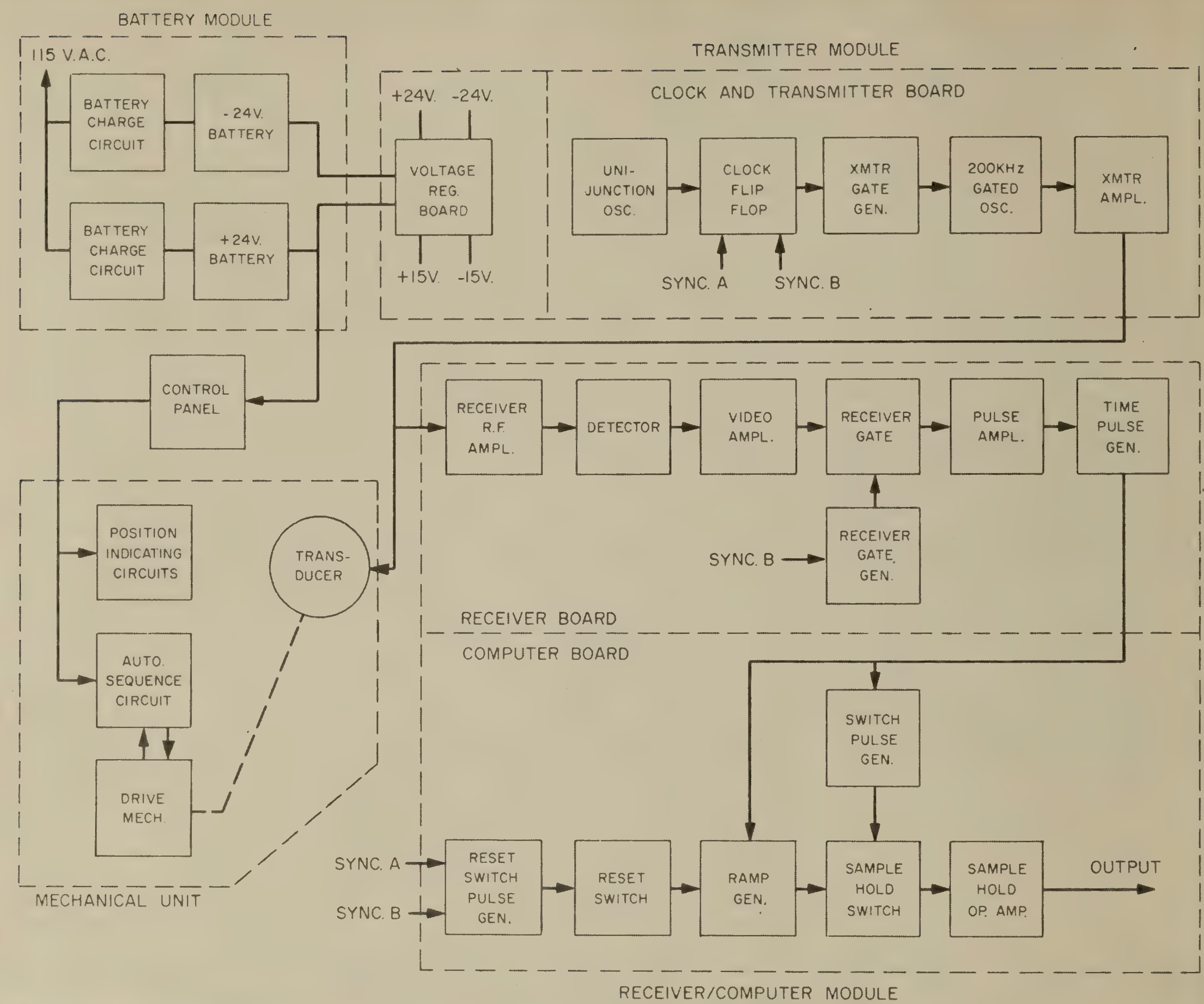


Figure 10.—Strip-chart recording of depth and position information.

are all switch selectable on the panel of the module.

The control panel connects to the mechanical unit to provide input voltage and output range and position signals. Output connectors provide a signal consisting of the two position signals added together as shown in figure 10. The push button for starting the sequence is located on the control panel. A push button and output jack, also on the control panel, provide remote marking capabilities.

Output signal and recording

The output signal, indicating depth, is a slowly varying d.c. voltage with a very low impedance. Although the basic instrument does not include a recording device, this output permits the use of a wide variety of recorders without adversely affecting the linearity of the instrument. The only restriction is that the recorder should require an input current of less than 1 milliampere. Currents in excess of this will not damage the equipment but will reduce its accuracy. Thus, any recorder used should have a minimum input resistance of 10 kilohms.

For most applications a two-channel recorder would be desirable—one channel to record depth as a voltage level and another channel to record position information. On all ranges, as selected by the RANGE switch on the instrument, full scale accuracy and linearity is better than 1 percent. For applications in which data are to be recorded for future processing by computers, a digital voltmeter that provides a digital output can be used to advantage. The output signals from the digital voltmeter may be recorded for later processing using a tape recorder or a paper tape punch machine.

Instrument Utilization

The instrument described in this article w designed to obtain detailed scour data f research purposes. It will be used as a part a large scale effort to collect data on many factors that influence the local sc process.

The concept and basic instrument des could, however, be adapted for use in insp tion or maintenance operations. In such appl tions, some reduction in accuracy and de could be tolerated, and a less sophistica design used. The mechanical unit descri here must be complex to provide the la number of data points necessary to obtai detailed scour-hole map. However, by reduc the number of data points to several in

(*Continued on p. 108*)

Drivers' Decisions in Overtaking and Passing

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The research reported in this article was concerned with how well drivers can judge the distance they require to overtake and pass another vehicle on the roadway. An experiment in which 20 drivers made estimates of overtaking and passing distances in their own car and in a Government car, at speeds of 18, 30, and 50 miles per hour, was carried out on an airplane runway. It was found that drivers are unable to estimate overtaking distances accurately, but rather tend to make dangerous underestimates, particularly when the car in front is moving rapidly. Applications of the research results are suggested for the design of highways and traffic control devices.

Reported by DONALD A. GORDON and TRUMAN M. MAST,[1]
Research Psychologists,
Traffic Systems Division

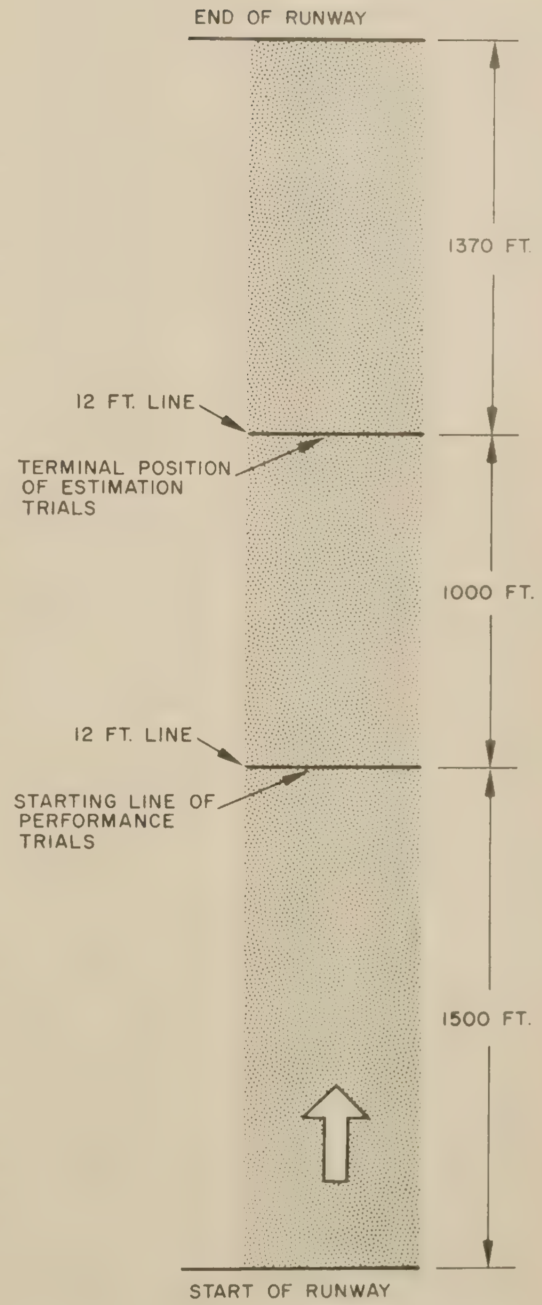

Figure 1.—The experimental track.

Introduction

ON a simple 2-lane rural highway, the driver of an automobile must often over-ake and pass a car ahead to maintain a easonable speed of travel. Even though the lriver is the essential element upon whose udgment the safety of passing performance epends, little is known about his decision rocesses.

To overtake and pass another vehicle, the river must carry out the passing maneuver 1 the time and space available. Accordingly, he maneuver can be analyzed in terms of our basic quantities:

- α is gap time or distance separating the vertaken vehicle and the vehicle in the op-osing lane.
- α' is the driver's estimate of gap available.
- β is the time or distance required by the river-car combination to perform the naneuver.
- β' is the driver's estimate of time or istance required to perform the maneuver.

The two prime quantities involve psychological haracteristics which are distinguished from hysical variables.

The driver's judgment in overtaking and assing involves a comparison of α' and β'. f the outcome is favorable, that is, the gap vailable, α, is judged to be longer than the istance required, β, with adequate safety nargin, the driver will accept the gap. If ot, he will reject it and wait for a longer gap. Vith practice, the driver is able to make the ap decision rapidly.

The $\alpha\beta$ concept also applies to the driver's ap judgments in merging, in passing an intersection, and in other driving decisions as well. When the driver makes a U-turn, the width of the road, α, is related to the turning radius of the car, β. In parking, the driver compares the parking space, α, with the width of the car plus the room required to open the doors, β.

Both α and β are measured in physical units of time and distance. Subjective quantities, α' and β', are also measured in physical units, and they may be obtained through psychological experimentation. Silver and Bloom measured gap size, α', by asking drivers to indicate the distance when an opposing car was just 12 seconds away (*1*).[2] β' can be measured by having the driver indicate the minimum distance at which he can just perform the maneuver. Whether time or distance is used to measure the gap depends on the application. Time is the usual measure of intersection gaps (*2, 3*), but both have been used in overtaking studies (*1, 4*).

Previous Research

The literature on overtaking and passing has been reviewed by Farber and Silver (*5*). Early studies were concerned mainly with establishing performance norms for traffic control. Matson and Forbes (*6*) and Prisk (*7*) give figures on overtaking distance when the pass was started at the same speed as the car ahead (accelerative pass) and when the following car had an initial speed advantage (flying pass). A distinction is also made between voluntary (unhurried) returns to lane and those in which the overtaking car was forced to return by the oncoming car.

[1] Dr. Mast is now Associate Professor of Psychology, State niversity of Montana, Bozeman, Mont.

[2] The italic numbers in parentheses identify the references listed on page 101.

The first psychological study of overtaking and passing was made by A. Crawford (*4*). Crawford thought of overtaking and passing judgments as psychophysical, and he carried out controlled experiments in which accepted gap distance, overtaking, and safety distances were measured. He also carried out a validating highway study in which overtaking vehicles were observed from the window of a light van. Crawford's findings on overtaking performance and safety distance will be discussed under *Results*.

Silver and Bloom showed that the driver could not make accurate α judgments. They instructed the driver to indicate when an oncoming car was just 12 seconds away, simulating a 12-second passing time, β. Without specific knowledge of the speed of the oncoming car, drivers gave their passing judgments at the same distance; but when they were told the speed of the oncoming car, they gave improved estimates of the 12-second-gap passing distance. Rockwell and Snider recently showed that the driver does make a limited use of oncoming car speed in making α estimates (*9*). The study reported here may be considered the converse of the Silver and Bloom study—α characteristics were simplified and standardized to test drivers' abilities to estimate β.

The need to consider the α and β characteristics of the overtaking decision was illustrated in a study conducted by Jones and Heimstra (*8*) in which drivers were told to indicate the last moment they could safely pass a lead car and avoid hitting an oncoming car. The drivers indicated the time, but did not actually pass. At the lead car speed of 60 m.p.h., 83 out of 190 judgments made during the study were shown to be unsafe; that is, the actual passing maneuver would have required more time than drivers gave it. The time required for the maneuver was determined in preliminary passing trials in which there was no opposing vehicle. Although Jones and Heimstra showed overtaking to be unsafe, their study does not tell whether drivers' errors were caused by the inability to assess the gap, α, by failing to estimate vehicular passing capability, β, or by both difficulties.

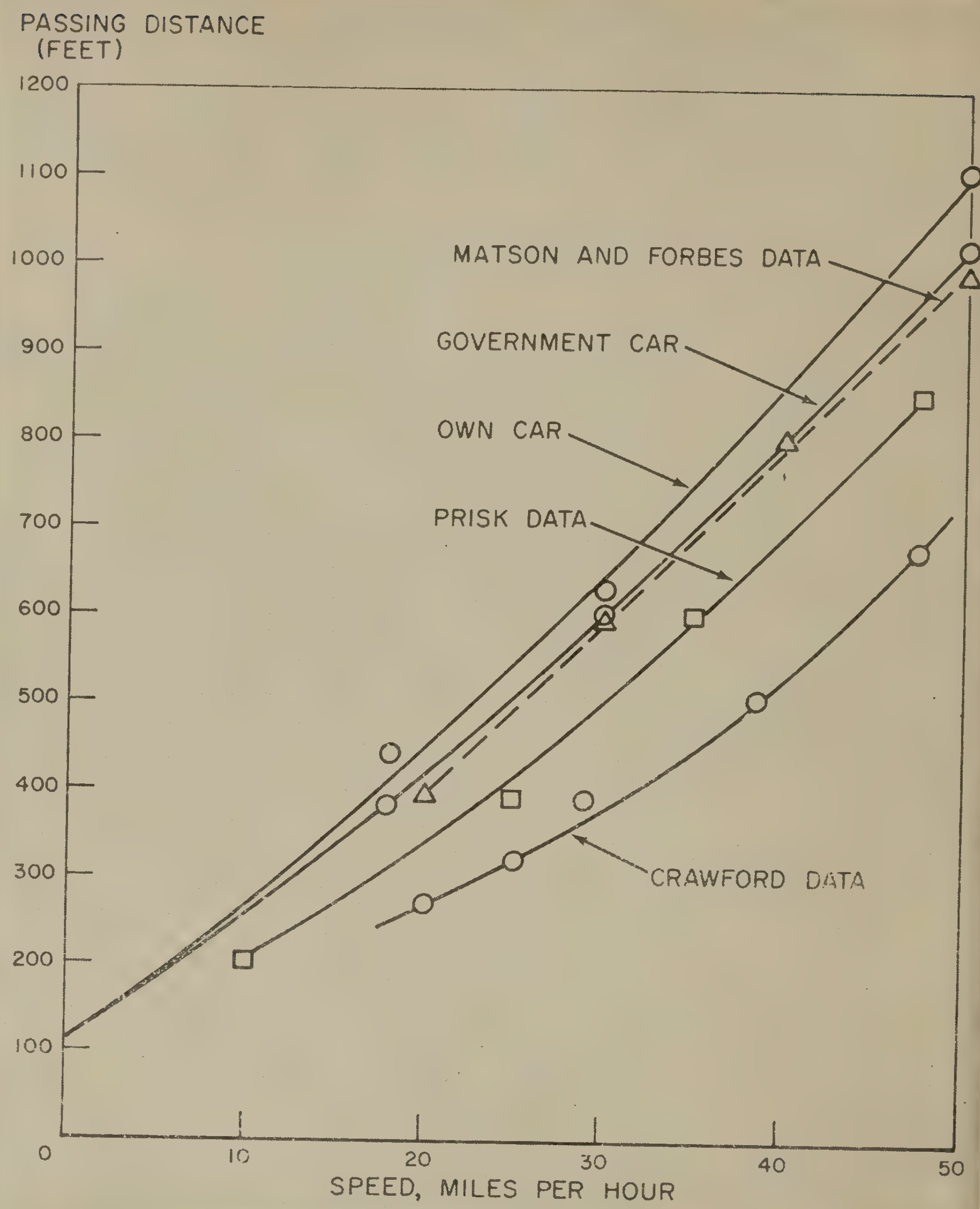

Figure 2.—Performance studies, overtaking and passing distances.

Research Reported Here

The research reported in this article was concerned with how well drivers can judge the distance they require to overtake and pass another vehicle on the roadway. Their estimations were simplified by terminating the maneuver at a fixed point along the road rather than by the passing of an oncoming car. In this way, errors in assessing the situation (α errors) were minimized. The drivers made the estimations in their own cars, and in another phase of the research, in a Government vehicle. These conditions indicate not only individual differences in performance, but also the effects of an unfamiliar vehicle.

Experimental track

The studies were carried out on the runway of the Beltsville Airport. (See fig. 1.) A 12-foot length of 2-inch reflectorized tape was placed across the driver's path, 1,500 feet from the start of the runway; another was placed 1,000 feet farther down the runway. The strips indicated to the driver the terminal position of the estimation trials and the starting position for performance trials. Each strip was made more conspicuous by a 12″ × 14″ white box positioned at the left margin. A numbered scale was laid out on the right edge of the runway.

Vehicles

In the first phase of the study, drivers operated a 1965 Government six-cylinder, 145-horsepower Plymouth sedan with which they were unfamiliar; in the second phase they used their own cars. No attempt was made to influence selection of the vehicles. All cars completed the tests except a 1959 Volkswagen, which could not overtake and pass another vehicle at 50 m.p.h. in the runway length.

The marking pistol

Positions on the runway where overtaki and passing occurred were indicated by marking pistol (American Automobile Assoc tion detonator) attached to the rear bump of each car. When the driver pressed a butto a solenoid release mechanism fired a shell co taining yellow chalk at the runway. When t subject's vehicle did not have the 12-volt ba tery needed to activate the solenoid, the e perimenter dropped a cloth marker to indica runway position.

Drivers

The 20 drivers who served as experimen subjects were employees from neighbori university and U.S. Government offic Drivers in the first phase included four ma and seven females with ages from 20 to years, and driving experience from 3 to years; the median age was 23 years and t median driving experience was 7 years. Th n the second phase included eight males and wo females with ages from 18½ to 46 years and riving experience from 2½ to 26 years; the nedian age was 20½ years and the median driving experience was 4¼ years. Drivers erved 4 hours each and were paid $2 an hour for their work.

Method and Procedure

The overtaking and passing observations vere part of a series of tests that also included braking and U-turns. The overtaking and passing procedure is described here.

Preliminary practice

Drivers drove to the end of the runway and back, twice, to familiarize themselves with he Government vehicle. Familiarization was liminated in the second phase when drivers ised their own cars.

Overtaking and passing estimations

Drivers followed the test car at a distance f 55 feet. They were instructed as follows: You will follow the car ahead and think of passing it. When you come to the closest point o the line where you can still pass, using naximum acceleration of the car, indicate the pot by pushing the button." The distance between the lead car and subject car was naintained by the experimenter's instructions o slow down or speed up. The experimenter lined a taped spot on the windshield with the ood and rear bumper of the lead car to naintain the 55-foot distance. The speeds of 8, 30, and 50 m.p.h. were controlled by the river of the lead vehicle. An experimenter tationed on the runway recorded the data. After each observation, the marking pistol was eloaded, and the lead and experimental cars riven to the starting point for the beginning f the next run.

Overtaking and passing performance

Performance trials were made after completion of the estimations. The driver followed he lead car at the scheduled pace. Instructions vere as follows: "Follow the car ahead at the istance I tell you. When you get to the line, vertake and pass the car ahead, as fast as ou can, and come back into the lane. Be sure ou swing back into the lane." When the car vas fully back in lane the experimenter in the test car pushed the pistol button. The experimenter on the runway then recorded the position of the chalk mark.

Three series of tests were run for both the estimation trials and the performance trials, the first series in each being a practice series. In each series, observations were made at speeds of 18 m.p.h., 30 m.p.h., and 50 m.p.h. Estimation trials followed each other without interruption, as did the later performance trials. The entire work was completed in a half-day, after which the driver was paid and dismissed.

Results

Performance β

Performance results are given in table 1. Standard deviations are maximum likelihood estimates. The variable error in the table is the mean deviation from the average of the two performances by each driver at each speed. Results are presented in graphical form in figure 2. Each point in the figure for Government car and own car represents the average of 20 observations. The zero point of 106 feet is the minimum distance required to pass a vehicle parked 55 feet in front of the starting line. The Matson and Forbes, Prisk, and Crawford data were presented for comparison.

The performance curves indicate that as speed increases, passing distance also increases but at an increasing rate. The least squares fit to the own car data is:

$$D=112.2+15.2\,V+.093\,V^2$$

Where

D = overtaking distance in feet
V = velocity in miles per hour

Performance of drivers using the Government car does not differ significantly from that of drivers using their own vehicles. The Matson and Forbes data points fall close to the Government car curve; the Prisk data have the same general form, but distances are about 100 feet less. Matson and Forbes and Prisk defined passing distance as car travel in the left lane, which is shorter than the passing distance defined here—from initial driver reaction to return to lane. Crawford's curves show still shorter distances, which perhaps is explained by his use of trained drivers and by other procedural differences. A complete analysis of these performance curves would consider vehicular accelerations at various speeds, the driver's willingness to use accelerative capacity of the car, and the driver's varying requirements for safety distance.

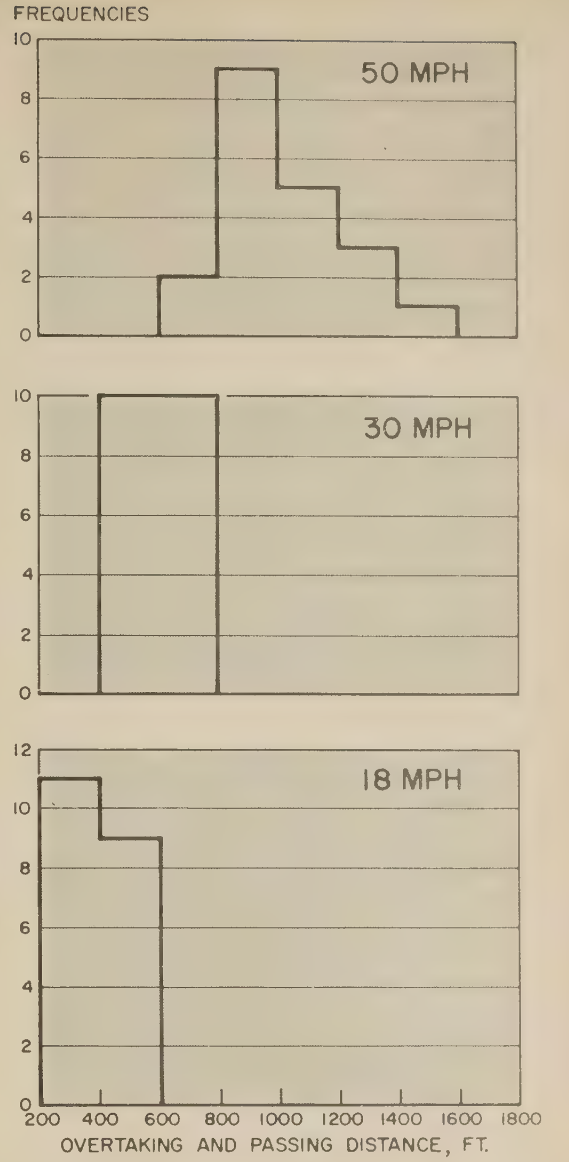

Figure 3.—Performance, overtaking and passing distances—Government car.

Drivers differ in their ability to pass, as indicated by the distributions plotted in figures 3 and 4. (See also standard deviations in table 1.) These differences were evident even when drivers used the same Government car. At 18 miles per hour, driver AR overtook in 284 feet, but driver GR required 455 feet. At 30 and 50 miles per hour, variability was larger than at 18 miles per hour. Some causes of these individual differences have been pointed out above. Drivers differ in reaction time, in willingness to use maximum acceleration of the vehicle, in safety distance requirements, and in the paths they take in returning to lane at the end of the maneuver.

The vehicle driven had more effect on passing distance than the driver who performed the maneuver. Variance in the own-car condition was significantly larger than in the Government-car condition in which the same automobile was used (f-test, .05 level, all speeds). Residual variance of own car

Table 1.—Performance, overtaking and passing distances

Performance	18 m.p.h. Government car	18 m.p.h. Own car	30 m.p.h. Government car	30 m.p.h. Own car	50 m.p.h. Government car	50 m.p.h. Own car
Overtaking and passing performance:						
Mean . . . feet	385.9	440.3	606.1	628.5	1,023.5	1,110.8
Standard deviation . . . feet	53.7	76.7	77.9	121.3	192.8	289.2
Standard deviation/mean . . . feet	0.139	0.174	0.129	.193	0.188	0.260
Variable error:						
Mean . . . feet	12.3	22.0	27.0	32.7	47.3	41.7
Standard deviation . . . feet	9.8	20.2	15.4	19.9	50.8	34.6
Variable error as percentage of performance . . . percent	3.19	5.00	4.45	5.19	4.62	3.76

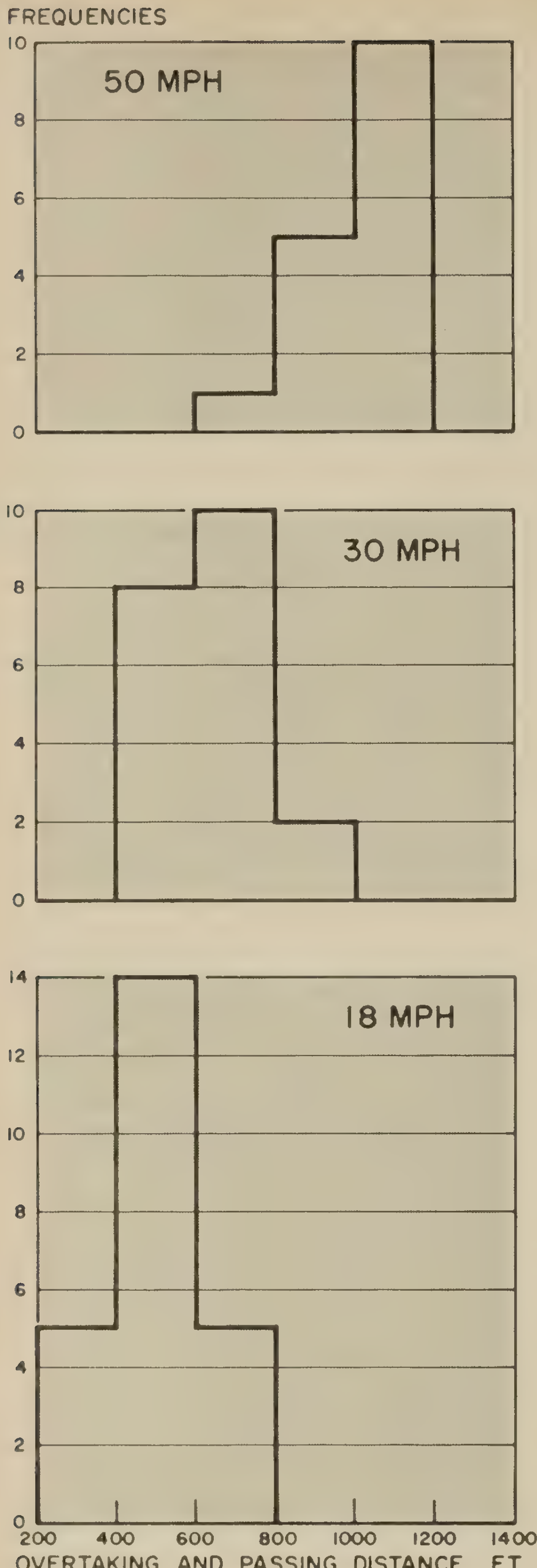

Figure 4.—Performance, overtaking and passing distances—drivers' cars.

minus Government car is larger than Government car variance at all speeds. These variance calculations involve squared standard deviations of overtaking and passing performance in table 1. The importance of vehicular effects can also be seen in the individual records. The difference in performance between the highest powered car, driven by a 46-year-old woman, and the minimum powered car, driven by a 19-year-old boy, was larger than any set of driver differences on the same (Government) vehicle. These vehicular and individual differences relate to the groups

Table 2.—Errors, overtaking and passing estimation

Errors	18 m.p.h.			30 m.p.h.			50 m.p.h.		
	Government car	Own car	Other	Government car	Own car	Other	Government car	Own car	Other
Constant error: [1]									
Mean ... feet	197.2	136.9	------	312.2	129.6	------	317.9	237.5	------
Standard deviation ... feet	179.5	111.9	------	205.5	120.5	------	208.7	176.1	------
Variable error:									
Mean ... feet	42.5	40.8	------	52.7	63.6	------	29.9	50.9	------
Standard deviation ... feet	30.5	33.4	------	40.1	41.8	------	14.4	44.7	------
Constant error/variable error	4.63	3.36	------	5.92	2.04	------	10.63	4.67	------
Constant error/overtaking performance	0.511	0.309	------	0.515	0.206	------	0.311	0.214	------
Underestimation errors:									
Number	4	2	------	7	7	------	12	14	------
Percent	20	10	------	35	35	------	60	78	------
Crawford Interpolated Data percent	------	------	7	------	------	39	------	------	76

[1] Sign of the error, plus or minus, has been disregarded.

studied and do not necessarily apply to the universe of cars and drivers on the road.

Drivers' errors

The errors made by drivers are analyzed in table 2. Constant error, listed for each speed, is the difference between each estimate and the mean of the two performances by the driver at that speed, averaged over all the drivers. Variable error is the deviation of each driver's constant error from his mean constant error, averaged over all the drivers. The underestimation errors occur when the constant error is negative. Frequency distributions of errors made in the Government and own car are plotted in figures 5 and 6. Each chart includes the 20 errors made at a particular speed.

According to the constant-error data in table 2 and the charts in figures 5 and 6, drivers are not able to estimate passing distance accurately. Constant error varies from about a fifth to a half of actual overtaking distance (table 2), and exceeds variable error at all speeds at the 0.01 significance level. It seems that drivers estimate their overtaking performance consistently but erroneously.

Drivers predict their overtaking performance better in their own cars than in an unfamiliar (Government) car, according to the constant error data, table 2. Errors in own car are significantly smaller than in the unfamiliar car (.05 sig. level, Fisher combination of experiments statistic, (*10*)). This finding implies that estimating vehicular performance, β', may be a learned aspect of driving skill. The finding also suggests that the driver's ability to estimate requirements for braking, U-turns, parking, and car following, may be a useful measure of his skill and effectiveness. Little is known about the nature of driving skills.

Negative estimating errors involving underestimation of maneuver distance are dangerous. Negative errors occur at all speeds, but are particularly frequent at high spee (See table 2 and figs. 5 and 6.) At 50 mil per hour, 60 percent of Government-c estimates and 78 percent own-car estimat would have been dangerous in the operatior situation. The finding that underestimati is most frequent at high speeds, wh accidents are most serious, is in close agr ment with Crawford's results. (See table

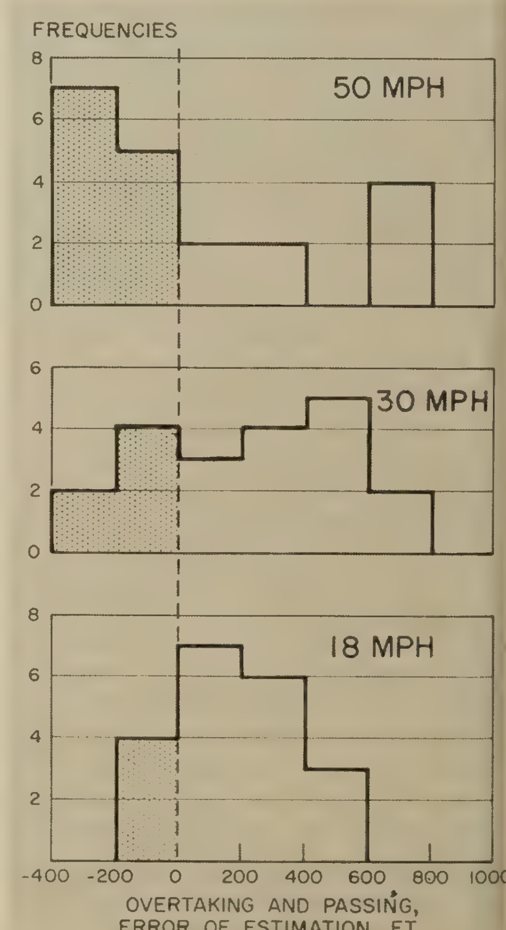

Figure 5.—Estimation errors in overtaki and passing—Government cars.

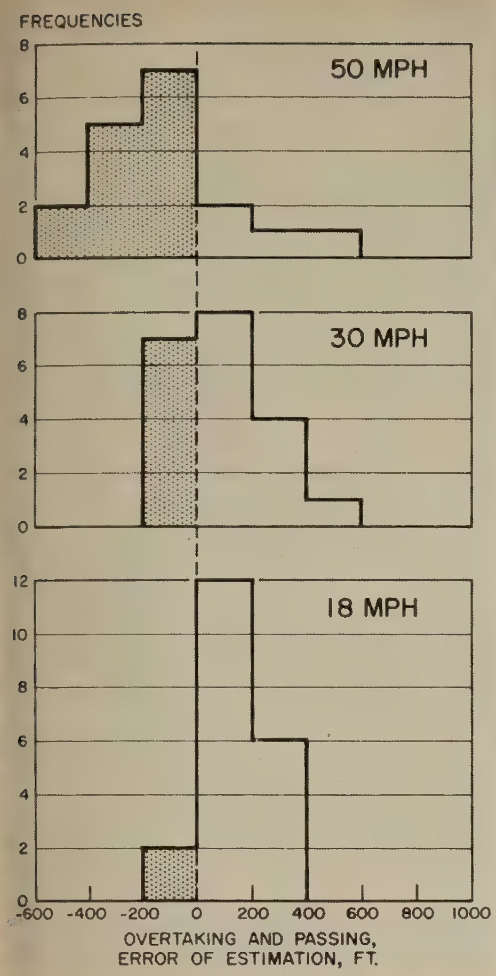

Figure 6.—Estimation errors in overtaking and passing—drivers' cars.

Driver's errors and underestimations in overtaking and passing may perhaps be explained by the difficulty of the judgment. Overtaking distance varies in proportion to speed, and there are as many overtaking distances as vehicular speeds. The driver cannot perform by simply learning a fixed distance, as might be the case in U-turns, or parking. The underlying speeds, accelerations, and distances are themselves subject to estimation error. For example, at 50 miles per hour, overtaking requires about 1,000 feet. An opposing vehicle, coming towards the driver at the same speed, would be twice as far away when the decision was made. The driver cannot be expected to make precise spatial judgments at such large distances.

The precise cause of underestimations at high-speeds is not known. One explanation might be that the driver is not fully aware of how performance requirements, β, increase with speed, and he may continue to act as he did at slower speeds. Whatever its cause, high-speed underestimation remains a pertinent fact that highway engineers must contend with in dealing with the overtaking and passing maneuver.

Nonetheless, overtaking and passing accidents are not very frequent, and this fact perhaps requires explanation. Several safety factors are inherent in the situation to aid the driver. The driver may avoid danger by not passing at high speeds, and he may insist on an adequate safety distance. If a wrong decision is made, he may drop back into his lane, and the overtaken and oncoming cars may slow down and move to the shoulder. Traffic controls such as passing zones and signs also aid the driver.

Summary

In the study reported, driver's estimations of overtaking and passing distance were compared with actual overtaking and passing distance. An experiment, in which drivers made estimates in their own (familiar) car and in a Government (unfamiliar) car at speeds of 18, 30, and 50 miles per hour, was carried out on an airplane runway. On the basis of the results, the following conclusions are reached:

- Drivers are unable to estimate overtaking and passing distances accurately. Mean error ranges from 20 to 52 percent of performance distance. Significantly larger errors are made in an unfamiliar car than in the driver's own vehicle.
- Negative errors of underestimation, where the maneuver required more space than judged, increase with speed. At 50 miles per hour, 60 percent of the estimates made by drivers in the Government car and 78 percent of those made in drivers' own cars are underestimations.
- Overtaking and passing requires proportionally more distance as lead-car speed increases. The curve relating overtaking and passing distance to lead-car speed is well fitted by a second degree equation. These results are in agreement with those of previous investigators.
- Vehicular differences affected passing distance more than did driver variance in the groups studied.
- It is suggested that the driver's decisions in overtaking and passing can be studied in terms of four basic quantities: α, the gap time or distance available for overtaking and passing; α', the driver's estimate of gap available; β, the time and distance required by the driver to perform the maneuver, and β', the driver's estimate of time or distance required.

Applications

The finding that the driver is unable to estimate accurately his overtaking and passing requirements and that underestimations are frequent at high speeds implies that the overtaking and passing maneuver requires guidance. Possible aids that can be given to the driver are as follows:

- Passing areas, and *no passing* signs—traditional aids to overtaking and passing.
- Speed limits and other speed regulation, particularly in passing zones.
- Driver education emphasizing no passing at high speeds and cooperation with overtaking drivers.
- Road design modifications such as wibe shoulders and addition of lanes.
- Traffic planning to minimize use of 2-lane rural roads.
- Electronic devices to inform the driver when it is safe to pass. Such devices are currently under development in the Traffic Systems Division, Office of Research and Development, Bureau of Public Roads (*11*).

The $\alpha\beta$ concept provides a theoretical framework that may be useful in studying driver decisions in intersection and merging gap acceptance, and in such maneuvers as U-turns, braking, parking, and car following. The β' β comparison may be useful as a measure of driving effectiveness in the study of learning and driving performance.

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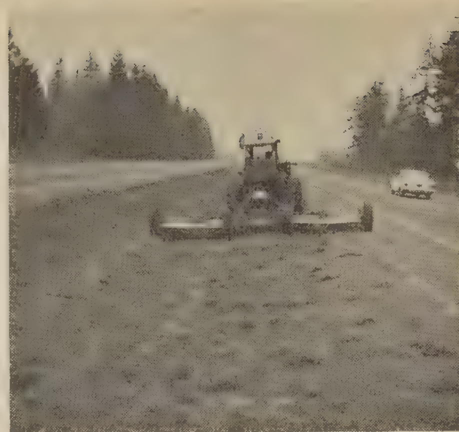
Effective and efficient highway maintenance is the objective of highway management research—one of the important facets of the Bureau of Public Roads' national program for research and development in highway transportation.



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Highway Maintenance Management Research—An Overview

Reported by [1] WILLIAM N. RECORDS,
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Introduction

DURING the past 50 years, highway maintenance management in the United States has experienced many changes. Most of them transpired through a process of gradual evolution and were based on intuition and pragmatic considerations, rather than on factual knowledge and scientific management principles. This process proved to be reasonably satisfactory between 1920 and 1949. Most maintenance organizations were satisfied with the status of their management and had no real reason to adopt a more sophisticated procedure. Therefore, it is not surprising to discover that maintenance management research was of little consequence during these years. Studies were few in number, limited in scope, and uncoordinated. Most of them were carried out informally, making it difficult to even document their existence. It would definitely be misleading to say that these efforts had a significant impact or that they constituted any kind of research program.

Beginning of Organized Highway Maintenance Management Research

In June 1950, an event signaled the beginning of an organized, formal maintenance management research program in the United States. The event was the initiation of the Connecticut Maintenance Study—a joint venture of the Bureau of Public Roads and the Connecticut State Highway Department. The objectives of the study were to develop basic facts concerning the performance of labor and equipment on field operations and to appraise management problems. Study results indicated that there were deficiencies and problems associated with field operations and there was a need for continued research. Prophetically, the report stated: "The further development and extension of the groundwork encompassed by this study can lead to the establishment of units of work and standards of maintenance accomplishments, thus making possible the estimation of labor and equipment requirements to perform the maintenance obligation in a particular area under certain given conditions."

The maintenance research program continued during the 8 years that followed the Connecticut Study, primarily because the Bureau of Public Roads retained an interest in it. About 20 small-scale studies were conducted on the field operations of State maintenance organizations. Results were not extensive enough to fully delineate management problems, but they did serve to verify two hypotheses: (1) Results of the Connecticut Study provided a good view of the situation in other States, and (2) many management problems were similar, varying only in degree from organization to organization.

[1] Presented at the Maintenance Management Workshop, Highway Research Board, Ohio State University, Columbus Ohio.

In 1959, the program received an impetus when the Bureau of Public Roads joined the Iowa State Highway Commission to conduct a study that was considerably larger in scope than the one in Connecticut. The Iowa maintenance study was primarily designed to produce facts that could be used by management to control and improve the economy of maintenance operations. It included collection of basic data concerning the performance of labor and equipment on field operations, variations in total workloads and work units, utilization of supervisory personnel, and other aspects of maintenance management. Considerable emphasis was placed on data analysis to pinpoint problems and develop possible solutions. In a few operations, proposed solutions were tested for practicality.

The Iowa Study received considerable publicity during 1960 and 1961. Its findings were accepted by many maintenance managers as indicative of the situation in their own organizations. At approximately the same time, other forces began operating to change managers' attitudes toward management and management research.

Maintenance Problems Promote Research

Between 1960 and 1967, maintenance organizations in this country were subjected to a number of external pressures that caused severe internal stresses. Among the most intense pressures were those due to:

- Addition of new facilities on the Interstate and other systems.
- Public demands for higher levels of maintenance.
- Rapid changes in the technology of highway design, materials, and equipment.
- A labor market which could not supply an adequate number of qualified personnel.
- Constrictions on maintenance budgets to make the maximum amount of funds available for badly needed construction projects.
- Campaigns to tighten up the fiscal and administrative control of highway organizations.

The type of management that had been tolerated for many years simply was not able to cope with the stresses induced by these pressures. Problems multiplied and managers became painfully aware of what was happening. Many concluded that their organization's management was deficient and needed improvement. As attitudes toward management changed, there was increased interest in all kinds of management research. The organized, formal program expanded considerably between 1960 and 1967, with studies covering a wide variety of subjects.

Three studies which related to costs for maintaining specific types of roads were conducted in Louisiana. These studies were aimed at developing a procedure for estimating costs through the use of mathematical regression models based on historical fiscal records. An Idaho study had a similar objective and used a like procedure. The Oklahoma Department of Highways also carried out a study of maintenance costs for specific types of roads. They used a technique that considered both historical fiscal data and deterioration ratings for selected test sections.

A major study of maintenance costs, conducted for the National Cooperative Highway Research Program, was primarily directed toward developing a method of predicting Interstate highway maintenance requirements. The technique used was similar to those for the aforementioned State studies. Cost data from selected test sections across the nation were analyzed to develop mathematical models for seven groups of maintenance activities that could be used to predict *requirement units*. A secondary objective of the study was to develop a new maintenance expenditure index.

Three research studies were conducted on roadside activites. In Louisiana, the State University identified optimum equipment and work methods for mowing highway roadsides. In Indiana, the Highway Commission emphasized development of comparative costs for different types of roadsides and mowing methods. In Ohio, the State University identified the most effective means of caring for Interstate roadsides.

In Illinois, New Jersey, New York, and Wisconsin, a series of studies was conducted for State Highway Departments and Toll Road Authorities. The studies were designed to establish long range requirements for major maintenance on high type facilities. In conjunction with detailed field inspection of facilities, they utilized new techniques for predicting pavement deterioration.

The objective of a major study in Los Angeles was to develop a program that would improve the planning, directing, and controlling of labor and equipment assigned to various field activities. An important feature of this study was the use of the industrial engineering technique, Methods-Time Measurement, to analyze each activity and to develop standards for work methods and performance. A similar project took place in San Diego County.

A Minnesota study utilized industrial engineering techniques to develop improved work methods, establish performance standards, and improve the maintenance reporting system. A smaller, but similar study was conducted in New Jersey.

The largest single study was carried out by the Virginia Department of Highways. This effort lasted 3 years and was designed to cover nearly every major aspect of maintenance management. It involved the collection of data concerning performance of labor and equipment, development and testing of improved work methods; establishment of quality, quantity, and performance standards; development and testing of a new reporting system; development and testing of a budgeting system; development and testing of training material; and work in several other areas.

The cited studies were started, and essentially completed, during the 8-year period ending in June 1968. They indicate the extent and scope of activities during this period but do not account for the entire research program. Nine other studies, started between 1960 and 1967, were not included because they are still active and will be described later. A few other studies have been omitted here because of their limited scope.

One other aspect of the completed studies deserves mention. More than half were funded through the Federal-aid Highway Planning Research Program (HP&R). This program provides for joint State-Federal financing of research in areas that have a significant influence on highway transportation in the United States. For many years, maintenance management has been recognized as one of these research areas. In 1964, this position was emphasized when a project for maintenance operations and management was included in the 27 top priority projects of the Bureau of Public Roads National Program for Research and Development in Highway Transportation. Partly as a result of this emphasis, annual Federal-aid expenditures in the maintenance area have more than doubled in the last 5 years.

Current Maintenance Research Program

Currently, the maintenance management research program includes 13 fully active studies. Eleven of these are being financed through the Federal-aid HPR program. Their estimated total cost is more than $2 million, and annual expenditures are about $700,000. The other two studies are financed entirely with State funds. Their estimated total cost is more than $500,000, and annual expenditures are about $150,000. The nature and scope of these studies vary considerably; six can be classified as comprehensive because they cover several aspects of maintenance management, five deal with the equipment and methods for specific activities, and two are concerned with costs. Summaries of pertinent facts about each study are presented in table 1. Other current informal research efforts, such as those underway in Illinois, New Jersey, and New York, may ultimately become a part of the formal program.

Some of the significant results that have emanated from these efforts are as follows:

- The research has clearly demonstrated that in most highway maintenance organizations management is beset by a number of problems including inadequate factual data concerning field activities; nonuniform standards or a lack of standards; ineffective procedures for planning and scheduling work; widely varying quality, productivity, and unit costs for field activities; ineffectual means of comparing actual and desired quality, service, level, and unit cost for maintenance activities; lack of a reliable means to forecast long range maintenance requirements; lack of a means to evaluate alternative policies; and shortage of trained personnel.
- New systems of maintenance field reporting have been developed and proven capable of supplying the kind of information

Table 1.—Summary of current maintenance management research studies

Study title	Agency	Estimated Cost	Period	Objectives
		Dollars		
Maintenance practices	Ark. State Highway Department (HP&R) [1]	169,000	July 1967–July 1972	Evaluate the maintenance accounting system and revise as needed Define maintenance standards Evaluate existing maintenance practices and develop improved practices Identify training needs; develop and test training materials
Maintenance management	La. Department of Highways (HP&R) [1]	575,000	Sept. 1965–July 1969	Define responsibilities and functions for various management levels Evaluate training needs; develop and test training materials Develop and pilot test a maintenance work reporting system Determine the most effective methods and staffing for maintenance activities Establish maintenance standards for quality, quantity, and productivity Develop and test an overall maintenance management system
Comprehensive maintenance	N.C. State Highway Commission (HP&R) [1]	220,000	July 1966–Dec. 1972	Determine the adequacy of the maintenance organization to carry out its assigned responsibilities and functions Evaluate the present maintenance management system with emphasis on reporting Determine the relationship between maintenance costs and factors such as traffic Determine major maintenance operations whose efficiency and economy can be improved; develop improved methods, etc. Evaluate maintenance facilities and materials
Highway maintenance management	S. Dak. Department of Highways	300,000	July 1968–Oct. 1970	Develop and test quality, quantity, and productivity standards for maintenance activities Develop and test a maintenance work reporting system Develop and test a maintenance work scheduling process Develop and test a maintenance budgeting process Develop a methods and training unit Conduct a performance laboratory to test developments
Maintenance management	Utah State Road Commission (HP&R) [1]	285,000	Apr. 1967–Aug. 1969	Establish quality, quantity, and productivity standards for maintenance activities Develop and test a maintenance work reporting system Design, develop, and test an overall maintenance management system Evaluate the field organization and resource utilization Prepare a plan for improving maintenance performance
Maintenance improvement program	Wash. State Highway Commission	250,000	July 1967–Dec. 1968	Develop standards for measuring performance of maintenance operations Establish procedures for maintenance planning and scheduling Provide data for improved maintenance budgeting and control Train maintenance supervisors
Tunnel cleaning method	Calif. Division of Highways (HP&R) [1]	117,000	July 1967–June 1972	Develop a tunnel cleaning method that is rapid, economical, nonhazardous, and nondestructive
Cost effectiveness of antiskid and deicing programs in Pennsylvania.	Pa. Department of Highways (HP&R) [1]	20,000	July 1968–June 1970	Study and evaluate existing snow and ice control practices Develop improved methods, equipment, and materials for snow and ice control
Winter maintenance for bituminous pavements.	Tex. Highway Department (HP&R) [1]	36,000	Sept. 1967–Aug. 1969	Evaluate existing practices for winter pavement maintenance Develop improved methods, equipment, and materials for winter pavement maintenance
Snow removal and ice control techniques at interchanges.	NCHRP [2]	50,000	Sept. 1967–July 1969	Identify and evaluate the factors which influence the efficiency of snow removal and ice control operations at interchanges Develop operational systems that will provide for efficient snow removal and ice control procedures on interchanges in both rural and urban locations
Develop performance budgeting system to serve highway maintenance management.	NCHRP [2]	250,000	Sept. 1968–Oct. 1970	Develop and test a model highway maintenance budgeting system
Maintenance formula application	La. Department of Highways (HP&R) [1]	60,000	July 1963–July 1969	Accumulate accurate cost data for testing and revising mathematical models to predict maintenance costs
Maintenance cost	Ohio Department of Highways (HP&R) [1]	380,000	July 1961–July 1972	Determination of reliable maintenance costs Determine the influence of major factors which contribute to maintenance costs Measurement of the level of maintenance and determination of the extent to which deficiencies exist in the current maintenance and operation of the highway system

[1] HP&R—Highway planning and research project (Federal-aid).
[2] NCHRP—National cooperative highway research program.

needed for management, fiscal accounting, and research purposes.

- Quality, quantity, and performance standards for maintenance activities have been developed and proven practical for operational use.
- Techniques for planning and scheduling maintenance activities on long range and daily bases have been developed and proven practical.
- A large fund of data concerning work methods, time utilization, and productivity of labor and equipment under typical field conditions has been accumulated and analyzed to determine some cause-effect relationships.
- Procedures for determining optimum staffing patterns and work methods have been developed.
- New equipment and methods have been developed and proven practical and economical for several maintenance activities.
- Performance budgeting systems for maintenance are being developed and tested for practicality.
- Procedures and data for forecasting long range maintenance requirements have been developed and proven useful.
- Techniques to enable management to evaluate alternative policies for investments, resource allocation, staffing, and other aspects of maintenance are being developed.
- Some materials and procedures for training maintenance personnel have been developed and tested.

At the present time it would be unrealistic to state that these research results have been widely translated into improved management. The current attitudes of administrators and managers have created a favorable climate their use, but unfortunately, each maintena organization must operate under its own se conditions and constraints. Thus, it is usu necessary to undertake some additional search to adapt results for a particular sit tion. This takes time. Still more time is quired for actual implementation. Hopefull significant number of organizations will begin this process, but it will be at lea years before there is a widespread impr ment of maintenance management in United States.

Finally, everyone involved in mainten management research needs to recognize the objective is not simply improved man ment. This is only the key that unlocks door leading to the ultimate goal—effec efficient maintenance for our nation's h ways.

(*Continued from p. 90*)

ıg installation and a tunnel is usually the .irtiest part of any highway.

To use a *maintenance factor* in designing ghting for tunnels is to admit that no amount ıf physical maintenance can keep the output f the lighting system up to its initial level. 'he value of the maintenance factor used ıdicates the amount of the uncontrollable epreciation that is expected and the amount f effort that should be devoted to overcome ıis depreciation. After the maintenance rogram is established, the designer can etermine an appropriate maintenance factor ›r the system. A maintenance factor range ·om 0.25 to 0.60 would be typical, depending n the proposed maintenance schedule.

pproach roadways

Current lighting criteria should govern the esign of any roadway lighting, and the resence of a tunnel will not necessitate any ıange in the criteria. If lighting is not in- alled on the approach roadways, a few undred feet of transition lighting leading to ınd from the tunnel may be used. When no ›adway lighting exists the night lighting in ıe tunnel should be designed to a minimum cceptable level to avoid abrupt lighting ansitions.

For daytime conditions, the roadway ap- roaching the tunnel can be designed to aid ıe road user's visibility by reducing the daption level. As the approach to the tunnel ill be either a detriment or an aid to the road ser's visibility, it is recommended that this rea have a low reflectance finish, including ark portal face and dark pavement surface.

ACKNOWLEDGMENTS

The authors wish to acknowledge the con- ributions of the following persons whose npublished papers and reports provided back- round material for the preparation of this rticle:

G. M. Simes, *Criteria For Tunnel Lighting.* imes Co., Inc., New York, N.Y., 1965.

Harold Skootsky and John R. Brass, *Versatile Lighting System for Highway Tunnels.* Presented to the Illuminating Engineering Society, San Francisco, Calif., September 1959.

Hristaki Sofokidis, *An Investigation of Colored Bituminous Pavements.* Unpublished Master's Dissertation, School of Engineering and Architecture, The Catholic University of America, 1964.

Henry W. Wenson, Jr., and H. S. Lewis, *Lighting of the Lower Deck George Washington Bridge.* Paper presented to the A.I.E.E. Production and Application of Lighting Committee, New York, N.Y., January 27, 1963.

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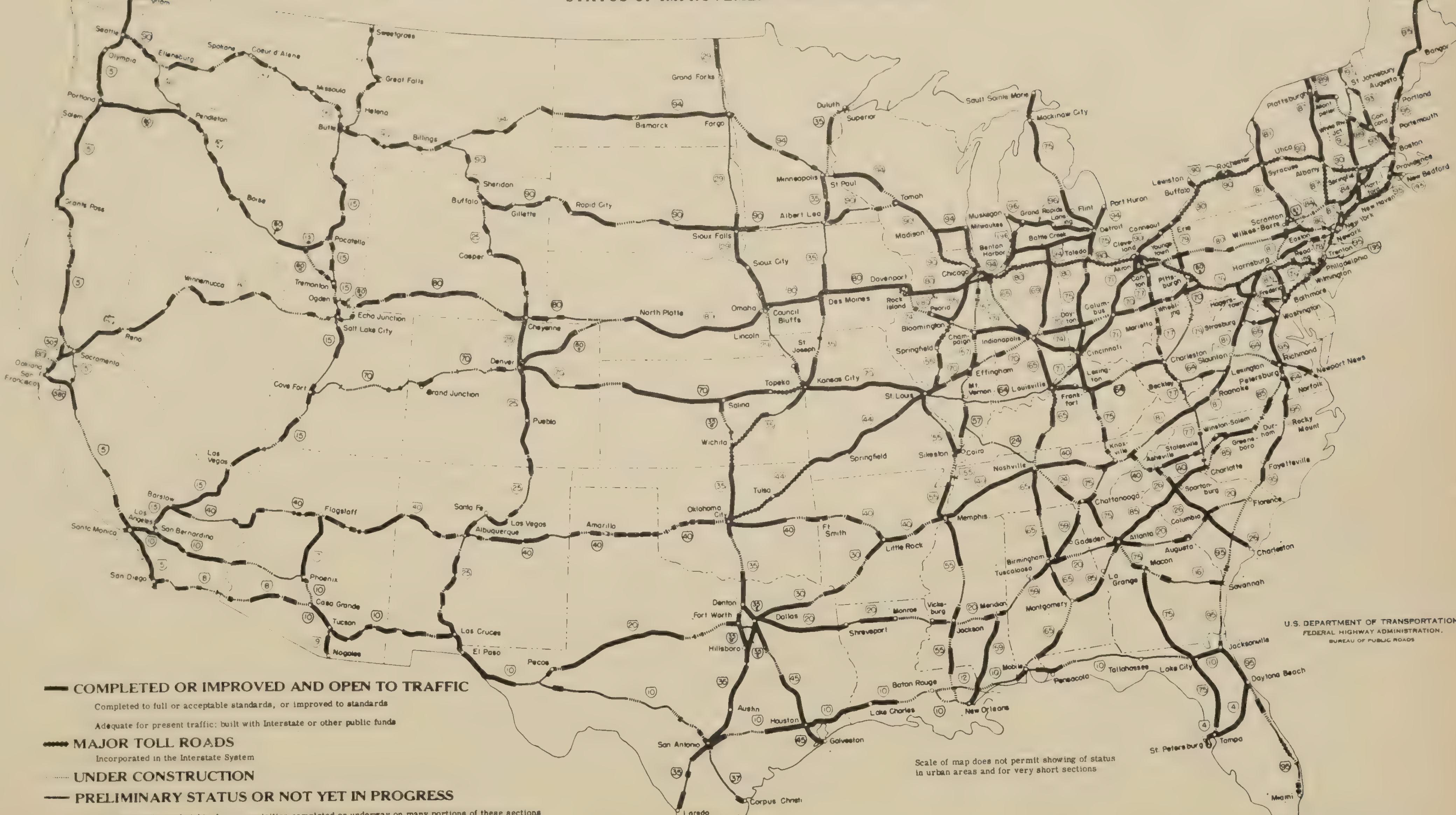
THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

STATUS OF IMPROVEMENT AS OF JUNE 30, 1968



U.S. DEPARTMENT OF TRANSPORTATION.
FEDERAL HIGHWAY ADMINISTRATION.
BUREAU OF PUBLIC ROADS

Scale of map does not permit showing of status in urban areas and for very short sections

COMPLETED OR IMPROVED AND OPEN TO TRAFFIC

Completed to full or acceptable standards, or improved to standards

Adequate for present traffic; built with Interstate or other public funds

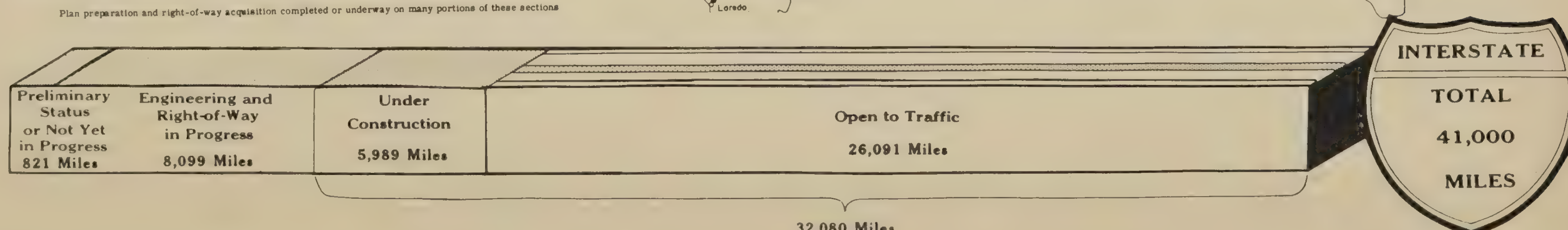
MAJOR TOLL ROADS

Incorporated in the Interstate System

UNDER CONSTRUCTION

PRELIMINARY STATUS OR NOT YET IN PROGRESS

Plan preparation and right-of-way acquisition completed or underway on many portions of these sections



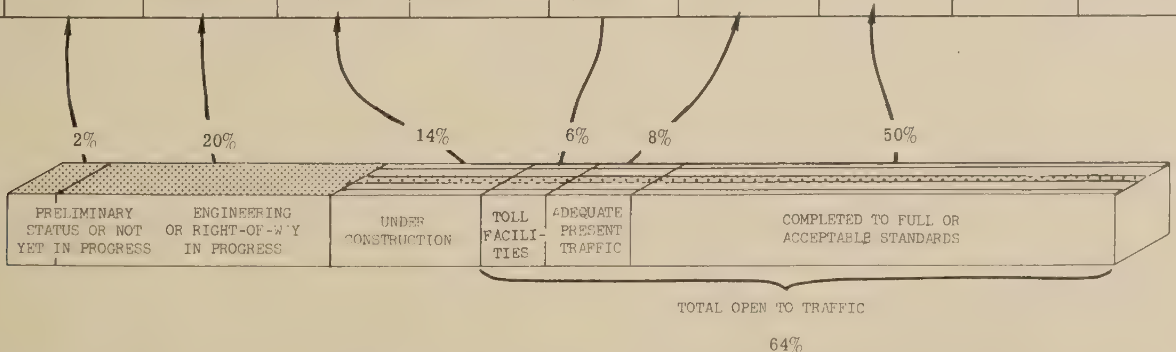
THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

INTERSTATE

IMPROVEMENT STATUS OF SYSTEM MILEAGE AS OF JUNE 30, 1968

TABLE I

STATE	PRELIMINARY STATUS OR NOT YET IN PROGRESS 1/	WORK IN PROGRESS			OPEN TO TRAFFIC				TOTAL DESIGNATED SYSTEM MILEAGE	STATE
		ENGINEERING OR RIGHT-OF-WAY	UNDER CONSTRUCTION	TOTAL UNDERWAY	TOLL FACILITIES	IMPROVED TO STANDARDS ADEQUATE FOR PRESENT TRAFFIC	COMPLETED TO FULL OR ACCEPTABLE STANDARDS	TOTAL OPEN TO TRAFFIC		
ALABAMA	-	211.2	181.4	392.6	-	141.1	343.7	484.8	877.4	ALABAMA
ARIZONA	1.0	179.9	246.9	426.8	-	258.1	481.4	739.5	1,167.3	ARIZONA
ARKANSAS	-	57.5	126.9	184.4	-	4.3	330.2	334.5	518.9	ARKANSAS
CALIFORNIA	-	427.0	352.5	779.5	10.2	307.5	1,067.5	1,385.2	2,164.7 2/	CALIFORNIA
COLORADO	119.1	126.7	76.0	202.7	-	115.8	497.1	612.9	934.7 3/	COLORADO
CONNECTICUT	-	23.1	11.2	34.3	16.4	47.4	197.5	261.3	295.6	CONNECTICUT
DELAWARE	-	9.4	10.4	19.8	14.3	0.9	5.6	20.8	40.6	DELAWARE
FLORIDA	14.2	328.3	124.5	452.8	44.8	-	644.7	689.5	1,156.5	FLORIDA
GEORGIA	-	307.2	217.6	524.8	-	7.0	576.6	583.6	1,108.4	GEORGIA
HAWAII	11.6	25.0	3.8	28.8	-	1.6	9.9	11.5	51.9	HAWAII
IDAHO	-	128.9	87.6	216.5	-	102.6	289.2	391.8	608.3	IDAHO
ILLINOIS	38.8	370.3	242.3	612.6	156.0	143.0	691.9	990.9	1,642.3	ILLINOIS
INDIANA	-	207.8	230.9	438.7	156.9	15.4	504.1	676.4	1,115.1	INDIANA
IOWA	-	140.5	65.8	206.3	3.6	-	499.1	502.7	709.0	IOWA
KANSAS	0.1	101.2	73.6	174.8	185.9	0.3	439.8	626.0	800.9	KANSAS
KENTUCKY	-	153.4	168.9	322.3	39.2	4.2	372.9	416.3	738.6	KENTUCKY
LOUISIANA	-	202.0	186.3	388.3	-	1.8	283.2	285.0	673.3	LOUISIANA
MAINE	1.8	33.4	1.2	34.6	58.0	99.4	118.3	275.7	312.1	MAINE
MARYLAND	19.2	26.7	31.8	58.5	53.0	70.9	152.5	276.4	354.1	MARYLAND
MASSACHUSETTS	4.3	36.2	51.4	87.6	135.8	27.4	196.0	359.2	451.1	MASSACHUSETTS
MICHIGAN	-	166.1	64.6	230.7	4.8	44.4	801.3	850.5	1,081.2	MICHIGAN
MINNESOTA	-	280.9	218.6	499.5	-	42.3	362.2	404.5	904.0	MINNESOTA
MISSISSIPPI	-	125.6	155.4	281.0	-	19.2	378.1	397.3	678.3	MISSISSIPPI
MISSOURI	0.6	269.2	63.9	333.1	0.3	174.5	611.4	786.2	1,119.9	MISSOURI
MONTANA	24.6	513.5	83.1	596.6	-	300.4	264.4	564.8	1,186.0	MONTANA
NEBRAKSA	-	92.6	50.6	143.2	0.2	12.9	321.3	334.4	477.6	NEBRASKA
NEVADA	-	129.5	36.6	166.1	-	5.3	363.2	368.5	534.6	NEVADA
NEW HAMPSHIRE	11.3	30.0	14.1	44.1	22.0	20.2	117.3	159.5	214.9	NEW HAMPSHIRE
NEW JERSEY	49.2	98.9	64.9	163.8	46.3	32.9	89.2	168.4	381.4 4/	NEW JERSEY
NEW MEXICO	37.5	204.2	118.5	322.7	-	61.0	577.2	638.2	998.4	NEW MEXICO
NEW YORK	22.4	63.3	90.2	153.5	491.8	52.2	504.0	1,048.0	1,223.9	NEW YORK
NORTH CAROLINA	-	200.0	131.9	331.9	-	17.3	421.0	438.3	770.2	NORTH CAROLINA
NORTH DAKOTA	62.6	47.2	68.8	116.0	-	51.9	340.3	392.2	570.8	NORTH DAKOTA
OHIO	8.8	190.9	240.2	431.1	206.4	55.0	829.3	1,090.7	1,530.6	OHIO
OKLAHOMA	-	58.5	146.8	205.3	174.1	23.3	394.7	592.1	797.4	OKLAHOMA
OREGON	18.1	65.5	2.5	68.0	-	111.1	537.8	648.9	735.0	OREGON
PENNSYLVANIA	37.2	171.8	342.1	513.9	360.2	8.4	656.0	1,024.6	1,575.7	PENNSYLVANIA
RHODE ISLAND	-	11.2	18.1	29.3	-	8.7	32.8	41.5	70.8	RHODE ISLAND
SOUTH CAROLINA	-	92.2	197.6	289.8	-	17.8	374.5	392.3	682.1	SOUTH CAROLINA
SOUTH DAKOTA	-	176.4	87.7	264.1	-	77.5	337.6	415.1	679.2	SOUTH DAKOTA
TENNESSEE	-	313.2	142.5	455.7	-	92.6	502.3	594.9	1,050.6	TENNESSEE
TEXAS	23.3	589.9	410.2	1,000.1	-	302.8	1,701.8	2,004.6	3,028.0	TEXAS
UTAH	50.8	402.4	171.0	573.4	-	36.3	273.3	309.6	933.8	UTAH
VERMONT	-	116.2	59.5	175.7	-	13.4	131.3	144.7	320.4	VERMONT
VIRGINIA	0.6	237.6	168.4	406.0	37.6	47.2	568.8	653.6	1,060.2	VIRGINIA
WASHINGTON	64.8	110.8	78.2	189.0	-	196.0	276.9	472.9	726.7	WASHINGTON
WEST VIRGINIA	45.7	166.3	69.1	235.4	87.2	0.3	143.8	233.3	514.4	WEST VIRGINIA
WISCONSIN	0.7	1.7	69.3	71.0	-	24.7	361.9	386.6	458.3	WISCONSIN
WYOMING	106.5	69.3	131.6	200.9	-	49.3	552.1	601.4	908.8	WYOMING
DISTRICT OF COLUMBIA	9.9	8.0	1.9	9.9	-	2.9	6.9	9.8	29.6	DISTRICT OF COLUMBIA
PENDING	36.4 5/								36.4 5/	PENDING
TOTAL	821.1	8,098.6	5,988.9	14,087.5	2,305.0	3,250.5	20,535.9	26,091.4	41,000.0	TOTAL



1/ Public hearings have been held on route location, and location studies are underway on many portions of the mileage in this column.
2/ Exclude the 17.2 mile Century Freeway (I-105) which was added to the system under the "Howard Bill."
3/ Excludes a 10.8 mile increase resulting from a major relocation of I-70, approved July 18, 1968. This increase will reduce the miles pending to 25.6 miles.
4/ Excludes the 34.4 mile Trenton-Asbury Park Spur (I-195) which was added to the system under the "Howard Bill" but includes that portion of I-278 mileage (7.0) deleted under the same bill.
5/ Consists of mileage which has not been assigned to any specific route and is a reserve for final measurement of the system.

Some Steam Baths Are Not So Hot!—

Leonard Bean, Materials Division, Bureau of Public Roads [1]

In many procedures described for inorganic analysis, a steam bath is specified for certain digestions. For example, in American Society for Testing and Materials (ASTM) Designation C 114–67, Section 80.1, silica is separated from portland cement by digesting a mixture of the cement sample with NH_4Cl and HCl on a steam bath for 30 minutes.

In recent work at the Public Roads laboratory, it was made clear that merely specifying the use of a steam bath is not sufficient to ensure complete decomposition of the cement sample and separation of the silica and, thus, secure correct results for SiO_2, Al_2O_3, CaO, and MgO.

The Public Roads laboratory was relocated recently, and after installation of facilities at the new location, an insufficient supply of steam was furnished to heat the steam baths. Usually, low results were obtained for SiO_2—as much as 0.5 percent absolute—and high results for Al_2O_3, CaO and MgO. Under the conditions at the newly installed laboratory, 100 ml. of water in a covered 150-ml. beaker on a steam bath could be heated no higher than about 63° C. This source of heat was not sufficient to decompose a sample of cement properly. By modifying the supply of steam, sufficient heat was supplied to the water in the steam bath to maintain it at a rolling boil. Under these conditions, 100 ml. of water in a covered 150-ml. beaker could be kept at 83° to 90° C. Decomposition and dehydration cement by the method cited then ga reasonable values for SiO_2 in standard samp of cement issued by the National Bureau Standards, as well as reasonable values f Al_2O_3, CaO, and MgO.

Accordingly, analytical chemists who use steam bath for such separations should certain that the heat source (steam, gas, electricity) can maintain the water in the ba at a rolling boil.

Furthermore, it is recommended that bod who write specifications for such analyses ASTM, Federal Committees, American As ciation of State Highway Officials, etc.—ta cognizance of this possible source of error. footnote or warning might well be inserted procedures requiring the use of a steam ba for decompositions such as the one cited he

[1] Essentially, this same information appeared in a Letter To The Editor, Materials Research and Standards, vol. 8, No. 6, June 1968, p. 51, published by the ASTM.

Ultrasonic Instrument for Determining Local Scour at Bridge Piers

(*Continued from p. 96*)

single plane, and by controlling the transducer position through mechanical linkage, the complexity and cost of the instrument could be substantially reduced. If the mechanical unit were simplified, the electronics package could also be reduced. A single 12-volt rechargeable power source could be used and the display/test module eliminated or replaced by a small strip chart recorder. In addition, for applications not requiring a high degree of bottom definition, a smaller transducer could be used.

Either the basic research unit or a simplified version could be equipped for remote monitoring operations.

ACKNOWLEDGMENTS

The authors are indebted to the U.S. Coast and Geodetic Survey, Oregon State Highway Department, and Region 8 of the Federal Highway Administration for their operation and aid in arranging and conduct the field test program.

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U.S. GOVERNMENT PRINTING OFFICE: 1968

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Freeways to Urban Development, A new concept for joint development (1966). 15 cents.

Guidelines for Trip Generation Analysis (1967). 65 cents.

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Highway Finance 1921–62 (a statistical review by the Office of Planning, Highway Statistics Division) (1964). 15 cents.

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Standard Traffic Control Signs Chart (as defined in the Manual on Uniform Traffic Control Devices for Streets and Highways) 22 x 34, 20 cents—100 for $15.00. 11 x 17, 10 cents—100 for $5.00.

Traffic Assignment Manual (1964). $1.50.

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Traffic Safety Services, Directory of National Organizations

Transition Curves for Highways (1940). $1.75.

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