Economic Study of Various Mounting Heights for Highway Lighting

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The basic purpose of this report is to study the cost-effectiveness of various luminaire mounting heights and to present a method of evaluating alternate lighting designs that will lead to more economical highway lighting.

Initial average horizontal footcandles and uniformity of illumination have been computed for one direction of two-, three-, and four-lane divided highways using overhead mercury luminaires mounted at 30, 40, 45 and 50-ft heights. The variation of footcandles and uniformity with different mounting heights and luminaire spacings are discussed. Estimated initial, equivalent annual capital, maintenance and power costs per mile are presented for overhead and bridge rail lighting. Floodlighting of interchange areas with luminaires mounted at 100 ft is evaluated, and costs are compared to a conventional system of overhead luminaires mounted at 30 ft.

It is concluded that lighting designs with mounting heights of 40 to 50 ft provide more economical and effective lighting than those requiring the usual 30-ft mounting height. Higher mounting heights normally provide for safer and more aesthetic lighting designs.

The information and techniques given should enable highway agencies to evaluate alternate highway lighting system designs more accurately, and thus provide a wiser expenditure of public funds.

•LIGHTING of controlled-access highways in urban areas is receiving more attention each year. As traffic volumes and operating speeds of vehicles have increased, demands for highway lighting have developed. Although several highway agencies have extensive lighting programs, many have limited programs or none at all.

Despite the fact that an economic study is generally a basic requisite for an engineering project, highway agencies have made little use of such studies when designing highway lighting. The information and techniques in this report will enable highway agencies to evaluate proposed lighting projects more accurately and to provide a wiser expenditure of public funds for these projects.

Methods for evaluating some of the cost differences of alternative designs are given, and other information is given on factors that may contribute to the design choice—factors which cannot be evaluated monetarily, such as aesthetics and safety.

The basic purposes of this report are to evaluate lighting designs of different mounting heights for controlled-access highways, to present a method of evaluating alternate lighting designs that will lead to more economical highway lighting, and to determine how mounting heights affect lighting cost. Designs are computed for use of (a) 250-watt

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lamps on two-lane roadways, (b) 400-watt lamps on two-, three-, and four-lane roadways, (c) 700-watt lamps on three- and four-lane roadways, (d) 1000-watt lamps on four-lane roadways, (e) bridge rail lighting, and (f) floodlighting an interchange area. The commonly used mounting height of 30 ft is compared to mounting heights of 40, 45, 50, 3½ (bridge rail) and 100 ft (floodlighting towers or poles).

The suggested method of an economy study can be used for evaluating all practical alternate lighting design proposals. This type of study can be used to support planning and decision-making, and it will result in more efficient and economical highway lighting installations, thus contributing to the safety and comfort of the road user, while enhancing the aesthetic quality of the highway.

HIGHWAY GEOMETRICS AND LIGHTING DESIGNS

The geometric and lighting design criteria are based on current design standards and practices. The designs were selected so that the principal variable would be the mounting height of the luminaire.

Only designs for divided, controlled-access highways are considered. The roadway for only one direction of a divided highway is evaluated. Comparable lighting designs are computed for two-, three- and four-lane pavements having 12-ft lanes with a 10-ft right shoulder, with the luminaire located over the right edge of traveled way. Interchange areas are evaluated separately. Bridge rail lighting is evaluated with the through roadway lighting.

A design level of initial illumination of 1.0 ft-c and average to minimum uniformity not exceeding 3 to 1 were used for all overhead lighting. In a few cases, design adjustment to produce acceptable lighting uniformity resulted in some deviation from the 1.0 ft-c. The minimum acceptable level of average initial illumination selected was 0.8 ft-c.

All overhead lighting designs are based on a single manufacturer's design charts, using clear mercury lamps. In the design for higher mountings, increased lamp wattages are required to keep the initial 1.0 ft-c illumination approximately constant. The 700-watt (34,600-lumen) and 1,000-watt (53,000-lumen) lamps are used when design requirements exceed the capacity of the 400-watt (19,500-lumen) lamp. The 250-watt (10,500-lumen) lamps are used for 30-ft mounting heights only. The 42-in., 33-watt (2,190 lumens at 300 ma) fluorescent lamps in 6-ft luminaires are used for bridge rail lighting design.

Bridge rail lighting, which would eliminate light poles, uses continuous fluorescent lights mounted adjacent to, or in lieu of, a bridge railing. Although the concept and design of low-mounted light is different from overhead lighting, comparisons are made on installations judged comparable. Horizontal footcandles, glare, and uniformity of illumination, which are the most common performance criteria used in designing a lighting system, do not appear to be a logical basis of comparison between low-mounted and overhead lighting. A recent research study (6) on bridge rail lighting reports that the average value of roadway illumination for rail lighting should be computed by a different method. Although the design methods are different, the low-mounted lighting is judged similar to the overhead system designs used in this study.

Other design criteria assumed to be constant for the lighting systems so that the principal variable would be the mounting height are:

1. Galvanized steel poles, anchor base, and concrete foundations;
2. Twelve-foot brackets, luminaire located over edge of traveled way;
3. Underground wiring system using cable-conduit;
4. Multiple system circuitry;
5. Power delivered at secondary voltage (no load center considered);
6. Median sufficient width so that lighting from oposite lanes not a factor;
7. Comparable pavement reflectance characteristics not requiring adjustments in computing average initial illumination;
8. Time and controls equivalent for all systems (therefore, not considered);
9. Medium semicutoff luminaires of IES types II and III (3); and
10. Ballast in luminaires.

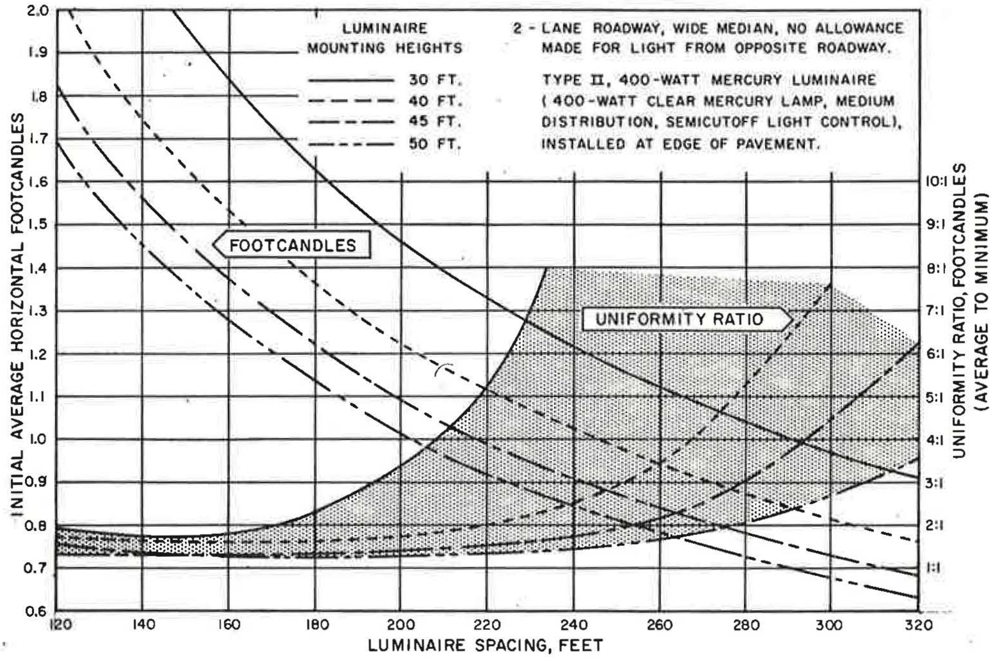

Figure 1. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for two-lane roadway.

Interchange floodlighting may be designed so that mounting heights of the luminaires range from 80 to 150 ft. Each interchange should be evaluated separately for the mounting heights that would best fit the geometric features. A floodlighting system differs somewhat in concept from the 30 to 50-ft mounting height designs. Computed design values may be similar to controlled lens lighting, whereas roadway brightness (measured foot-Lamberts) may differ. The floodlighting design generally used was considered to be comparable to the overhead system designs.

The interchange area selected (Fig. 1) consists of 6.75 mi of separate roadways. Floodlighting designs using the 400 and 1000-watt lamps are evaluated. An industrial type, symmetrical distribution luminaire design using the 1000-watt lamps is also evaluated.

COST DATA CONDITIONS AND ESTIMATES

The cost data in this report are based on information considered typical of national averages. These data are given as a basis for determining relative initial, operating, and maintenance costs for lighting systems in which luminaires are installed at different mounting heights. These cost data should not be used as a guide for estimating the cost of specific highway lighting projects because material delivery charges, electric energy, labor rates, and other costs may vary with geographical locations.

Initial costs for individual items are combined to obtain a total initial cost per mile, which was statistically converted and is restated as an equivalent annual cost. Luminaire maintenance and lamp replacement costs are also computed and are stated as equivalent annual costs. The estimated costs of luminaire cleaning and lamp replacement are based on maintenance being performed by owners and users. Repairs necessitated by vandalism, pole knockdowns, and other miscellaneous factors are considered in the evaluation.

The basic formula used to determine the equivalent annual capital cost, EAC, of a lighting system for a life expectancy of n years, from an initial cost, C, at an interest rate i percent is

$$EAC = C \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

The expression $i(1 + i)^n/(1 + i)^n - 1$ is called the uniform series capital recovery factor. As crf represents the uniform series capital recovery factor, the formula becomes EAC = C (crf - i% - n). For the computations in this study, n = 20 and i = 6%; therefore

$$EAC = C\ (crf - 6\% - 20)$$

The basic formula to find the present worth of a single investiment (I), n years in the future, at an interest rate i% is as follows:

$$PW\ of\ I = I \frac{1}{(1 + i)^n}$$

The expression $1/(1 + i)^n$ is called the single payment present worth factor. As pwf' represents the single payment present worth factor, the formula becomes PW of I = I (pwf' - i% - n). For the computations in this study, i = 6% and n = number of years hence that an investment is proposed; therefore

$$PW\ of\ I = I\ (pwf' - 6\% - n)$$

Normally, the lighting system constructed and operated by a governmental agency is financed from road user taxes in a method similar to that used to finance roadway construction. The road-user taxpayer, if allowed to keep this tax money, could invest it and earn a return. This lost-investment-opportunity cost should be the minimum interest used for determinations of the equivalent annual cost for an initial lighting investment.

TABLE 1

6 PERCENT COMPOUND INTEREST FACTORS[a]

Year	Single Pavyment Present Worth Factor (pwf')	Uniform Series Capital Recovery Factor (crf)
1	0.9434	1.06000
2	0.8900	0.54544
3	0.8396	0.37411
4	0.7921	0.28859
5	0.7473	0.23740
6	0.7050	0.20336
7	0.6651	0.17914
8	0.6274	0.16104
9	0.5919	0.14702
10	0.5584	0.13587
11	0.5268	0.12679
12	0.4970	0.11928
13	0.4688	0.11296
14	0.4423	0.10758
15	0.4173	0.10296
16	0.3936	0.09895
17	0.3714	0.09544
18	0.3503	0.09236
19	0.3305	0.08962
20	0.3118	0.08718

[a]These factors are based on investments made at the end of each year (maintenance, replacement and operation costs are assumed to be charges paid at the end of each year); zero time (n = 0) is assumed to be the day the installation is completed and operational.

A minimum interest rate should be established that is based on rates of investment opportunities foregone by the taxpayers, but it should be tempered by the element of risk for the 20-yr predicted life of the lighting system. The minimum attractive interest rate should include a safety factor as recognition that even the best engineering estimates are subject to error. Therefore, an interest rate of 6 percent is used for all present worth and capital recovery computations (Table 1). A 20-yr equipment life with no salvage value is used because 20 years is estimated to be the economic life of a majority of the system components.

It is assumed that the lighting system is owned by a governmental agency, which would eliminate taxes and insurance costs from the evaluation.

Procedures for maintaining a highway lighting system should be considered in the design of the system. However, because of the variations in mounting heights and the uncertainty in determining a maintenance factor for bridge rail lighting, and to a lesser degree for the 100-ft

TABLE 2

LUMINAIRE AND LAMP MAINTENANCE COST DATA

Luminaire Mounting Height (ft)	Luminaire Cleaning Schedule	Est. Cost of Cleaning Each Luminaire ($)	Lamp Wattage	Lamp Group Replacement Schedule (yr)	Est. Lamp Cost ($)
3½	Semiannually	2.00[a]	33	2	2.00
30	Semiannually	1.50	250	4	8.00
			400		8.00
40	Annually	1.50	400		8.00
			700	4	14.00
			1000		16.00
45	Annually	1.75	400		8.00
			700	4	14.00
			1000		16.00
50	Annually	2.00	400		8.00
			700	4	14.00
			1000		16.00
100	Biannually	3.00	400	4	8.00
			1000		16.00

[a]Estimate based on current maintenance practice, but more frequent cleaning would obviously be required to make this type lighting comparable with overhead lighting.

mounting heights, maintenance factors such as lumen maintenance and dirt were not included in the evaluation of the designs reported here. The omission of maintenance factors permitted logical comparisons of the designs. Luminaire cleaning schedules vary, depending on the mounting height, highway geometrics, traffic volumes, and location. The luminaire and lamp maintenance cost data selected for this study are given in Table 2; material and installation cost estimates are given in Table 3; and cost summary data are given in Tables 4 to 8. The total kilowatt electric load per luminaire is based on lamp wattage, plus ballast loss wattage, plus a line loss of 5 percent. Lighting operation is estimated at 4,000 hr/yr. The assumed current cost is $0.015 per kilowatt hr. Example computations for initial cost estimates and maintenance cost estimates are included in Appendixes A and B.

TABLE 3

MATERIAL AND INSTALLATION COST ESTIMATE

Item	Cost ($)					
	3½ Ft	30 Ft	40 Ft	45 Ft	50 Ft	100 Ft
Luminaire and ballast						
6-ft fluorescent	126	-	-	-	-	-
250-w mercury	-	92	-	-	-	-
400-w mercury	-	92	92	92	92	-
700-w mercury	-	-	144	144	144	-
1000-w mercury	-	-	158	158	158	-
400-w mercury floodlight	-	-	-	-	-	125
1000-w mercury floodlight	-	-	-	-	-	200
Lamps						
42-in. T6 fluorescent	2	-	-	-	-	-
250-w mercury	-	8	-	-	-	-
400-w mercury	-	8	8	8	8	8
700-w mercury	-	-	14	14	14	-
1000-w mercury	-	-	16	16	16	16
Poles	-	200	250	275	325	2000
Installation per luminaire[a]	40	350	400	425	450	750

[a]Including foundations, bolts, wiring, conduit, trenching, and all miscellaneous labor and materials; per pole.

TABLE 4

COST SUMMARY FOR TWO-LANE ROADWAY

Design and Cost Data	Mounting Height					
	30 Ft	30 Ft	40 Ft	45 Ft	45 Ft	50 Ft
Light distribution type	II	II	II	II	II	II
Lamp watts	250	400	400	400	400	400
Uniformity ratio	3.0:1	3.0:1	3.0:1	3.0:1	1.6:1	1.4:1
Avg. initial horizontal footcandles	0.83	1.50	1.00	0.79	1.00	1.00
Minimum footcandles	0.29	0.50	0.33	0.27	0.64	0.72
Luminaire spacing, ft	190	195	250	280	220	210
Luminaires, no./mi	28	27	21	19	24	25
Initial cost per mile	$18,200	$17,550	$15,750	$15,200	$19,200	$21,875
Annual costs per mile						
Equivalent capital	$ 1,587	$ 1,530	$ 1,373	$ 1,325	$ 1,674	$ 1,907
Equivalent maintenance	129	124	65	64	81	90
Power	512	770	599	542	684	713
Total	$ 2,228	$ 2,424	$ 2,037	$ 1,931	$ 2,439	$ 2,710

TABLE 5

COST SUMMARY FOR THREE-LANE ROADWAY

Design and Cost Data	Mounting Height							
	30 Ft	40 Ft	40 Ft	40 Ft	45 Ft	45 Ft	50 Ft	50 Ft
Light distribution type	II	II	II	II	II	II	II	II
Lamp watts	400	400	400	700	400	700	400	700
Uniformity ratio	3.0:1	3.0:1	2.3:1	3.0:1	1.8:1	3.0:1	1.8:1	3.0:1
Avg. initial horizontal footcandles	1.60	0.83	0.96	1.29	0.90	1.02	1.00	0.85
Minimum footcandles	0.53	0.27	0.42	0.44	0.50	0.33	0.55	0.28
Luminaire spacing, ft	150	255	220	225	220	265	190	290
Luminaires, no./mi	35	21	24	24	24	20	28	18
Initial cost per mile	$22,750	$15,750	$18,000	$19,392	$19,200	$17,160	$24,500	$16,794
Annual costs per mile								
Equivalent capital	$ 1,983	$ 1,373	$ 1,569	$ 1,691	$ 1,674	$ 1,496	$ 2,136	$ 1,464
Equivalent maintenance	161	65	75	104	81	91	101	87
Power	998	599	684	1,174	684	978	798	880
Total	$ 3,142	$ 2,037	$ 2,328	$ 2,969	$ 2,439	$ 2,565	$ 3,035	$ 2,431

TABLE 6

COST SUMMARY FOR FOUR-LANE ROADWAY

Design and Cost Data	Mounting Height								
	30 Ft	40 Ft	40 Ft	40 Ft	45 Ft	45 Ft	50 Ft	50 Ft	50 Ft
Light distribution type	III	III	II	III	II	III	III	II	III
Lamp watts	400	400	700	1,000	700	1,000	400	700	1,000
Uniformity ratio	3.0:1	2.4:1	3.0:1	3.0:1	3.0:1	3.0:1	2.2:1	3.0:1	3.0:1
Avg. initial horizontal footcandles	1.09	1.00	1.13	1.80	0.91	1.42	1.00	0.80	1.28
Minimum footcandles	0.36	0.43	0.36	0.60	0.30	0.47	0.47	0.27	0.43
Luminaire spacing, ft	185	180	220	210	255	250	160	280	265
Luminaires, no./mi	29	29	24	25	21	21	33	19	20
Initial cost per mile	$18,850	$21,750	$19,392	$20,600	$18,018	$18,354	$28,875	$17,727	$18,980
Annual costs per mile									
Equivalent capital	$ 1,643	$ 1,896	$ 1,691	$ 1,796	$ 1,571	$ 1,600	$ 2,517	$ 1,545	$ 1,655
Equivalent maintenance	134	90	104	118	96	104	119	92	104
Power	827	827	1,174	1,725	1,027	1,449	941	929	1,380
Total	$ 2,604	$ 2,813	$ 2,969	$ 3,639	$ 2,694	$ 3,153	$ 3,577	$ 2,566	$ 3,139

TABLE 7

COST SUMMARY FOR 3½-FT MOUNTING HEIGHT[a]

Initial cost per mile	$220,200
Annual costs per mile	
Equivalent capital	19,197
Equivalent maintenance	7,995
Power	4,290
Total	$ 31,482

[a]Design: 3½-ft roadway lighting designs provide for two continuous rows of luminaires, one on each side of roadway. This design is identical for two-, three-, or foui -lane roadways. The luminaire is assumed to replace the top bridge rail. This design requires 1625 liminaires/mi.

SAFETY

Few subjects have received so much attention and so little opposition as highway safety. The three major variables of of highway safety are the driver, the vehicle, and the highway. Each variable considered separately is complex and indefinite; combined, these variables present a mass of intangibles so nebulous and replete with unsupported opinions that it is impractical to establish costs for accidents.

A recent study (7) reports that lighting contributes to safer highway operations during darkness, but formal research has not yet evaluated the degree of safety provided at night by highway lighting, nor has it established the degree of hazard created by the presence of lighting poles along the highway during daylight hours as well as at night. Regardless of this lack of conclusive evidence, it seems logical, when considering safety, to favor a lighting system designed for fewer poles per mile. It also seems logical to assume that operation in the interchange area would be safer if the number of lighting poles were reduced and the poles were located farther from the edge of the travelway. Towerlighting, in lieu of roadside poles, would provide such a situation. Lighting the entire interchange area rather than only the roadways might also improve safety.

The ability to see an object is reduced by glare in the field of view. The glare may be reduced by increasing the luminaire mounting height when candlepower values remain constant. If glare is reduced, it follows that the result will be better visibility and improved safety.

The authors, supported by observations, believe that an improvement in the uniformity of illumination, even if it involves a slight reduction in level of intensity, would provide better highway lighting. This is one of the advantages of higher mounting heights and should be evaluated as a safety improvement.

Bridge rail lighting cannot be evaluated in the same manner as general highway lighting; poles on bridges are not considered hazards because they are located on top of or behind the bridge parapet. Because the mounting height of the bridge rail lighting is approximately on a level with the driver's eye, any resultant glare would be a negative value in highway safety considerations. Also, because of the lack of light directed

TABLE 8

COST SUMMARY FOR INTERCHANGE FLOODLIGHTING[a]

Design and Cost Data	Mounting Height			
	30 Ft	100 Ft	100 Ft	100 Ft
Light distribution type	II	Flood	Floor	V
Lamp watts	400	400	1000	1000
Uniformity ratio	3:1	Approx. 3:1	Approx. 3:1	Approx. 2:1
Avg. initial horizontal footcandle	1.5	Approx. 1.0	Approx. 1.0	Approx. 1.0
Total no. of luminaires	183	492	204	108
Total no. of poles	183	12	12	27
Luminaires per pole	1	41	17	4
Initial costs	$118,950	$98,436	$77,064	$101,628
Annual costs				
Equivalent capital	10,370	8,582	6,718	8,860
Equivalent maintenance	844	2,268	1,269	672
Power	5,216	14,022	14,076	7,452
Total	$ 16,430	$24,872	$22,063	$ 16,984

[a]Through roadways are two 12-ft lanes, and all ramps are one lane except for the directional ramp which is two lane.

to the top and rear of the vehicles, a negative safety value may be introduced in the evaluation of bridge rail lighting. However, driving conditions during fog or other bad weather may be improved by bridge rail lighting because roadway delineation is improved.

AESTHETICS

All other design features being equal, the height of the pole can either enhance or detract from the aesthetic quality of the highway. On narrow roadways, lighting from 30-ft mounting heights is satisfactory. On wide roadways designed with a wide median, or more than one median, a 30-ft mounting height may require four or more rows of poles. The result could be an unsightly "forest of poles." A higher mounting height, combined when necessary with either 700 or 1,000-watt luminaires, may permit a reduction in both the number of rows and number of poles, which would improve the appearance of the highway at all times.

The taller poles are aesthetically acceptable when the ratios of roadway widths to pole heights are considered. When the design norm is considered to be 24-ft, two-lane, two-way roadway (two 12-ft lanes and two 10-ft shoulders) equipped with 30-ft poles, the ratio of roadway width to height of pole is 44:30, or approximately 1.5:1. Therefore, a 50-ft pole should be acceptable for roadway widths of 75 ft or more, and 100-ft poles or towers should be acceptable for roadway widths of 150 ft or more. Also, in areas where the type of property development adjacent to the highway is higher than the lighting poles, i.e., where there are industrial plants, high-rise apartments, or deep roadway cuts, taller poles, or even lighting towers, blend more readily with the local environment than the shorter poles. However if the adjacent area has one-story dwellings and the roadway cuts are shallow, use of shorter poles may be more desirable.

Towerlighting in wide interchange areas appears to be aesthetically desirable where acceptable width to height ratios exist. Lighting at night of landscaped areas between ramps enhances the appearance of the entire interchange area.

The spill of light off the highway, which may occur when the mounting heights are higher than the surrounding areas, could be either a positive or a negative factor in the design evaluation of highway lighting. The quality of the factor would depend on the property and the property owner. In a highly developed area where crime is a problem, spilled light could be an asset for owners of business and residential property. In relation to police protection, lighting is an asset in any area. Spilled light could be a negative factor and a source of complaints in private residential areas where crime is not a problem. In apartment dwelling and business areas, lighting is normally furnished in walking and parking areas, so spilled light from the highway may be desirable.

Bridge rail lighting has been promoted as an aesthetic improvement although it may break the continuity of overhead lighting for the highway. The use of rail lighting rather than lighting poles on bridges, seems to present a more pleasing appearance during the day. This factor would be more important in designs for bridge lighting on a parkway or scenic highway.

As in the evaluation of safety, a monetary value cannot be assigned to the aesthetic qualities of highway lighting, but for specific conditions some thought should be given to choosing a design to blend with the highway and adjacent property.

DISCUSSION OF RESULTS

The safest and most aesthetic overhead lighting system may be considered the one which provides adequate and effective illumination with the fewest poles. The number of poles per mile can be reduced by using higher mounting heights combined, when necessary, with higher wattage luminaires and lamps. As poles are the most costly component of the lighting system, a design which reduces the number of poles generally offsets the cost of taller poles, larger foundations, and larger luminaires. Lamps are a small part of the cost.

Three factors are of prime consideration in the effectiveness of any highway lighting system: level of illumination, uniformity of illumination, and control of glare. The uniformity of illumination may be more important than the footcandle level of illumination. And, as the mounting height of lamps is increased, the apparent improvement in light distribution may be better than a comparison of average to minimum uniformity ratios would indicate. It seems that the ratio of maximum to minimum illumination values should receive more consideration when alternatives are evaluated. Further study to determine a more positive evaluation of light distribution related to uniformity in level of illumination is recommended. Results of such a study might show that the road user's ability to perform the driving task is improved more by better uniformity in level of illumination than by an increase in the footcandles of illumination.

Luminaires having cutoff vertical light distribution help to reduce glare and may provide better visibility for the motorists than semicutoff luminaires. The least glare control is possible when noncutoff luminaires are used, and they probably should not be considered for expressway lighting.

With narrow medians, the higher the mounting height the better distribution of light on the opposite roadway. Because the position of the luminaire in relation to the traveled way is not as critical when higher mountings are used, it may be possible to use shorter bracket arms with some saving in initial cost.

When 30-ft mounting heights are used, a pronounced bright spot is present under or near each luminaire. The size and brightness contrast of these spots can be reduced considerably by use of higher mountings. Less variation is present in pavement brightness and the frequency of eye adaptation is lessened because the driver is not traveling through a succession of intermittent bright spots.

Figures 2 through 7 show that the 30-ft mounting height designs are more sensitive to spacing-uniformity ratios. As the mounting height is increased, the spacing-uniformity curves become flatter, indicating that the uniformity ratio is less sensitive to differences in luminaire spacing. This also suggests that the differences between designed

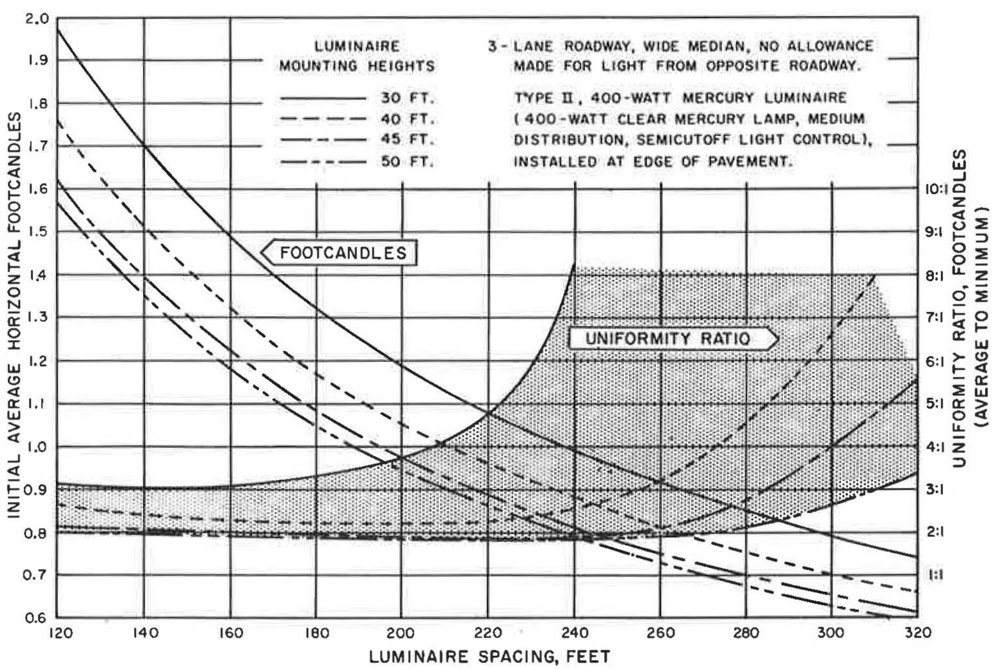

Figure 2. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for three-lane roadway.

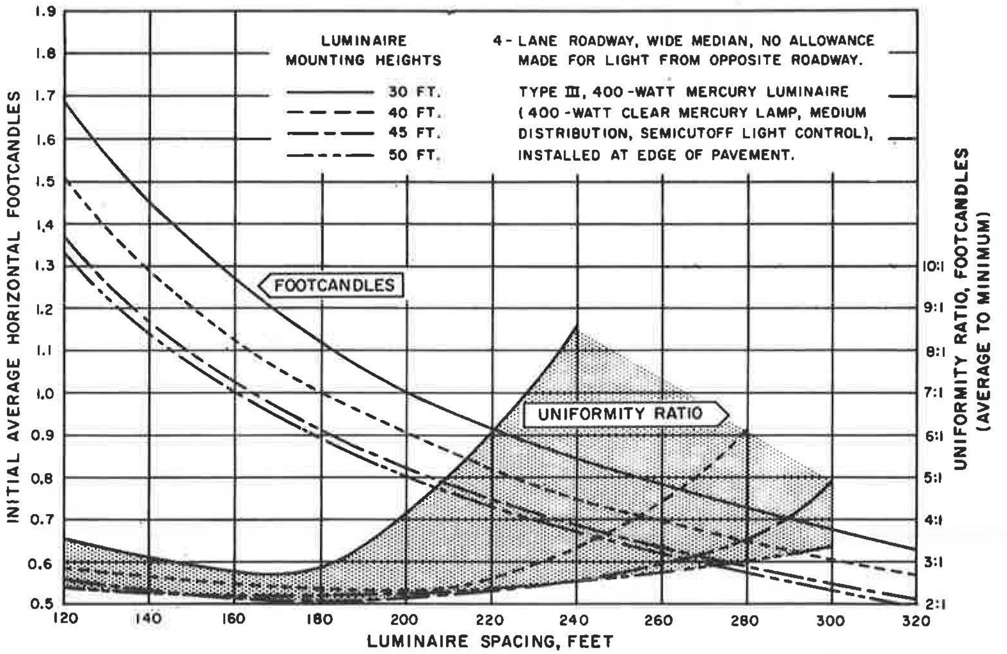

Figure 3. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for four-lane roadway for 400-watt lamp.

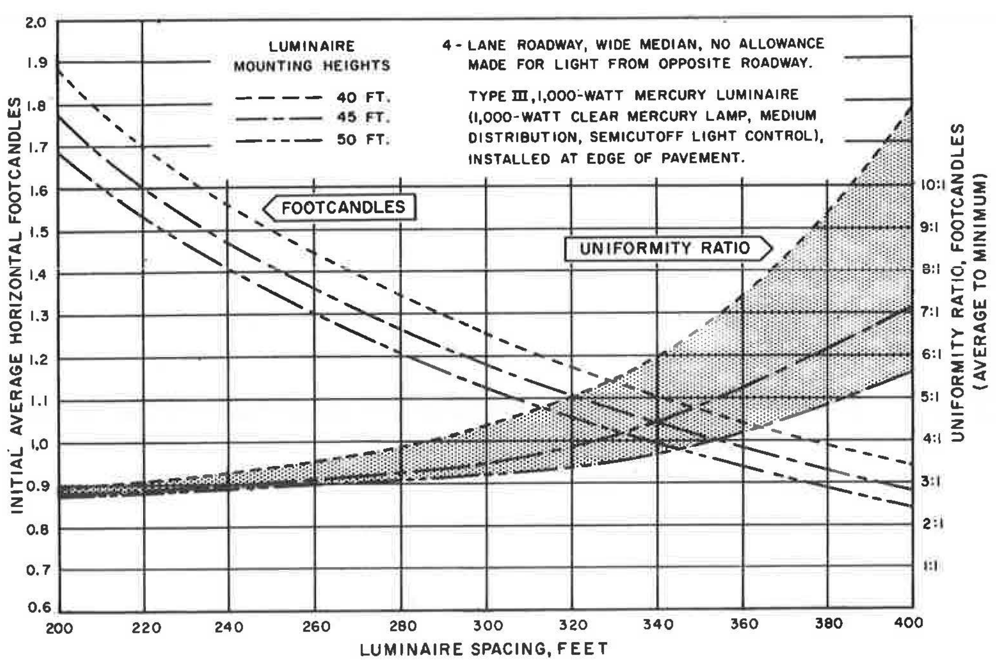

Figure 4. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for four-lane roadway for 1000-watt lamp.

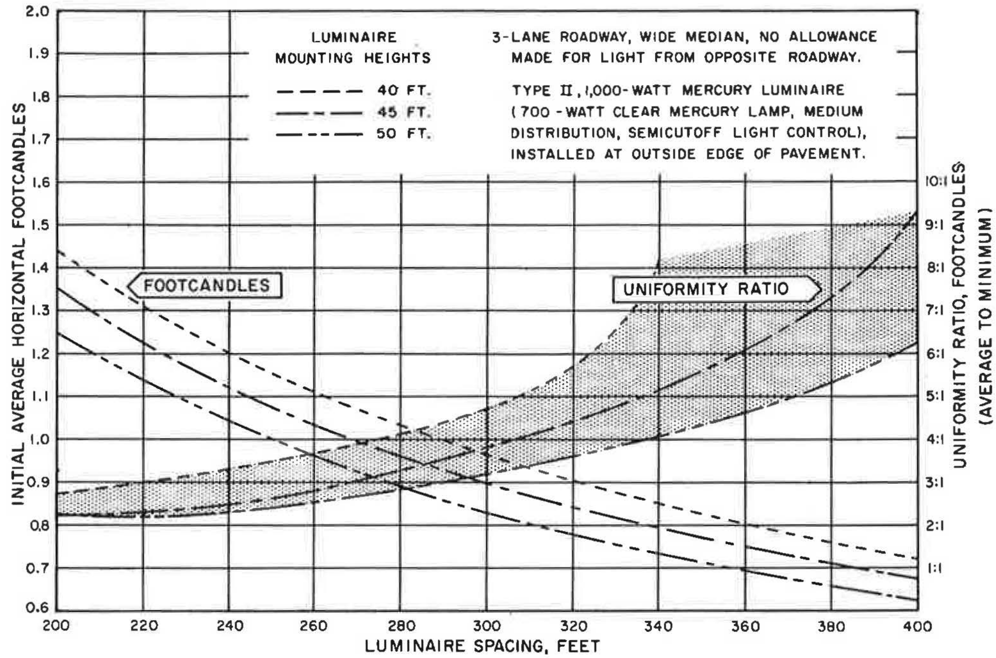

Figure 5. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for three-lane roadway.

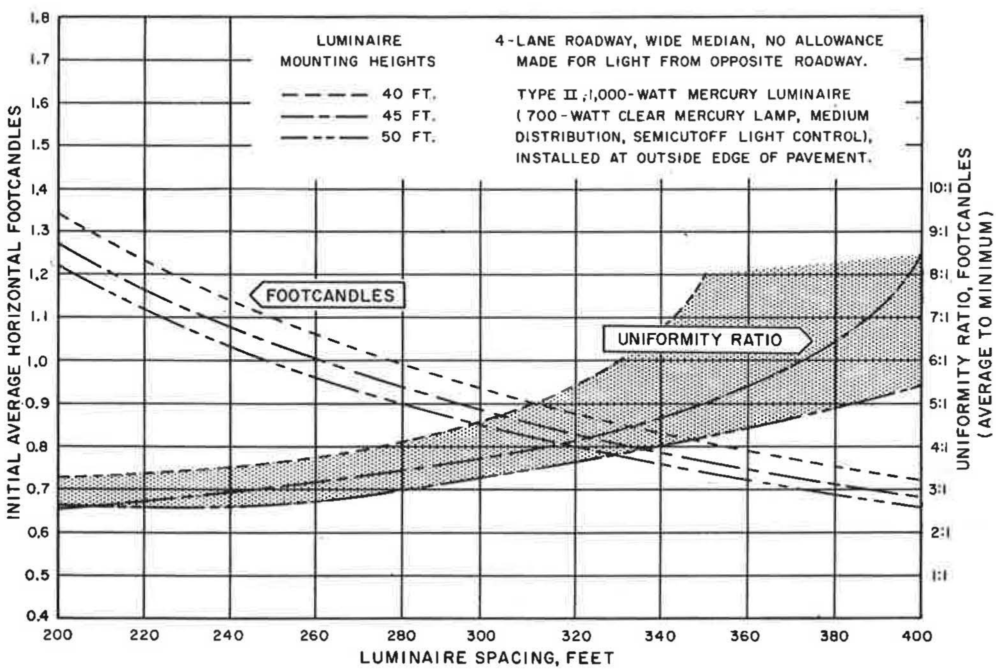

Figure 6. Initial average footcandles and lighting uniformity ratio for different mounting heights and luminaire spacing for four-lane roadway.

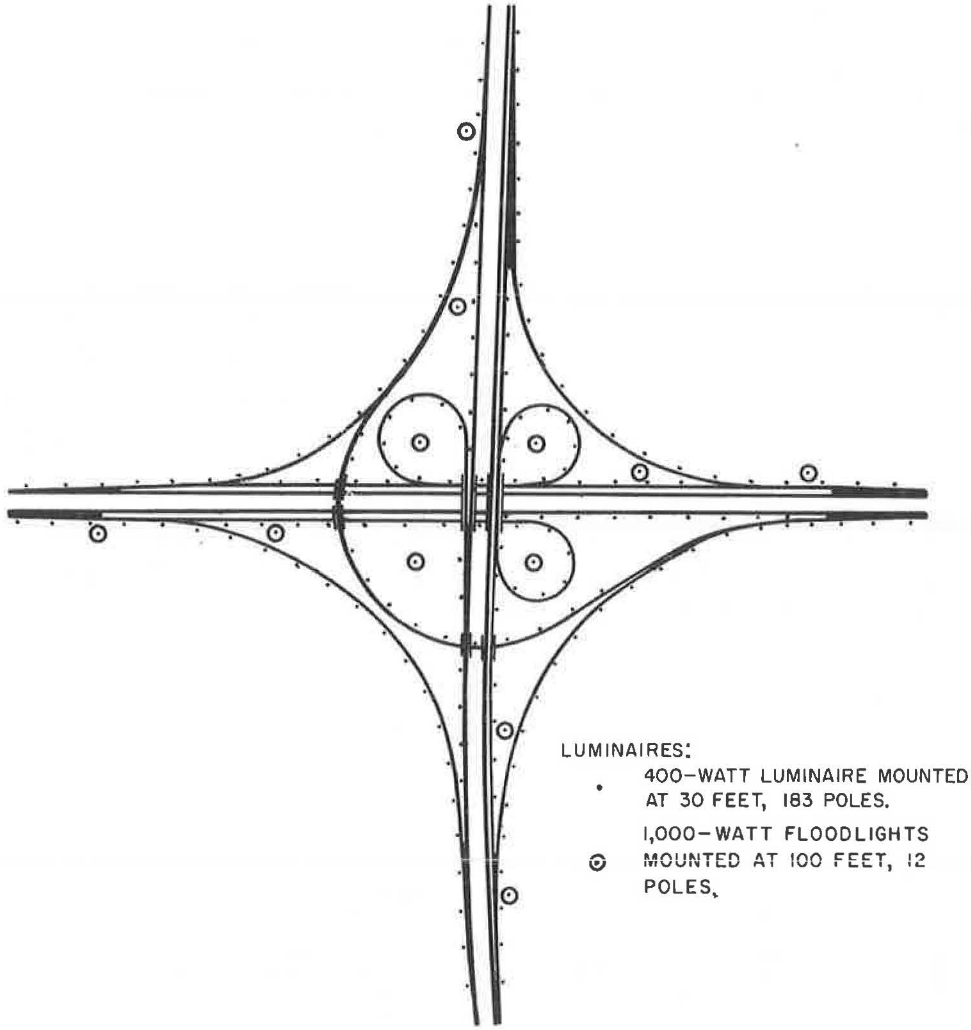

Figure 7. Interchange layout of lighting poles for 30 and 100-ft mounting heights.

and actual lighting results would be less as the mounting height is increased. A cost-effective analysis indicates that a mounting height of 30 ft is seldom the most desirable lighting for a divided, controlled-access highway.

The family of curves (Figs. 2-7) can aid in the preliminary design of a lighting system. For example, for a 30-ft mounting height of luminaires on a two-lane roadway, 1.5 initial footcandles are required for a 3:1 lighting uniformity ratio and 1.4 footcandles for a 4:1 uniformity ratio (Fig. 2). At the 30-ft mounting height it also shows that it is impractical to design for an 0.8 to 1.2 initial average horizontal footcandle level of illumination and provide an acceptable uniformity ratio.

A comparison with the 40-ft mounting height shows that designs for an 0.8 to 1.2 average level of illumination can be obtained with uniformity ratios of 8:1 or 1.7:1. For the same intensity, the uniformity ratio varies from 2.7:1 to 1.4:1 for a 45-ft mounting height and 1.6:1 to 1.2:1 for a 50-ft mounting height.

An analysis of the design and cost data indicates that a 45-ft mounting height would be the most economical lighting design for a two-lane roadway (Table 4). This height would also be better than a 30-ft mounting height in relation to safety and aesthetics.

A 50-ft mounting height would provide the most effective lighting, the best uniformity in illumination, and the least glare. The 30-ft mounting height would provide the greatest value of average initial footcandles.

For a three-lane roadway, a mounting height of 40 ft would be the most economical design (Table 5). A 45-ft mounting height would provide the most effective lighting. At a mounting height of 50 ft, glare would be least; also, the 50-ft mounting height design would provide the best system in relation to safety and aesthetics. The 30-ft mounting height results in the highest average initial footcandles. On the basis of the cost-effectiveness evaluation, the use of either a 45 or 50-ft mounting height would be favored.

On a four-lane roadway, a 50-ft mounting height would be a better lighting system on the basis of economy, uniformity, effectiveness, glare, safety and aesthetics (Table 6). The 40-ft mounting height would provide the most initial footcandles of illumination.

Bridge rail or low-mounted continuous fluorescent lighting (3½ ft) should be restricted to locations where overhead lighting cannot be used (Table 7). The total annual cost for such an installation is approximately 10 times that of conventional overhead lighting systems. Pavement brightness requirements may be met on two-lane roadways at the 3½-ft mounting height, but whether these requirements are met on three- and four-lane roadways is questionable. Although a rail lighting system contributes to the aesthetic appearance of a bridge and helps delineate the roadway at night, the problems inherent in maintaining such a lighting system, coupled with the increased annual cost, should rule out such a design except under unusual circumstances. Exposure of luminaires to dirt from frequent splashing from moisture on the highway makes it impractical to maintain the same degree of cleanliness possible with overhead lighting.

Definite conclusions regarding towerlighting for interchange areas from heights of 100 ft cannot be made from a study of a single interchange (Table 8). Several alternate systems are possible, and it appears that costs may be about equal to the costs of a conventional 30-ft mounting height design. Interchange floodlighting has not been used in this country, but installations now exist in Europe (12, 13). Safety and aesthetic considerations favor this type of lighting for interchanges because fewer poles are required, and recent lamp developments may encourage its use in the future. Actual installations are needed to evaluate fully the effectiveness and economy of this type lighting.

Flexibility in choice of equipment and design of highway lighting systems seems to increase in relation to the mounting height of the systems. Studies to determine the pavement brightness, glare and effectiveness in fog or wet pavement are needed.

The cost-effectiveness evaluation of specific lighting installations may vary, depending on warranting conditions, the type of property development adjacent to the highway, the highway geometrics, and the personal choice of the decision maker. Also, additional information regarding the differences in design criteria and field measurements would influence the final decision.

CONCLUSIONS

Highway lighting systems designed to use luminaires mounted at heights of 40 to 50 ft would be more economical and effective than designs for luminaires mounted at 30 ft. Use of these higher mounting heights generally would provide safer and more aesthetic lighting. The previously accepted standard mounting height of 30 ft may be considered undesirable for divided highways.

Many facets of the current design criteria need reevaluation in view of higher mounting height designs and recent lamp developments. Uniformity should be studied and thoroughly analyzed because the maximum to minimum ratio of illumination uniformity is a more logical basis for comparison of a lighting system's effectiveness than the average to minimum ratio currently in use.

The designs using higher mounting heights are more flexible and can be readily modified to use new lamp and luminaire improvements. Recent trends in lamp development are toward increased lamp efficiency and higher lumen output.

The cost of continuous low-mounted fluorescent bridge rail lighting is considerably greater than that of overhead lighting. Considering the questionable effectiveness and impractical maintenance of bridge rail lighting, it is concluded that it would not be a wise investment of public funds.

The cost information in this report is a relative value, and should not be used for project justification or budget preparation.

Whether future experimentation or research furnishes factual data or not, an engineering study such as this can lead to better lighting systems by providing a means for making relative comparisons of proposed designs. Even without more research or factual data, this type of study can be a means of comparing alternatives which will provide more economical and effective highway lighting systems.

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Appendix A

EXAMPLE COMPUTATIONS FOR INITIAL COST ESTIMATES[a]

M. H. (ft)	Installation Cost per Luminaire ($)	Luminaires per Mile	Initial Cost per Mile ($)	Equivalent Annual Capital Cost[b] ($)
3½	168	1625	220,200[c]	19,197
30	650	28	18,200	1,587
30	650	27	17,550	1,530
40	750	21	15,750	1,373
45	800	19	15,200	1,325
45	800	24	19,200	1,674
50	875	25	21,875	1,907
100	6422[d]	12[e]	77,064[f]	6,718[g]

[a]For two-lane roadway: initial cost per mile = installation cost/luminaire × number of luminaires/mile; installation cost/luminaire from Table 3; and number of luminaires/mile from Table 4.
[b]Equivalent annual capital cost = initial cost per mile × (crf - 6$ - 20).
[c]$168 × 1,625 - $52,800 (cost of top br. rail) = $220,200.
[d]Cost of a single 100-foot pole with seventeen 1,000-watt floodlights.
[e]No. of 100-ft poles in the interchange area.
[f]Initial cost of lighting interchange.
[g]Equivalent annual capital cost of lighting interchange excluding maintenance and power.

Appendix B

EXAMPLE COMPUTATIONS FOR MAINTENANCE COST ESTIMATES

Equivalent annual maintenance cost per luminaire = Annual cost of cleaning (from Table 2) + Equivalent annual cost of lamp replacement

Equivalent annual cost of lamp replacement = I (pwf' - 6% - n) (crf - 6% - n)

3-½ ft M.H.: I = $2.00; n = 2, 4, 6, 8, 10, 12, 14, 16 and 18

400-watt lamp (30 ft M.H., 40 ft M.H., 45 ft M.H., 50 ft M.H., 100 ft M.H.): I = $8.00; n = 4, 8, 12 and 16

1000-watt lamp (30 ft M.H., 40 ft M.H., 45 ft M.H., 50 ft M.H., 100 ft M.H.): I = $16.00; n = 4, 8, 12 and 16

For 3½ ft M.H.

I	n	(pwf' - 6% - n)	PW
$2	2	0.8900	$1.78
2	4	0.7921	1.58
2	6	0.7050	1.41
2	8	0.6274	1.25
2	10	0.5584	1.12
2	12	0.4970	0.99
2	14	0.4423	0.88
2	16	0.3936	0.79
2	18	0.3503	0.70
		Total PW =	$10.50

Equivalent annual cost of lamp replacement for 3-½ M.H. per luminaire is

10.50 (crf - 6% - 20)

10.50 (0.08718) = $0.92

For 30, 40, 45, 50, and 100 ft M.H.:
400-watt lamp (1000-watt lamp)

I	n	pwf' - 6% - n	
$8 ($16)	4	0.7921	$ 6.34 ($12.67)
8 (16)	8	0.6274	5.02 (10.04)
8 (16)	12	0.4970	3.98 (7.95)
8 (16)	16	0.3936	3.15 (6.30)
			$18.49 $36.96

Equivalent annual cost of lamp replacement per luminaire is

$18.49 ($36.96) × (crf - 6% - 20)

$18.49 ($36.96) × (0.08718) =

$ 1.61 ($ 3.22)

(1) M.H.	(2) Annual Cost of Cleaning ($)	(3) Equiv. Annual Cost of Lamp Replacement ($)	(2) + (3) Equiv. Annual Maintenance Cost Per Luminaire ($)
3½ ft	4.00	0.92	4.92
30 ft (250 w)	3.00	1.61	4.61
30 ft (400 w)	3.00	1.61	4.61
40 ft (400 w)	1.50	1.61	3.11
45 ft (400 w)	1.75	1.61	3.36
50 ft (400 w)	2.00	1.61	3.61
100 ft (400 w)	3.00	1.61	4.61
40 ft (1000 w)	1.50	3.22	4.72
45 ft (1000 w)	1.75	3.22	4.97
50 ft (1000 w)	2.00	3.22	5.22
100 ft (1000 w)	3.00	3.22	6.22

Equivalent annual maintenance cost per mile (M) = Equivalent annual maintenance cost per luminaire (X) + Number of luminaires per mile (Y)

M for two-lane roadway:

M.H. (ft)	X	Y	M
3½	$4.92	1625	$7,995.00
30	4.61	27	124.47
30	4.61	28	129.08
40	3.11	21	65.31
45	3.36	19	63.84
45	3.36	24	80.64
50	3.61	25	90.25
100	4.61	41[a]	189.01[b]
100	6.22	17[a]	105.74[c]
100	6.22	4[a]	24.88[d]

[a] Average number of luminaires per 100-ft pole.
[b] Maintenance cost per 100-ft pole with forty-one 400-watt floodlights.
[c] Maintenance cost per 100-ft pole with seventeen 1000-watt floodlights.
[d] Maintenance cost per 100-ft pole with 4 type V industrial luminaires.