ANALYSIS AND DESIGN PROCEDURES FOR THE PENNSYLVANIA HIGHWAY LIGHTING NEEDS STUDY

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A highway lighting needs study was conducted to determine the financial implications of bringing Pennsylvania's highway lighting into compliance with the federal requirements resulting from the Highway Safety Act of 1966. The study involved the collection and analysis of data taken at a sample of more than 1,200 sites from the population of 4,591 sites that require lighting under the federal standards. Procedures were developed to facilitate the rapid design of lighting where none existed, the evaluation of lighting at existing installations, and the redesign of existing inadequate installations. Installation, maintenance, and energizing costs were then estimated. The techniques developed for the study are presented and discussed in terms of their value to the project. Applications of the design and analysis are then discussed in terms of their potential for time savings in preliminary design and cost estimation for highway lighting installations.

•THE FEDERAL Highway Safety Act of 1966 (1) called for the establishment of standards for highway lighting in recognition of the significance of highway lighting for the safety and operational efficiency of certain design elements of highways. The lighting warrants subsequently developed (2, 3) essentially require that adequate lighting be provided at all interchanges on expressways, at intersections of arterial streets in urban and suburban areas, at tunnels and long underpasses, and at all locations where accident records indicate a high incidence of nighttime accidents. Each state was required to prepare a plan that would ensure the lighting of such sites to avoid a reduction of federal-aid highway funds. To obtain the information necessary to develop a highway lighting plan, the Pennsylvania Department of Transportation commissioned the Pennsylvania Transportation and Traffic Safety Center of the Pennsylvania State University to conduct a study of lighting needs.

The purposes of the study were to determine the extent of highway lighting needs as defined by the federal warrants and to estimate the financial consequences of compliance with these standards. State highway lighting specifications were to be applied to the design and evaluation of sites that met federal warrants for lighting. The study was completed in December 1970 (4).

Initial phases of the project indicated that more than 4,500 sites within the commonwealth met federal warrants for lighting. Because time and budget constraints precluded the possibility of a complete investigation of all sites, a sampling procedure was developed to provide data from which adequate estimates of statewide lighting needs could be made. Data were subsequently collected for 1,236 sites from the total population of 4,591 sites. At each site within the sample, it was necessary to design lighting where none existed, to evaluate the adequacy of existing installations, and to redesign existing inadequate installations so that installation, maintenance, and energizing cost estimates could be made. Because of the number of sites involved, procedures had to be developed to facilitate the rapid determination of lighting needs at each of the 1,236 sampled sites.

The purpose of this paper is to describe the analysis and design procedures used to determine Pennsylvania's highway lighting needs. Emphasis is placed on the application of the techniques to the highway lighting needs study (3). However, the procedures appear to have applications beyond the specific requirements of the study. The possible uses of the procedures and their potential for saving time and effort are discussed in the conclusions.

LIGHTING SPECIFICATIONS

Specifications for highway lighting in Pennsylvania (5) require a minimum average horizontal illumination of 0.8 footcandle at the pavement surface and a uniformity ratio of not more than 6 to 1 in any case and not less than 4 to 1 when obtainable within the 0.8 minimum footcandle illumination requirement. In definitional matters, the Pennsylvania specifications follow those developed by the Illuminating Engineering Society (6). Methods and procedures prescribed by the Illuminating Engineering Society are to be used to calculate average illumination and uniformity ratios. Pennsylvania specifications further state that standard design will consist of 400-W clear, color improved, or white mercury vapor lamps utilizing luminaires with type 2 or type 3 distributions mounted at no less than 30 ft. All nonstandard equipment must meet the average illumination and uniformity ratio requirements to be approved.

It was decided for purposes of this study to use standard 400-W luminaires mounted at 30 ft for lighting unlighted sites. Existing lighting facilities that utilized 175-, 250-, 400-, 700-, or 1,000-W mercury vapor lamps were to be accepted if they met average illumination and uniformity ratio specifications. Discussions with informed sources during the data collection effort indicated that there were few if any 250- or 700-W lamps in use in the commonwealth. Based on this information and the fact that most existing 250- and 700-W installations could be changed to 400- and 1,000-W installations respectively with very minor modifications, these 2 lamp wattages were excluded from further consideration. All other luminaire types were to be deemed inadequate except for fluorescent luminaries in tunnels or long underpasses. These assumptions formed the basis for development of the analytical procedures.

DATA

The data required to meet the objectives of the study consisted of 2 basic groups: cost data and data collected at sites. The cost data included installation, maintenance, and energizing costs. Installation costs were obtained from bid prices on contracts throughout the commonwealth. Approximately 150 cost components were tabulated by geographic area. Maintenance costs were obtained from contracts with companies providing highway lighting maintenance, including utility companies. Energizing costs were obtained from utility companies.

Data regarding the sites that met federal lighting warrants were collected from representatives of the Pennsylvania Department of Transportation and were supplemented with on-site investigations where "as-built" plans were not available. Programmed projects to be built before 1975 that met warrants for lighting were also included in the study. The data included the site location, the pavement dimensions to be lighted, and the quantity of existing lighting equipment at the site. If lighting was present, further information was recorded regarding the equipment type and placement, the mounting heights of luminaires, and the overhang of the luminaire beyond the pavement edge. A sketch of the layout was made with the luminaire locations and distances indicated where necessary for understanding of the configuration.

The 2 groups of data formed the basis of the analysis. It was necessary to evaluate the site data to determine the costs for installation, maintenance, and energizing that would be incurred in the process of compliance with federal standards and state lighting specifications. Estimates of statewide costs could be made for the entire population of such sites when the analysis of the sampled sites was completed.

DATA ANALYSIS

Because of the large number of sites that had to be examined, it was not practical to apply the raw cost data collected to each site. A simple technique had to be developed that would give fairly accurate results. It was found that installation costs could be estimated adequately by the following formula:

$$I = aX_1 + bX_2 + X_3 \quad (1)$$

where

I = total installation cost,
X_1 = cost per luminaire (including all cost elements that vary directly with the number of luminaires),
X_2 = cost per linear foot (including all cost elements that vary directly with site dimensions),
X_3 = lump-sum cost per installation (including all items that are independent of the size of the installation),
a = number of luminaires in a given design, and
b = total linear feet of roadway in a given design.

The values of X_1, X_2, and X_3 were found to vary somewhat with geographic location; X_1 decreased in large urban areas, and X_2 and X_3 increased in such areas. X_1 was also dependent on the lamp wattage. Maintenance costs were difficult to determine because of the varying policies regarding contracts and maintenance practices. A statewide average was finally decided on depending only on lamp wattage. Energizing costs were determined by calculating the power consumption of an installation (assuming certain system power losses) and a burning time of 4,100 hours/year.

Procedures for evaluating the site data were developed to provide inputs for the cost equations. Each site was examined first to determine whether it was lighted. If it was not lighted, lighting was designed for the installation. If it was lighted, the adequacy of the installation was determined. At inadequately lighted locations, a redesign was made that used as much of the existing equipment as possible. Installation costs were determined for designed and redesigned locations. Maintenance and energizing costs were then calculated for all sites. Figure 1 shows a flow diagram of this process.

The first decision could be made directly from information contained on the data sheets. The next step involved either the design or evaluation of lighting. These tasks and the redesign of inadequate existing installations were performed with a series of lighting design curves.

Lighting Design Curves

Average horizontal footcandles at the pavement surface are a function of lamp wattage, mounting height, luminaire spacing, pavement width, luminaire overhang, and other variables associated with the type of luminaire employed. The formula is

$$FC = (L \times U \times M)/(W \times S) \quad (2)$$

where

FC = average maintained footcandles;
L = end-of-life vertical lumens;
U = utilization factor (a function of mounting height, roadway width, and overhang);
M = maintenance factor to account for dirt accumulation on the luminaire (0.8 by Pennsylvania specifications);
W = roadway width to be lighted, in ft; and
S = luminaire spacing, in ft.

This formula suggests that, for a given wattage, mounting height and average footcandle illumination (and assuming a zero overhang), a graph can be plotted of maximum pole spacing versus roadway width. Such a graph should be a hyperbola because of the inverse relation between pavement width and pole spacing.

A further examination of the recommendations of the Illuminating Engineering Society indicates that type 2 light distributions should be used only up to pavement widths of 1.75 times the luminaire mounting height. From 1.75 to 2.75 times the mounting height, type 3 light distributions should be used. This information can also be easily represented on a graph of maximum luminaire spacing versus roadway width for the conditions specified above.

The only remaining problem involves the effect of the uniformity ratio specification on the maximum allowable luminaire spacing. The effect cannot be determined by direct examination because the uniformity ratio must be calculated from isofootcandle diagrams. Isofootcandle diagrams are produced by manufacturers of specific equipment types and are developed according to procedures suggested by the Illuminating Engineering Society. Thus, any design curves developed from such data must be specific for that piece of equipment. The photometric data used to develop the curves for this study came from one manufacturer.

After several manual calculations were made to try to isolate the effect of the uniformity ratio on luminaire pole spacing, it was determined that the uniformity specifications controlled maximum spacing only for narrow pavement widths. The maximum uniformity (6 to 1) was always the controlling factor. In cases where the uniformity ratio was lower than 4 to 1, it was impossible to increase the ratio and still remain within the 0.8 minimum average footcandle requirement.

Calculations of the maximum spacing for a group of different luminaire wattages and mounting heights were made. A pavement width of 20 ft (30 ft for 1,000-W luminaires) was used as the minimum width to be considered. If the uniformity ratio governed the spacing of the minimum width, a trial-and-error procedure was followed to find the point where the minimum average illumination became the controlling factor. The next point checked was for a pavement width 1.75 times the mounting height, the point past which type 3 luminaires were required and behind which type 2 luminaires would be used. The last point used in development of the graph was one for which the pavement width was 2.75 times the mounting height, the maximum allowable pavement width for type 3 light distributions. The 3 or 4 points calculated were then plotted on the graphs with straight lines drawn between points as shown in Figures 2, 3, and 4.

As indicated earlier, one would expect the curves to be hyperbolic in shape. It was, therefore, necessary to test the accuracy of the linearity assumption. Between every pair of points used for producing the design curves, a check was made between the pole spacing predicted by the graph and a calculated pole spacing. Table 1 gives the results of this check. The maximum error was 4.17 percent with an average error of 1.06 percent. This was felt to be well within the desired accuracy for this study. It should be pointed out, however, that greater accuracy could have been obtained had more points been calculated for the graph. Another check was made to determine the difference in the pole spacing resulting from using another manufacturer's photometric data. The differences between the 2 sets of calculations were insignificant and could be attributed to the uncertainty of readings for the utilization factor. Thus, the design curves were accepted as valid for estimating the pole spacing required for lighting pavement areas of various widths.

It should be reiterated at this point that the lighting design curves were developed for the specific set of conditions listed below:

1. A minimum average maintained horizontal illumination of 0.8 footcandle;
2. A maximum uniformity ratio of 6 to 1 and a minimum of 4 to 1;
3. Medium, semi-cutoff, type 2 and type 3 clear mercury vapor lamps; and
4. A zero overhang of luminaire from the curb face.

The zero overhang assumption was used because it was found that a positive overhang (i.e., the luminaire is over the roadway) can be corrected for by the assumption that the pavement width is to be reduced by the amount of overhang with little loss of accuracy. Negative overhangs can be corrected for by adding the overhang to the pavement width. Other lighting specifications or equipment types would result in different lighting design curves.

Lighting Design for Unlighted Sites

For unlighted sites, the design curve for 400-W luminaires mounted at 30 ft was used. For interchanges, the lighting design curves were used to determine the number

Figure 1. Flow diagram of site data analysis.

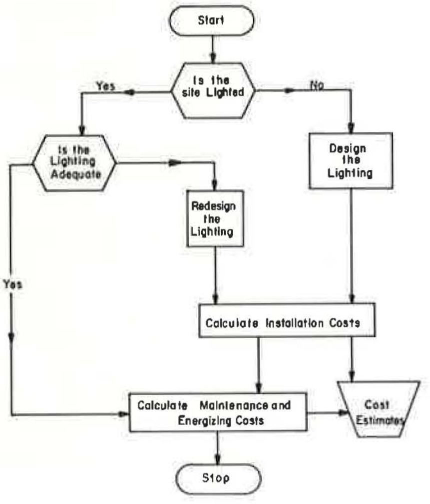


Figure 2. Design curves for 175-W luminaires.

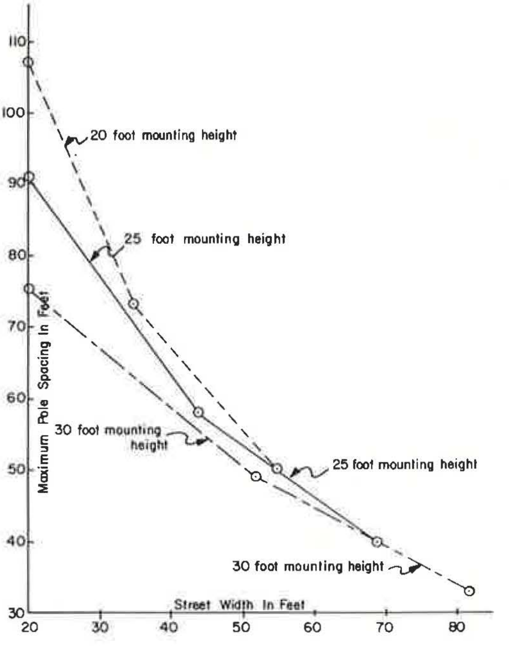


Figure 3. Design curves for 400-W luminaires.

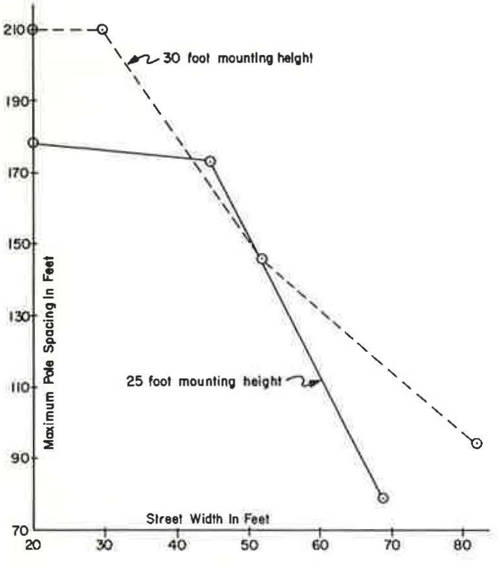
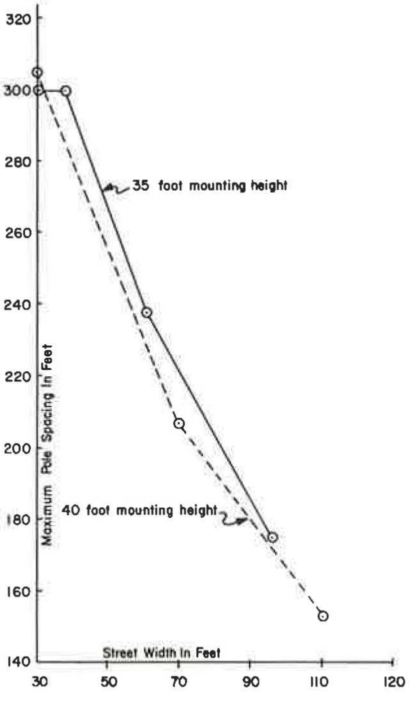


Figure 4. Design curves for 1,000-W luminaires.



of luminaires necessary to light the various lengths of different pavement widths. The total number of luminaires and the linear feet of roadway to be lighted were recorded. Ramps with widths of less than 20 ft were considered to be 20 ft wide. When medians were wider than 20 ft, the lighting was provided separately for each direction of traffic through the interchange area. High night accident sites (i.e., locations where accident records indicated a high incidence of nighttime accidents) were handled in a similar fashion.

Intersections posed a slightly different problem. Specifications suggest that the intersection area itself should be lighted, but they do not indicate how much beyond the intersection boundaries the lighting should extend. For this study, it was decided to light the intersection 5 ft beyond each of the boundaries. Thus, for a 24- by 24-ft intersection, two 24-ft pavement widths would be lighted for a distance of 34 ft. Notice that this procedure provides twice the lighting in the intersection area and follows recommendations by the Illuminating Engineering Society. The lighting design curves were used to determine the number of luminaires necessary to light intersections according to the indicated procedure. The routine nature of the design of lighting at unlighted locations allowed the analysis to be computerized. Nearly all new lighting designs were made with the computer and with the procedures developed; however, designs for tunnels and long underpasses had to be carried out on a site-by-site basis because of their unique characteristics.

Checking the Adequacy of Existing Installations

Data on existing lighting included the location of luminaires, the overhang, the pole spacing, and the luminaire type. As previously indicated, if the luminaires provided were not mercury vapor, they were considered inadequate. Mercury vapor luminaires were considered inadequate if not mounted high enough. The minimum allowable heights used in this study were 20 ft for 175-W lamps, 25 ft for 400-W lamps, and 35 ft for 1,000-W lamps.

From the data on luminaire type, mounting height, and pavement width, the maximum pole spacing was found from the design lighting curves. If the pole spacing measured in the field was less than, or equal to, the design pole spacing, the site was considered adequately lighted. The number and wattage of the existing luminaires were recorded for later use. If the pole spacing was greater than the maximum allowable, the sites were placed in the group of inadequately lighted locations. Tunnels and long underpasses had to be examined site by site because of the lack of height within the structure to provide a luminaire mounting height of more than 18 ft.

Redesign of Inadequately Lighted Sites

The redesign of inadequately lighted sites required a further categorization of what the redesign involved. Each redesign was placed in 1 of the following 5 categories:

1. New poles and luminaries added to existing installation,
2. Existing luminaries replaced on existing poles,
3. A combination of 1 and 2,
4. Redesign based on partial salvage, and
5. Redesign based on no salvage.

Figures 5, 6, 7, 8, and 9 show examples of the redesign process. The average spacing calculations shown were multiplied by the number of luminaires to indicate the length of roadway involved in the installation.

Figure 5 shows the addition of a luminaire to light the 20-ft legs of the intersection. Figure 6 shows the replacement of nonstandard luminaires with standard luminaires. Figure 7 shows a site where one of the existing luminaries is replaced on the existing pole. The partial salvage category is shown in Figure 8 where 2 of the existing poles were used to mount standard luminaires and a new luminaire was added to light the north-south legs of the intersection. Five existing poles were removed by this redesign. A site was placed in category 5, shown in Figure 9, only when luminaires were mounted at less than 20 ft or when the luminary was gas or fluorescent or when it was a

Table 1. Calculated and graphically determined maximum luminaire spacings.

Lamp Wattage	Mounting Height	Roadway Width	Graph Predicted	Calculated	Error[a] Amount	Error[a] Percent
175	20	30	84	84	0	0
175	20	45	61	59	+2	+3.39
175	25	30	77	76	+1	+1.32
175	25	55	50	48	+2	+4.17
175	30	35	63	65	-2	-3.08
175	30	60	45	44	+1	+2.27
400	25	40	174	169	+5	+2.96
400	25	55	131	131	0	0
400	30	33	201	199	+2	+1.00
400	30	40	181	176	+5	+2.84
400	30	65	124	124	0	0
1,000	35	45	280	280	0	0
1,000	35	75	212	214	-2	-0.93
1,000	40	55	243	236	+7	+2.97
1,000	40	85	187	189	-2	-1.06

[a]Average = +1.06 percent; maximum = +4.17 percent.

Figure 5. Lighting design for case 1.

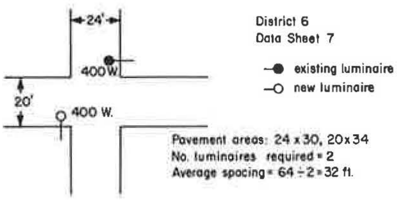


Figure 6. Lighting design for case 2.

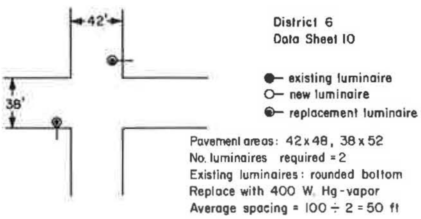


Figure 7. Lighting design for case 3.

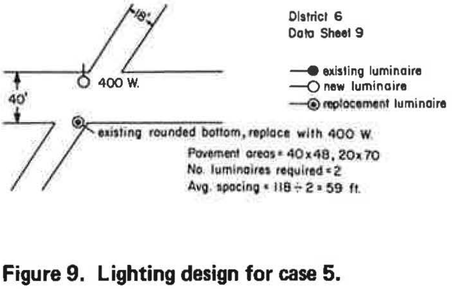


Figure 8. Lighting design for case 4.

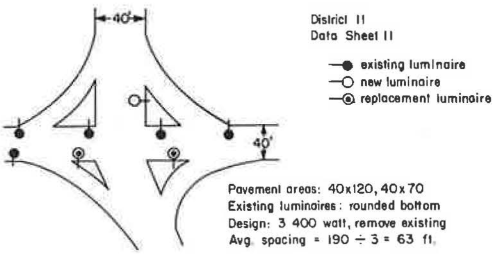
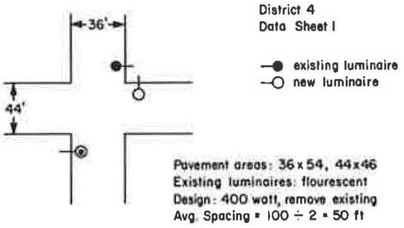


Figure 9. Lighting design for case 5.



nonstandard fixture type. In all other situations, at least 1 pole could be utilized in the new design.

For each of the redesign locations, the number of new luminaires, old luminaires, lamp wattage, and linear feet of the installation were recorded. All sites that were redesigned plus all sites that had no existing lighting were then examined to determine installation costs.

Installation Costs

Installation costs for sites with no existing lighting were calculated with Eq. 1. Previous steps in the analysis had determined the wattage and number of luminaires required for adequate lighting and the linear feet of roadway involved in the site; the geographic location was known from the data collection sheets. Thus, application of Eq. 1 was simply a "plug-in" process. For inadequately lighted locations (category 5, complete redesign, no salvage), the same process was followed. Costs for removing existing equipment were assumed to be covered by the scrap value of that equipment.

Costs for redesigned locations requiring the addition of luminaires to the existing equipment were calculated with a modified version of Eq. 1. Costs per luminaire and cost per linear foot were left unchanged, but the lump sum cost was prorated by the ratio of the new to the total luminaires. The resulting equation was

$$I = aX_1 + bX_2 + CX_3 \qquad (3)$$

where I, a, X_1, b, X_2 and X_3 were defined earlier, and C = number of new luminaires/total number of luminaires.

The installation costs for sites that required new luminaries on existing poles were calculated as follows:

$$I = dX_4 \qquad (4)$$

where

I = installation cost;
d = number of new luminaries to be put on existing poles; and
X_4 = that portion of the cost per luminaire (X_1 defined above) involving the lamp, lamp housing, wiring, ballast, transformer base, and photoelectric cell costs.

Category 3 redesign utilized both Eqs. 3 and 4 to determine installation costs.

Installation costs for sites where some of the equipment could be utilized in the new design were calculated with Eq. 5. The equation assumes that one pole can be completely salvaged and that 25 percent of the remaining equipment not including X_4 (described above) could be utilized in the new design. The lump sum item, X_3, was not considered applicable because it essentially represents the cost of providing a power supply, which must have existed for the old installation.

$$I = aX_4 + 0.75\,(a - 1)\,(X_1 - X_4) + 0.75bX_2 \qquad (5)$$

where all terms are defined above.

As indicated earlier, redesign for tunnels and long underpasses had to be calculated on a site-by-site basis because each site was unique. At this point in the analysis, the installation costs were available, indicating the equipment and construction costs of providing adequate lighting at each data point. The next step was to determine maintenance and energizing costs.

Maintenance and Energizing Costs

Maintenance and energy costs were calculated for all lighting at locations that met the federal standards for lighting both for existing lighting and for that additional equipment required to light existing inadequate and unlighted sites. Energizing costs were calculated as follows:

$$E = 0.41NWe \tag{6}$$

where

E = annual energizing costs;
N = number of luminaires;
W = power consumption (208 W for 175-W luminaires, 450 W for 400-W luminaires, and 1,058 W for 1,000-W luminaires); and
e = unit energy cost (2.25 cents/kW-h).

Maintenance costs were determined as follows:

$$M = Nm \tag{7}$$

where

M = annual maintenance cost;
N = number of luminaires; and
m = unit maintenance cost ($17/year for 175-W luminaires, $17/year for 400-W luminaires, and $21/year for 1,000-W luminaires).

As with earlier calculations, the maintenance and energizing costs for tunnels and long underpasses were handled independently because of their unique character. All other cost-estimating procedures were actually performed with the computer and the equations presented above.

The information available at this point in the analysis included the cost (installation, maintenance, and energizing) information for each site in the sample and the number of such sites within the state. All of the existing and future interchanges (planned for construction by 1975) and all tunnels and long underpasses were included in the sample data. Therefore, the statewide costs for these categories were simple additions of the site costs. The sample rate for intersections was 43 percent of the population and that for high night accident sites was 8 percent. Average costs per site type were calculated by the number of such sites in the state to obtain an estimate of the total costs for installation, energizing, and maintenance.

CONCLUSIONS

The procedures developed for the Pennsylvania highway lighting needs study would appear to have applications beyond their use in the study in 3 areas—lighting design, evaluation of existing lighting, and preliminary cost estimating. Some of the applications are obvious; however, further remarks seem appropriate.

The lighting design curves developed for the study give approximations of the maximum pole spacing for varying widths of pavement to be lighted. Each curve assumes a given level of illumination, a minimum and a maximum uniformity ratio, a given overhang of luminaire, photometric data from a specific manufacturer for a specific luminaire type, and other variables whose values are related to the luminaire type. These curves were deemed adequate for estimating the lighting requirements of currently unlighted sites and to evaluate the adequacy of existing lighting. The maximum error of the lighting design curves was found to be slightly more than 4 percent, which is well within the expected accuracy of other data used in the study. Similar lighting design curves could be developed for any particular set of lighting specifications and equipment and used in preliminary lighting design or for preliminary evaluation of existing lighting.

In the presentation of the lighting design curves, it was noted that further accuracy could have been obtained had more points been calculated in the pole spacing-roadway width plane. Taking this idea further, one asks why photometric data from manufacturers could not be in the form of lighting design curves instead of, or in addition to, isofootcandle diagrams and utilization curves. In fact, a similar idea utilizing different types of lighting design curves is illustrated in American Standard Practice for Roadway Lighting (6, p. 36). With the wide range of state specifications for lighting currently in use, this might require the preparation of many separate curves for each luminaire type; however, the reduction of effort required to design lighting with this procedure would seem to be well worthwhile.

Designing lighting with the aid of lighting design curves would require one reading from the graph to determine pole spacing. Corrections for horizontal and vertical roadway curvature would then have to be applied. The use of isofootcandle diagrams and utilization factor curves to determine pole spacing requires a minimum of 2 graph readings plus a calculation to determine average illumination and as many as 9 graph readings and 3 calculations to check (for 3 points) the uniformity ratio. Then, should the uniformity ratio prove inadequate, a new estimate of the pole spacing must be made and the entire process repeated. Thus, the design curves could easily save hours in the design of lighting for an interchange. Similar savings would result from the use of such curves to evaluate the adequacy of existing lighting.

The cost estimating procedures developed for the highway lighting study appear to be valuable for the preliminary estimation of construction and equipment costs. Instead of a procedure that prices each item independently to estimate costs for final design, a formula similar to Eq. 1 could be developed to estimate costs for preliminary design. Such procedures should also result in time savings.

It is realized that the exact cost formulas and lighting design procedures presented in this paper might not be applicable to particular requirements beyond the scope of the study conducted. It is believed, however, that the basic techniques developed and employed in the study represent a starting point for the development of lighting design and cost estimating procedures that will greatly simplify the task of the highway lighting design engineer.

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