Table 1. Estimated BCDs for roadway lighting for a single source.

		BCD (cd/m^2 000s)					
		Mounting Height at 3-m Lateral Distance (m)			Mounting Height at 9.1-m Lateral Distance (m)		
Longitudinal Distance (m)	Background Luminance (cd/m^2)	9.1	11	12	9.1	11	12
27	0.0034	11	14				
	0.034	23	25				
	0.34	45	51				
	3.4	89	100				
	34	180	200				
55	0.0034	17	17	21	21	21	24
	0.034	34	38	38	41	45	45
	0.34	69	72	79	82	86	93
	3.4	137	140	160	160	170	180
	34	270	290	310	330	340	380
82	0.0034	24	24	27	27	27	31
	0.034	48	51	51	55	55	58
	0.34	96	99	110	110	110	120
	3.4	190	200	210	220	220	230
	34	380	400	410	450	450	480

Notes: 1 m = 3.3 ft; 1 cd/m^2 = 0.292 footlambert.
Empty cells indicate < 20° cutoff to the top of the windshield.

under way to study such multiple-source effects.

In the meantime, Merle Keck of Westinghouse and Ramkumar Viswanathan of Kansas State each did analyses that related some representative roadway-lighting conditions to those involving a single light source. Table 1 shows BCDs estimated from an analysis based on the regression equation from the single-source experiment.

It was assumed that a varying visible portion of a 0.13-m^2 (200-in^2) cobrahead luminaire was mounted at 9.1 m (30 ft), 11 m (35 ft), or 12 m (40 ft). The driver's line of sight was assumed to be 1.2 m (4 ft) above the ground. The lights were assumed to be either 3 m (10 ft) or 9.1 m (30 ft) to the side of the driver's track. The BCD was examined at 27 m (90 ft), 55 m (180 ft), and 82 m (270 ft) longitudinally from the light.

In some cases, the light at closer distances was above the occluding windshield top. The BCDs may be appraised by observing that Viswanathan and I made a few luminance measurements of roadway lights in our neighborhood that ranged from 21 000 cd/m^2 (6000 footlamberts) to 86 000 cd/m^2 (25 000 footlamberts) (for mercury, high- and low-pressure sodium). If such an actual source luminance was viewed in a position where a lower BCD luminance was expected, one might expect at least half the observers to be uncomfortable. Thus, some analyzed conditions will be problems, some will not. Generally, most discomfort problems can be avoided by raising the mounting height. Other analysis is under way to figure out how to cope with skewed distributions of observers within conditions so as to specify various percentages of observers who would be discomforted.

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Publication of this paper sponsored by Committee on Visibility.

Economic Models for Highway and Street Illumination Designs

Richard W. Slocum and Daniel R. Prabudy, Research and Development Division,
Ministry of Transportation and Communications, Ontario

A key issue in the field of illumination is energy conservation. At the same time, the application of economic resources should be optimized. For instance, to save energy, roadway illumination lamps can be replaced by more efficient lamps that provide the same light for less wattage. However, such energy savings may be offset by other cost elements. For these reasons, detailed cost calculations are needed to ensure lighting investment optimization. The cost-effectiveness of lighting systems can be established by the discounted total cost or annual equivalent cost models described in this report. These economic models allow various cost items, such as capital outlay, maintenance, and operational and en-

ergy costs, to be compared realistically by taking into account discount rates and inflation rates. Consideration of inflation is particularly important here because some costs, notably energy, may inflate at higher rates than other costs. The methods given in this paper provide for the inclusion of projected dollar cost inflation in the analysis. A computer program for the models has been developed, copies of which may be obtained from the author, and can be used independently or in conjunction with the overall illumination program. This computer program allows a comparison of different strategies by varying the input values of costs, as well as inflation and discount rates. The most effective design solution can then be identified and considered in the overall evaluation of the alternatives. The program should be a useful tool in selecting designs of light sources and other features of roadway lighting systems.

Efficient resource allocation is an ever-present objective of government spending. Cost-effectiveness modeling can assist in reaching this objective. Such models provide a cost comparison between various means of providing a given level of service. This paper describes methodologies for cost-effectiveness modeling of highway and street-lighting design alternatives. One can test different lighting system design parameters and their arrangements to obtain equal level of service (illuminance or luminance). The onus is on the lighting design engineers to test the parameters with different inputs and to compare how they satisfy a prescribed level of service. Because this area is discussed in Jung and Blamey (1), such comparisons are not included in this paper.

The key considerations in cost-effectiveness modeling are as follows:

1. Assumption of equal level of service for investment alternatives obviates the need for benefit estimation.
2. Cost elements are analyzed over a given time period or life cycle.
3. Inflated dollar or constant dollar figures are important.
4. Salvage value is considered to be insignificant (as a simplifying assumption).

The models discussed herein were developed because of the need to consider the effect of inflated costs (especially energy costs) on alternative highway and street-lighting designs. The rates of inflation are different for energy, material, and labor. The two models are the discounted total cost (DTC) and the annual equivalent cost (AEC). Both models will provide an economic cost comparison. Preference is given to the DTC method because it considers each year in the analysis period and does not rely on averaging some costs that may occur, for example, only every four years. The AEC method does allow the user to make more rapid calculations, albeit with somewhat rougher results than the total cost approach.

A number of costs are incurred in the provision of lighting. These costs change over time, some more so than others. The models presented here attempt to consider the effect of changing future costs and to discount them by some rate of discount. The rate of discount used can vary. One could choose, for example, the rate of interest on long-term government securities, the social time preference rate, or the opportunity cost rate of interest (2). Notwithstanding the rate chosen, a range of rates should be tested to determine the sensitivity of the decision to the selected rate. Note that the discount rate will often include an implicit factor for inflation.

Although the standard approach would use constant dollars with relative inflation, in actual experience inflation is rarely computed and included in cost-effectiveness analysis. The models presented here allow the reader to use projected inflation rates for each factor of cost, with no sacrifice in the relevance of the resulting cost comparison between lighting designs.

HIGHER-PERFORMANCE FACTORS

A given standard of illumination can be provided along a roadway by various design alternatives with respect to pole spacing, mounting height, lamp type, and luminaire type. A given lamp type has its own performance curve over time (lamp lumen depreciation curve) and its own burn-out rate (lamp mortality curve). Figure 1 (3) illustrates examples of these curves.

For instance, out of any given group of lamps, usually more than 10 percent will burn out during the first 16 000 h of operating time. This is equivalent to about four years of operation. The number of operating hours varies, depending on the type of lamp. During the same time, the lamp lumen output of remaining lamps may have decreased to a point where it gives illuminance near the minimum design level at the roadway surface. This usually occurs when the lumen output is about 85 percent of the initial lumens. At this point, a total group relamping of the lamps should be done.

Lamps burn independently of each other and at different rates. Their burn-out time may be weeks, months, or even years apart. Because it is not desirable to have even one lamp out at any given time, spot relamping must be carried out.

The amount of dirt that accumulates on the luminaire hardware surfaces greatly depends on environmental factors. The ambient category of several selected localities (4) is shown below:

Ambient Category	Description	Suspended Particulates ($\mu g/m^3$)
1	Clean, average for areas remote from pollution sources	0-150
2	Heavy traffic, light industrial	150-300
4	Moderate industrial, some smoke- or dust-generating activities nearby	300-600
8	Dirty, numerous smoke- or dust-generating sources nearby	600-1200
16	Very dirty, heavy smoke at luminaire elevation	1200-2400

Table 1 (4) shows luminaire dirt depreciation values for the ambient categories against cleaning intervals. Regular luminaire cleaning will contribute to higher illuminance on the road surface.

Given the above parameters and maintenance methods and by using known unit costs, the annualized and/or DTCs of alternative lighting systems can be calculated.

DISCOUNTED TOTAL COST

The following formulas describe the discounted total cost method (5). The general formula is

$$DTC = C_0 + \sum_{i=1}^{n} C_i/(1+r)^i \qquad (1)$$

where

DTC = discounted total cost,
C_0 = initial cost,
C_i = cost in year i,
r = discount rate, and
n = analysis period (years).

When constant dollars are used, DTC is the economic value of future expenditures expressed as if spent today. Since there is a benefit to delaying costs, future costs are discounted in computing their "present value".

The use of inflated dollars will also capture the relative resource value of alternative investments; DTC will approximate present value, depending on the discount rate used. If inflation is used, it must be included in all of the cost elements. If inflation is not used, the models revert to traditional constant dollar comparisons.

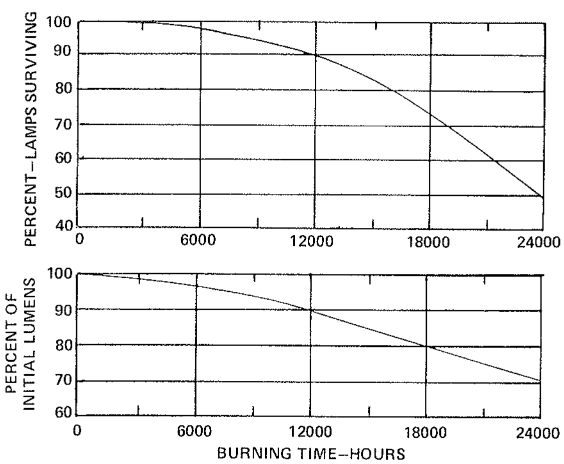
By using the general framework above, the following highway and street-lighting specific formula is presented:

$$DTC = [1000B_1(C_1 + C_4 + C_{11})/B_2 + 1000(C_2 + C_3)/B_2 + C_5 + C_6]$$
$$+ \sum_{i=1}^{n} [1/(1+r)^i](1+I_1)^i (B_1 B_3/B_2)(T_6 \cdot C_7 + 12C_8)$$
$$+ \sum_{i=1}^{n} [1/(1+r)^i] C_{10}(1+I_3)^i$$
$$+ \sum_{i=1}^{n} [1/(1+r)^i] B_{4i} [C_4(1+I_2)^i + C_9 \cdot T_4 (1+I_3)^i]$$
$$+ \sum_{\alpha=1}^{\alpha=n/T_1} [1000B_1/(1+r)^{\alpha T_1} B_2] [C_4(1+I_2)^{\alpha T_1} + C_9 \cdot T_3 (1+I_3)^{\alpha T_1}]$$
$$+ \sum_{\alpha=1}^{\alpha=n/T_2} [1000B_1/(1+r)^{\alpha T_2} B_2] [C_9 \cdot T_5 (1+I_3)^{\alpha T_2}] \qquad (2)$$

where

- DTC = discounted total cost per kilometer of roadway;
- B_1 = number of luminaires per pole;
- B_2 = pole spacing (m);
- B_3 = lamp wattage;
- B_{4i} = number of burnt-out lamps per kilometer in year i for annual spot-relamping purposes;
- C_1 = cost of one luminaire;
- C_2 = cost of one pole;
- C_3 = cost of one foundation;
- C_4 = cost of one lamp;
- C_5 = cost of equipment, wire, switching, and so forth per kilometer of roadway;
- C_6 = total initial labor cost per kilometer of roadway;
- C_7 = energy cost per kilowatt hour;
- C_8 = demand charge per kilowatt per month;
- C_9 = cost of labor and vehicle per hour;
- C_{10} = miscellaneous maintenance cost per kilometer of roadway per year;
- C_{11} = cost of one bracket;
- T_1 = relamping period (years);
- T_2 = cleaning period (years);
- T_3 = relamping time per luminaire (h);
- T_4 = spot-relamping time (h);
- T_5 = cleaning time per luminaire (h);
- T_6 = hours of operation per year;
- I_1 = expected annual rate of inflation for electricity rates;
- I_2 = expected annual rate of inflation for lamps or materials;
- I_3 = expected annual rate of inflation for maintenance labor;
- r = discount rate; and
- n = investment life (years).

Figure 1. Examples of lamp lumen depreciation curve and lamp mortality curve (250-W Lumalux).



The above formula represents the discounted total cost per kilometer of roadway, which is the initial cost plus discounted total energy costs and the remaining operating costs throughout the investment life n, usually 20 years.

The initial cost includes materials and labor for installation of foundations, poles, brackets, lamps, luminaires, switchings, wirings, equipment, and so forth. Operating cost is cost incurred for energy and

Table 1. Luminaire dirt depreciation values for ambient categories against cleaning intervals.

Luminaire Category	Ambient Category	Cleaning Interval (years) 1	2	3	4	5	6	7
1 (open)	1	0.95	0.90	0.81	0.64	0.48	0.39	0.33
	2	0.89	0.80	0.64	0.40	0.29	0.19	0.13
	4	0.78	0.63	0.40	0.19	0.10	0.07	0.05
	8	0.55	0.37	0.18	0.06	0.04	0.03	0.02
	16	0.32	0.16	0.05	0.02	0.02	0.01	0.01
2 (ventilated)	1	0.97	0.94	0.89	0.79	0.70	0.62	0.53
	2	0.92	0.88	0.80	0.63	0.47	0.38	0.32
	4	0.86	0.78	0.62	0.39	0.28	0.19	0.13
	8	0.73	0.58	0.38	0.18	0.09	0.06	0.04
	16	0.50	0.32	0.16	0.05	0.03	0.02	0.02
3 (semi-sealed)	1	0.97	0.94	0.91	0.83	0.76	0.69	0.62
	2	0.93	0.90	0.83	0.71	0.58	0.46	0.39
	4	0.87	0.81	0.70	0.47	0.35	0.27	0.20
	8	0.76	0.65	0.44	0.26	0.15	0.09	0.06
	16	0.56	0.38	0.23	0.08	0.05	0.03	0.02
4 (tightly sealed)	1	0.98	0.96	0.95	0.91	0.87	0.83	0.80
	2	0.95	0.94	0.91	0.85	0.80	0.75	0.70
	4	0.91	0.89	0.84	0.75	0.67	0.58	0.50
	8	0.83	0.79	0.72	0.57	0.42	0.35	0.29
	16	0.67	0.61	0.49	0.31	0.22	0.15	0.10

maintenance. Maintenance includes materials and labor for spot and group relamping, cleaning, and miscellaneous repairs for items other than lamps. Pole repairs or replacement would be a function of the accident rate. For simplicity, only the labor inflation rate I_3 is included in miscellaneous maintenance C_{10}.

The number of burnt-out lamps in any given year is given by the lamp mortality curve of the particular type of lamp. Spot relamping requires a cumulative function within a group-relamping period to allow for the probability of the replaced lamps themselves burning out. Then the same cycle is repeated for the next group-relamping period.

Demand charge per kilowatt per month depends on the total demand of wattage per month in a certain area. For example, an area may require an estimated consumption of 100 MW energy per month; the power company must make that amount available monthly. The cost incurred for mobilization of equipment, labor, installation, and other operations varies according to the wattage requirements.

ANNUAL EQUIVALENT COST

The annual equivalent cost method uses the capital recovery factor to annualize initial costs (6, 7). This annualized initial cost, added to the annual operating cost, is the AEC for that particular year. The general formula is as follows:

$$AEC = C_0 \cdot CRF + C_a \quad (3)$$

where

$CRF = [r(1 + r)^n]/[(1 + r)^n - 1]$,
CRF = capital recovery factor,
n = investment life (years),
AEC = annual equivalent cost,
C_o = initial capital cost, and
C_a = annual operating cost for the reviewed year.

$C_o \cdot CRF$ gives the annualized initial cost that is fixed for every year of investment life. It is also known as the annual fixed charges for the initial cost. Annual operating cost C_a varies from year to year, depending on the actual cost incurred for the year in review. The initial annual operating cost is usually known at the time of investment and will be assigned to C_a. For the following years, an assumed annual inflation rate I is used to reasonably predict the annual operating costs. Applying I to C_a, Equation 3 becomes

$$AEC_y = C_o \cdot CRF + C_a (1 + I)^Y \quad (4)$$

where

I = general annual inflation rate;
y = year in review, $1, 2, \ldots n$; and
AEC_y = inflated annual equivalent cost at year y.

The other notations are as previously defined. However, this general inflated annual equivalent cost (given in Equation 4) does not distinguish differing rates of inflation for the factors of cost.

By adapting Equation 4 specifically to highway and street lighting and considering the different annual inflation rates for energy, lamps, materials, and maintenance labor, the following formula results:

$$\begin{aligned} AEC_y = {} & [1000 B_1 (C_1 + C_4 + C_{11})/B_2 + 1000 (C_2 + C_3)/B_2 + C_5 + C_6] \\ & \times [r(1+r)^n]/[(1+r)^n - 1] \\ & + [B_1 \cdot B_3 (T_6 \cdot C_7 + 12 C_8)/B_2] (1 + I_1)^y + C_{10} (1 + I_3)^y \\ & + B_{4a} [C_4 (1 + I_2)^y + C_9 \cdot T_4 (1 + I_3)^y] \\ & + (1000 B_1/B_2) [C_4 (1 + I_2)^y + C_9 \cdot T_3 (1 + I_3)^y]/T_1 \\ & + (1000 B_1/B_2) [C_9 \cdot T_5 (1 + I_3)^y]/T_1 \end{aligned} \quad (5)$$

where

$B_{4a} = (B_{41} + B_{42} + B_{43} + \ldots + B_{4T_1})/T_1$, and
$B_{41} \ldots B_{4T_1}$ = numbers of burnt-out lamps in year 1, 2 ... T_1.

If the group-relamping period T_1 = 4 years (which is usually so), $B_{4a} = (B_{41} + B_{42} + B_{43} + \ldots + B_{4T_1})/T_1$ becomes $B_{4a} = (B_{41} + B_{42} + B_{43} + B_{44})/4$.

The value B_{4a} is the average annualized number of burnt-out lamps per kilometer in a relamping period T_1. This number is assumed to be a fixed number of burnt-out lamps for each year of the relamping period. Since the pattern of lamp burnouts is the same for the following periods, it is also fixed for each year throughout the investment life.

Costs for group relamping and cleaning must also be annualized. The assumed cost of lamps and labor at the time of investment is averaged throughout the relamping period T_1. (See the last two factors of Equation 5.)

The value y can be chosen for any future year to test the effect of inflation on annual total cost.

COMPUTER PROGRAM

A computer program (Illum III) has been developed for use by the highway and street-lighting design engineer and may be used independently or in conjunction with Illum I and II. The Illum I program contains calculations of illuminance, luminance, and glare. The Illum II program is for preliminary analysis for efficient roadway lighting design. The overall program is called the Illumination Design Systems Program. By inputting the design and cost parameters, the user will be able to compare the cost-effectiveness of alternative designs and to test the sensitivity of the result under various assumptions with regard to inflation.

The Illum III program is in conversational mode and includes both DTC and AEC. It calculates the annual equivalent cost, computed at 10, 15, and 20 years. It is available on request for a nominal charge. A manual example problem for the DTC and AEC formulas is presented in the next section of this paper.

EXAMPLE PROBLEM

The example problem that follows for discounted total cost and annual equivalent cost formulas uses metric units and manual calculations. The problem illustrates the practical use of the formulas to determine current and future costs.

The input figures in this example problem have been chosen to be as close as possible to typical values. They are listed as follows:

B_1 = 2,
B_2 = 53.34 m (175 ft),
B_3 = 250 W high-pressure sodium,
B_{41} = 0.375,
B_{42} = 1.500,
B_{43} = 1.875,
B_{44} = 3.750 (see explanation below for B_{41} to B_{44}),
C_1 = \$150,
C_2 = \$300,
C_3 = \$100,
C_4 = \$30,

C_5 = \$15 000,
C_6 = \$750,
C_7 = \$0.025,
C_8 = \$2.50,
C_9 = \$30,
C_{10} = \$350,
C_{11} = \$50,
T_1 = 4 years,
T_2 = 4 years,
T_3 = 1 h,
T_4 = 1 h,
T_5 = 0.50 h,
T_6 = 4000 h,
I_1 = 10 percent = 0.10,
I_2 = 8 percent = 0.08,
I_3 = 6 percent = 0.06,
r = 8 percent = 0.08, and
n = 20 years.

The above input figures are valid only for the reviewed system. These figures may vary with the size of the system.

Refer to Figure 1. The curves shown are for typical 250-W high-pressure sodium lamps. The group-relamping period for 250-W high-pressure sodium lamps is 16 000 h. At this point, the lamp lumen output has decreased to 85 percent of the initial lumens. After the first year, or 4000 h of operating time, the lamp mortality is 1 percent. Thus, $B_{41} = 0.01 \times 1000 \times B_1/B_2$. Values of B_1 and B_2 are 2 and 53.34, respectively. Therefore, $B_{41} = 0.01 \times 1000 \times 2/53.34 = 0.375$. This real number is the average number per kilometer of burnt-out lamps in the first year of the whole system in review. For example, the number of burnt-out lamps in a 16-km (10-mile) highway system during the first year is $B_{41} = 0.01 \times 1000 \times 2 \times 16/53.34 = 6$. The average number of burnt-out lamps per kilometer is $6/16 = 0.375$.

By using the preceding mathematical procedure and by inputting a lamp mortality of 4, 5, and 10 percent for the second, third, and fourth years, respectively, the B_{42}, B_{43}, and B_{44} values are calculated and quoted in the input figures. Values of B_{41} to B_{44} are repeated for every four-year relamping cycle—that is, when i = 5, $B_{4i} = B_{41}$; when i = 6, $B_{4i} = B_{42}$; and so on.

In this example, the probability of the new spot-replaced lamps burning out is neglected because they are quantitatively insignificant in comparison to the number of burnt-out lamps of the originally installed or group-installed lamps. However, if desired, they can be included in the calculation.

By using the input figures, DTC and AEC can be calculated from Equations 2 and 5, respectively, as follows:

$$\begin{aligned} DTC = {} & [1000 \times 2(150 + 30 + 50)/53.34 + 1000\,(300 + 100)/53.34 + 15000 + 750] \\ & + \sum_{i=1}^{20} (1/1.08^i)\,(1.1)^i\,(2 \times 250/53.34)\,(4000 \times 0.025 + 12 \times 2.50) \\ & + \sum_{i=1}^{20} (1/1.08^i)\; 350(1.06)^i \\ & + \sum_{i=1}^{20} (1/1.08^i)\, B_{4i}\,[30(1.08)^i + 30 \times 1(1.06)^i] \\ & + \sum_{a=1}^{a=5} (1000 \times 2/(1.08)^{4a} \times 53.34)\,[30(1.08)^{4a} + 30 \times 1(1.06)^{4a}] \\ & + \sum_{a=1}^{a=5} (1000 \times 2/(1.08)^{4a} \times 53.34)\,[30 \times 0.50 \times (1.06)^{4a}] \qquad (6) \end{aligned}$$

Substituting values of B_{4i} according to the number of years i and the calculated factors results in DTC = 31 872.98 + 29 716.38 + 5784.80 + 2042.73 + 10 142.86 + 2259.28 = 81 819.03. Thus, the discounted total cost is \$81 819.03/km.

$$\begin{aligned} AEC_y = {} & [1000 \times 2 \times (150 + 30 + 50)/53.34 + 1000(300 + 100)/53.34 + 15\,000 + 750]\,(0.08 \times 1.08^{20})/(1.08^{20}-1) + \\ & [2 \times 250/53.34)\,(4000 \times 0.025 + 12 \times 2.50]\,1.1^y + \\ & 350 \times 1.06^y + 1.875\,(30 \times 1.08^y + 30 \times 1 \times 1.06^y) + \\ & (1000 \times 2/53.34)\,(30 \times 1.08^y + 30 \times 1 \times 1.06^y)/4 + \\ & (1000 \times 2/53.34)\,(30 \times 0.50 \times 1.06^y)/4 \end{aligned}$$

$$AEC_y = 3246.54 + 1218.60\,(1.1)^y + 912.43\,(1.06)^y + 337.46\,(1.08)^y.$$

Substituting number of years in review gives annual equivalent cost for that year. Following are the annual equivalent costs for years 10, 15, and 20, respectively:

$$AEC_{10} = 3246.54 + 1218.60\,(1.1)^{10} + 912.43\,(1.06)^{10} + 337.46(1.08)^{10} = 3246.54 + 3160.73 + 1634.02 + 728.55 = 8769.84$$

$$AEC_{15} = 3246.54 + 1218.60\,(1.1)^{15} + 912.43\,(1.06)^{15} + 337.46(1.08)^{15} = 3246.54 + 5090.39 + 2186.69 + 1070.48 - 11\,594.10$$

$$AEC_{20} = 3246.54 + 1218.60\,(1.1)^{20} + 912.43\,(1.06)^{20} + 337.46(1.08)^{20} = 3246.54 + 8198.13 + 2926.29 + 1572.89 = 15\,943.85$$

The annual equivalent costs for years 10, 15, and 20 are \$8769.84, \$11 594.10, and \$15 943.85, respectively.

CONCLUSION

This paper has addressed the question of how to treat lighting-system cost components that are subject to varying inflation rates. A computer program has been developed that is generally applicable, with or without inflation, and DTC and AEC models offer the lighting design engineer the opportunity to include unadjusted projected inflation in a system-cost calculation. As with most models, their usefulness is only as good as the quality of engineering and economic data used. Although the reliability of economic predictions of inflation is open to question, the computer model allows the user to test for the sensitivity of a wide range of possible inflation rates and mixes of costs.

This paper addressed the straightforward world of equal system benefits, but additional research is required to develop models for the economic comparison of lighting systems that yield differing levels of service.

ACKNOWLEDGMENT

We wish to thank the following for their contributions to this paper: P. Mok, Computer Systems Branch, and A. Maghsoudi, Highway Wayside Equipment Research Section, for developing the computer program mentioned in this paper; V. McCullough and F. Tung, Electrical Design Section, for their constructive comments and criticism on aspects of lighting engineering; F. W. Jung, Program Manager, Highway Wayside Equipment Research Section, for his time, valuable comments, and guidance that made the writing of this paper possible; M. Hastay, Department of Economics, Washington State University, for discussion and insights on theoretical aspects of the economic models; and GTE Sylvania, Rexdale, Ontario, for permission to reproduce the lamp curve shown in Figure 1. While we acknowledge the valuable assistance of these individuals and GTE Sylvania, any errors and omissions are our sole responsibility.

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Publication of this paper sponsored by Committee on Visibility.

Abridgment

Test of 400-W High-Pressure Sodium Vapor Lighting

Michael C. Belangie, Research and Development Unit, Utah Department of Transportation, Salt Lake City

At present, 400-W high-pressure sodium vapor (HPS) lamps are advertised as having an average life expectancy of 24 000 h, the equivalent of six years of operation. The cost in labor and equipment to replace a single lamp in Utah is about 90 percent of the initial cost of a 400-W HPS lamp.

Since both lamp and maintenance costs are rising rapidly, inferior lamp performance will place an unnecessary, unprogrammed cost on lighting maintenance programs. The results of this test indicate that manufacturer-supplied lamp mortality data should not be considered reliable (performances of between 35 percent and 50 percent were typical). These findings strongly suggest that users should develop and implement contractual mechanisms for enforcing performance specifications in regard to the advertised life of the lamp.

QUALIFICATIONS ON THE USE OF THIS REPORT

Substantial technological modifications have occurred since these lamps were manufactured. Therefore, the lamp mortality data described here are only applicable to the lamps and fixtures available from the manufacturers in late 1971 and early 1972 and in the lamp-and-fixture combinations used in this test. The direct application of these findings to lamps and fixtures currently being manufactured is therefore strongly discouraged.

However, until the manufacturers can unequivocally demonstrate that their products will perform as advertised, the user is fully justified in assuming that manufacturer-supplied lamp mortality data may be questionable.

BACKGROUND

HPS lighting was first used in Utah in 1968. During that year, contracts were let for more than 1400 lighting units; these were the initial elements in an installation that would number more than 6600 operational luminaires by 1977.

In 1977, 81 percent (5533 luminaires) of this system was composed of 400-W HPS units; the remainder of the system was composed of 250-W HPS (13 percent) lamps and either 400-W or 250-W mercury vapor units (6 percent). Since 1968, the advertised average life expectancy of the 400-W HPS lamp has increased from 6000 h (1.5 years) to 15 000 h (3.75 years) in 1971 and, most recently, in 1976 to 24 000 h (6 years).

In 1971, substantial concern over the costs resulting from the terms of utility maintenance agreements had surfaced within the Utah Department of Highways. The lack of hard data on the validity of the advertised increases in lamp life compounded the problem. This study was initiated to address both problems.

FINDINGS

Four test groups of 12 luminaires each were operated on a 10-h on, 2-h off continuous cycle for two years (14 360 h of operation) (1). Replacement of burnouts occurred during the first year of operation only. Figure 1 depicts the performance of each test group. Performance of each group has been divided into three categories:

1. Original: performance of the initial 12 operating lamps;
2. Original and replacement: performance of the original 12 operating lamps plus any replacements made during the course of the test;
3. Original, replacement, and infant: performance of the original 12 operating lamps plus any replacements, including lamps that burned out the first time they were energized (infant mortality).

Only one test group (Lamp B in Fixture X) performed without a single failure during the two-year test. The other three test groups all had failures. Lamp A in Fixture W had 9, 5 of which occurred in the first year and were replaced. Lamp D in Fixture Z had 12 failures, 4 of which occurred in the first year and were replaced. Lamp C in Fixture Y had 15 failures in the first year