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# Public Roads

## A JOURNAL OF HIGHWAY RESEARCH

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

# Public Roads

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Snow removal operation on Idaho State Highway 21 (Forest Highway Route 25) between Idaho City and Lowman. (Photo courtesy of Idaho Department of Highways.)

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# Highway Lighting Maintenance

**Reported by JAMES A. HOGAN,**
**Area Engineer, Iowa Division**

BY THE FEDERAL HIGHWAY
ADMINISTRATION

*Highway lighting, previously limited to major metropolitan areas, today includes nearly all urban sections of the Interstate System, as well as many other urban freeways and expressways. The research reported here concerns the maintenance factor used in highway lighting design—specifically its relationship to actual maintenance practices of State highway departments.*

*Response from a nationwide survey indicated that maintaining highway lighting, in many cases, was not a function of State highway departments. Rather it had become the responsibility of local jurisdictions or utility companies.*

*It is evident that lighting maintenance has been neglected. But, as this research shows, the relatively low cost of an adequate lighting maintenance program would greatly increase the light output of highway lighting systems.*

### *Introduction*

BEFORE the Interstate System, highway lighting was generally limited to major metropolitan areas. Today it is included in nearly all urban sections of the Interstate System as well as in many other urban freeways and expressways. In recent years it also has been extended to an increasing number of major rural intersections and interchanges. Highway lighting, therefore, has evolved to a position of major importance in highway design, and most State highway departments have expanded their staffs of ighting engineers to meet the increasing demand for lighting design.

Just as any other part of the highway ystem, lighting cannot be a *one-shot* operation. A continuing maintenance program is needed o assure that the quality of illumination does not become less than the minimum values stablished when the lighting system was designed. Without an adequate maintenance program even the best designed lighting installations soon lose much of their effectiveness.

When applied to highway lighting, the term maintenance can include different types of work—the restoration of a light pole that has been damaged by vehicle impact, for xample, or the replacement of an electric able damaged by rodents. In this paper, however, maintenance is limited only to those outine practices used to control the reduction f the quality of illumination of a highway ghting system. These routine maintenance practices include lamp replacement and uminaire cleaning.

The purpose of this paper is to investiate the need for highway lighting mainenance as it relates to the lighting design nd maintenance practices of State highway departments.

### *Maintenance as a Design Consideration*

The basic formula used in lighting design is

$$FC=\frac{(LL)\times(CU)\times(MF)}{(\text{spacing})\times(\text{rdwy. width})}$$

Where,

$FC$ = average maintained footcandles of illumination at the time of lowest light output by the luminaire.
$CU$ = coefficient of utilization.
$MF$ = maintenance factor.
Spacing = longitudinal spacing of luminaires (feet).
Rdwy. width = width of the roadway (feet).
$LL$ = initial lamp lumens.

This formula is generally used to calculate either the illumination level provided by a specific design or the maximum spacing of luminaires which will result in a specific illumination level.

Both the initial lamp lumens and coefficient of utilization are constant for a given luminaire, lamp, mounting height and overhang, and can be obtained from the manufacturers photometric data. The roadway width is not a variable in lighting design but is determined by traffic volume needs. As a result in calculating either the luminaire spacing or average maintained illumination for a specific highway facility and luminaire, the maintenance factor is the only variable.

The maintenance factor (*MF*) consists of two components: (1) lamp lumen depreciation factor (*LLD*)—a multiplier used to relate the initial lumen output of a new lamp to the decreased output of the lamp at a specified

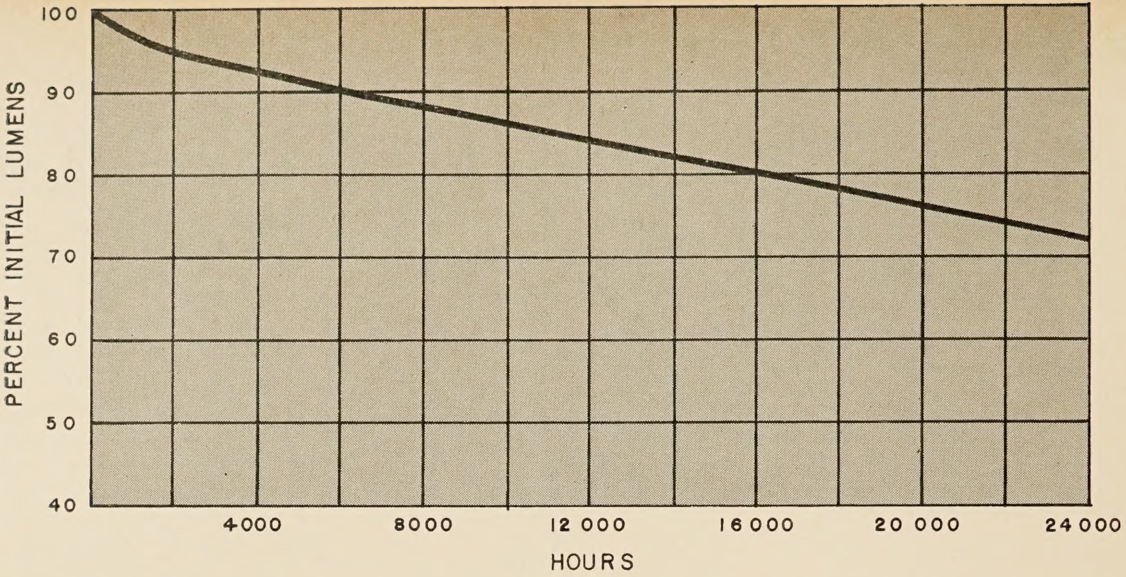

*Figure 1.—Typical lumen depreciation curve for mercury vapor lamps (11).*

time during the lamp's life; and (2) luminaire dirt depreciation factor (*LDD*)—a multiplier used to relate the initial illumination from a clean, new luminaire to the reduced illumination from dirt accumulation on the optical surfaces at the time cleaning is anticipated.

The product of *LLD* and *LDD* is the total maintenance factor, which takes into account the combined effect of lamp depreciation and luminaire dirt accumulation, and relates the initial illumination to that at the time of lowest light output.

*LLD* occurs at a fairly constant and predictable rate from the time the lamp is new until it burns out. The amount of light loss can be estimated quite accurately for any lamp from the lumen depreciation curve provided by the lamp manufacturer. Figure 1 shows a lumen depreciation curve for a typical mercury vapor lamp. From this curve, for the particular lamp being used, it is possible to estimate the amount of light output after any number of burning hours. The value used in lighting design is based on the time interval schedule for lamp replacement.

The *LLD* factor is not easily obtained. It varies considerably, depending on the type of luminaire, the ambient environment of the luminaire, and the amount of time elapsed from the initial installation to luminaire cleaning. For any given type of luminaire and cleaning schedule, the luminaire dirt depreciation factor used in design should be based on the ambient conditions prevailing at the particular location under consideration.

The effect of the maintenance factor on design calculations is illustrated in tables 1 and 2. In table 1 the average maintained footcandles of illumination were calculated for a typical luminaire with a constant spacing of 200 feet, using several maintenance factors. In table 2 the maximum luminaire spacings to provide an average maintained illumination of 0.6 ft.-c. were calculated for the same luminaire and maintenance factors.

As given in tables 1 and 2 both the luminaire spacings and average maintained footcandles of illumination vary considerably within the range of maintenance factors examined. If the cost of a lighting installation is assumed to be approximately proportional to its luminaire spacing, selecting the appropriate maintenance factor can have a significant economic effect. For a given luminaire spacing, selecting the appropriate maintenance factor assures that the resulting illumination levels will not be either significantly greater than or less than those determined necessary at design.

In its proposed revision of the American Standard Practice for Roadway Lighting, the Illuminating Engineering Society (IES) discusses the effects of illumination depreciation (*1*).[1] Causes of depreciation are divided into three categories: optical, electrical, and mechanical factors. Although only the optical factors relate to luminaire cleaning and lamp replacement schedules, the proposed IES revisions recommend inclusion of all three factors in design calculations. The following section of the proposed IES revisions relate to illumination depreciation and provide some guidelines for design values for each of the optical, electrical, and mechanical factors.

### "3.3 Illumination Depreciation

"(a) The recommended values of table II represent average illumination when the luminaires are at their lowest output. This condition occurs just prior to lamp replacement and luminaire washing. It is impossible to attempt the design of a lighting system without knowing in advance the light losses to be expected. Even when the Light Loss Factors are considered and allowance for them is incorporated in an operating service plan, lighting levels may still be reduced to less than 60 percent of initial at terminal points in the servicing schedule. In the absence of group lamp replacement and luminaire wash g schedules appropriate to local conditions, e average system illumination can fall bel w 50 percent of the initial value.

"(b) There are three general causes f depreciation. They are Optical, Electric l, and Mechanical Factors.

"(c) Optical performance depreciation is a major factor. One of the principal illuminati n losses is lamp lumen depreciation with in e aging. Lamp manufacturers provide da a showing light output for average lamps r ative to operating time. It is sometim s expressed as mean lumen output during rat d life. Lamp lumen output values used for desi n purposes should be determined by a thorou h study of such data and other lamp operati g characteristics. The value selected should e that which occurs at the time of la replacement.

**Table 1.—Effect of maintenance factor illumination level**

| Maintenance factor | Average maintained illumination (ft.-c.)[1] |
|---|---|
| 0.60 | 0.54 |
| .65 | .59 |
| .70 | .63 |
| .75 | .68 |
| .80 | .72 |

[1] CU=0.30; LL=24,000; spacing=200 ft.; rdwy. wid =40 ft.

**Table 2.—Effect of maintenance factor luminaire spacing**

| Maintenance factor | Luminaire spacing (ft.)[1] |
|---|---|
| 0.60 | 180 |
| .65 | 195 |
| .70 | 210 |
| .75 | 225 |
| .80 | 240 |

[1] CU=0.30/LL=24,000; rdwy. width=40 ft.; avg. mai ft.-c.=0.60.

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[1] Italic numbers in parentheses identify the bibliographic references listed on page 239.

Table 3.—Studies of costs and output resulting from various cleaning/relamping programs (2)

| Cycles in years | | Minimum output as percent of initial | Lamps and labor | Added to costs of energy plus plant | |
|---|---|---|---|---|---|
| Clean | Relamp | | | Low [1] | High [2] |
| Every: | Every: | | | | |
| 6 | 6 | 35.0 | 2.92 | 24.59 | 109.92 |
| 4 | 4 | 44.2 | 3.68 | 25.35 | 110.68 |
| 2 | 4 | 58.0 | 4.00 | 25.67 | 111.00 |
| 2 | 2(½) [3] | 60.6 | 4.00 | 25.67 | 111.00 |
| 3 | 3 | 53.3 | 4.50 | 26.17 | 111.50 |
| 1½ | 3 | 65.5 | 5.02 | 26.69 | 112.02 |
| 1½ | 1½ (½) [3] | 67.5 | 5.02 | 26.69 | 112.02 |
| 1 | 3 | 70.0 | 5.33 | 27.00 | 112.33 |
| 2 | 2 | 63.6 | 6.13 | 27.80 | 113.13 |
| 1 | 1(½) [3] | 75.0 | 6.75 | 28.42 | 113.75 |

| | |
|---|---|
| [1] Energy at $0.01 per kilowatt hour | $19.00 |
| Plant $80.00/30 years | 2.67 |
| | 21.67 |
| [2] Energy at $0.05 per kilowatt hour | $95.00 |
| Plant $120.00/10 years | 12.00 |
| | 107.00 |

[3] The practice of relamping 50 percent of the group at each cleaning, rather than 100 percent at every other cleaning, somehat improves minimum levels.

"(d) The balance of the Optical is due argely to dirt accumulation and is called uminaire Dirt Depreciation. It is a function f the kind of area, volume of traffic, mounting eight, degree of luminaire gasketing and time ince last cleaning (excessive age or extended leaning intervals may result in dirt baked on reflector surfaces so firmly that it cannot be removed by normal washing). Tests have shown that dirt collection on luminaires along heavily traveled freeways can reduce light output by 20 percent in a 6-month period. Business street luminaires may lose 10 percent in 7 months. While local residential or outlying highway locations may have losses of only 5 percent. The maintenance program should be based on measurements of actual local conditions, but *annual washing schedules* are likely to be justified for luminaires along freeways, expressways, major and collector roadways. An appropriate average loss value with annual washing is 20 percent which produces a maintenance factor of 0.80.

"(e) Mechanical and Electrical factor losses vary with the degree of inspection (both shop and field) and care taken during installation. An allowance of 10 percent is reasonable, which produces a factor of 0.9.

"(f) The overall depreciation factor to be used is calculated by multiplying each separate factor. A typical combined Mechanical Electrical and Luminaire Factor would be on the order of 0.9×0.8=0.7. With group replacement of lamps having a 0.8 factor, the resultant overall factor would be 0.6. Under poorer maintenance conditions, overall factors as low as 0.4 may be applicable."

The proposed IES revisions recognize the different rates of luminaire dirt accumulation, depending on the ambient conditions at the location of the lighting system. It further states that the value selected for lamp lumen depreciation should be that which occurs at the time of lamp replacement.

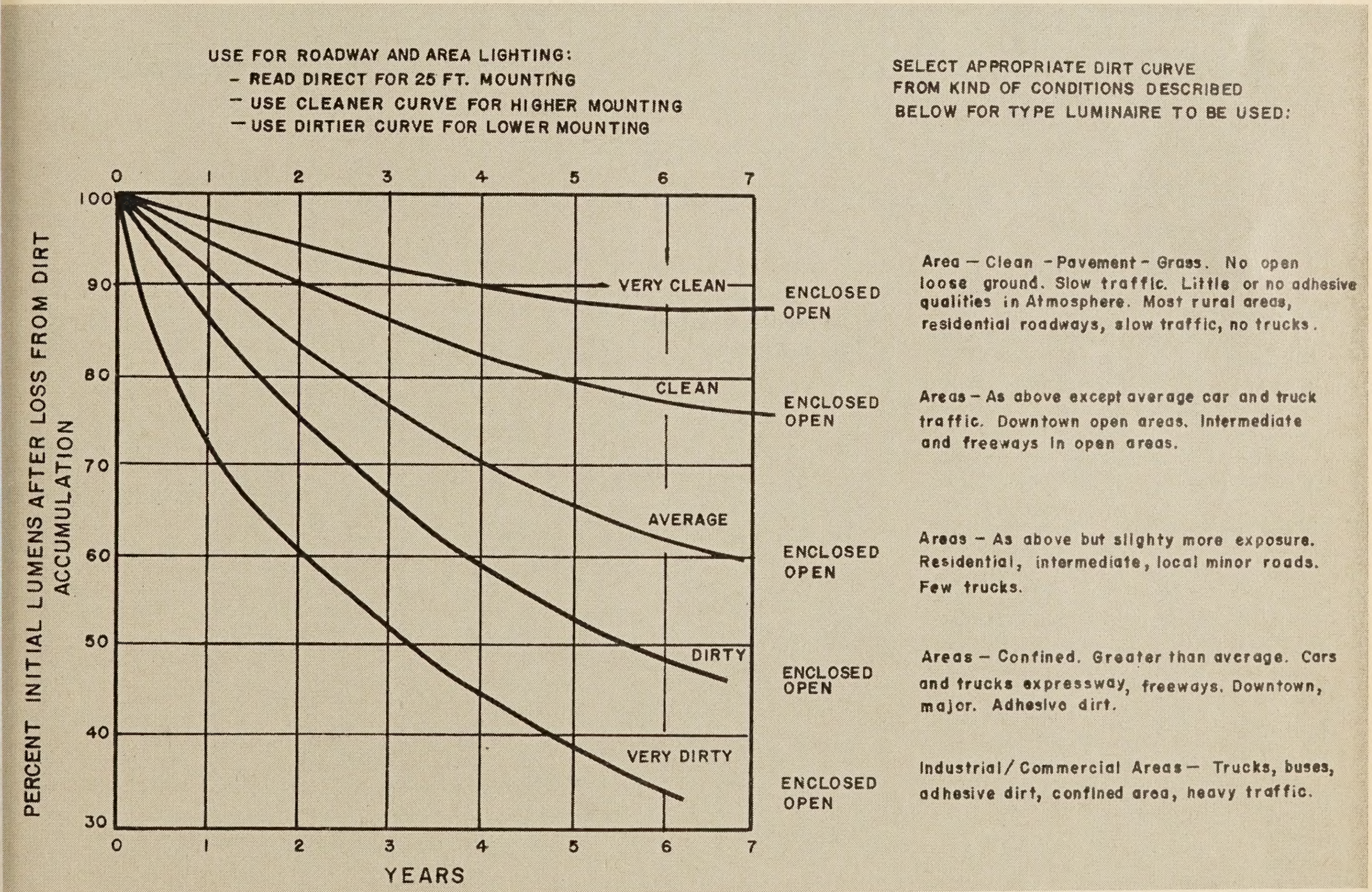


*Figure 2.—External luminaire dirt depreciation curves (3).*

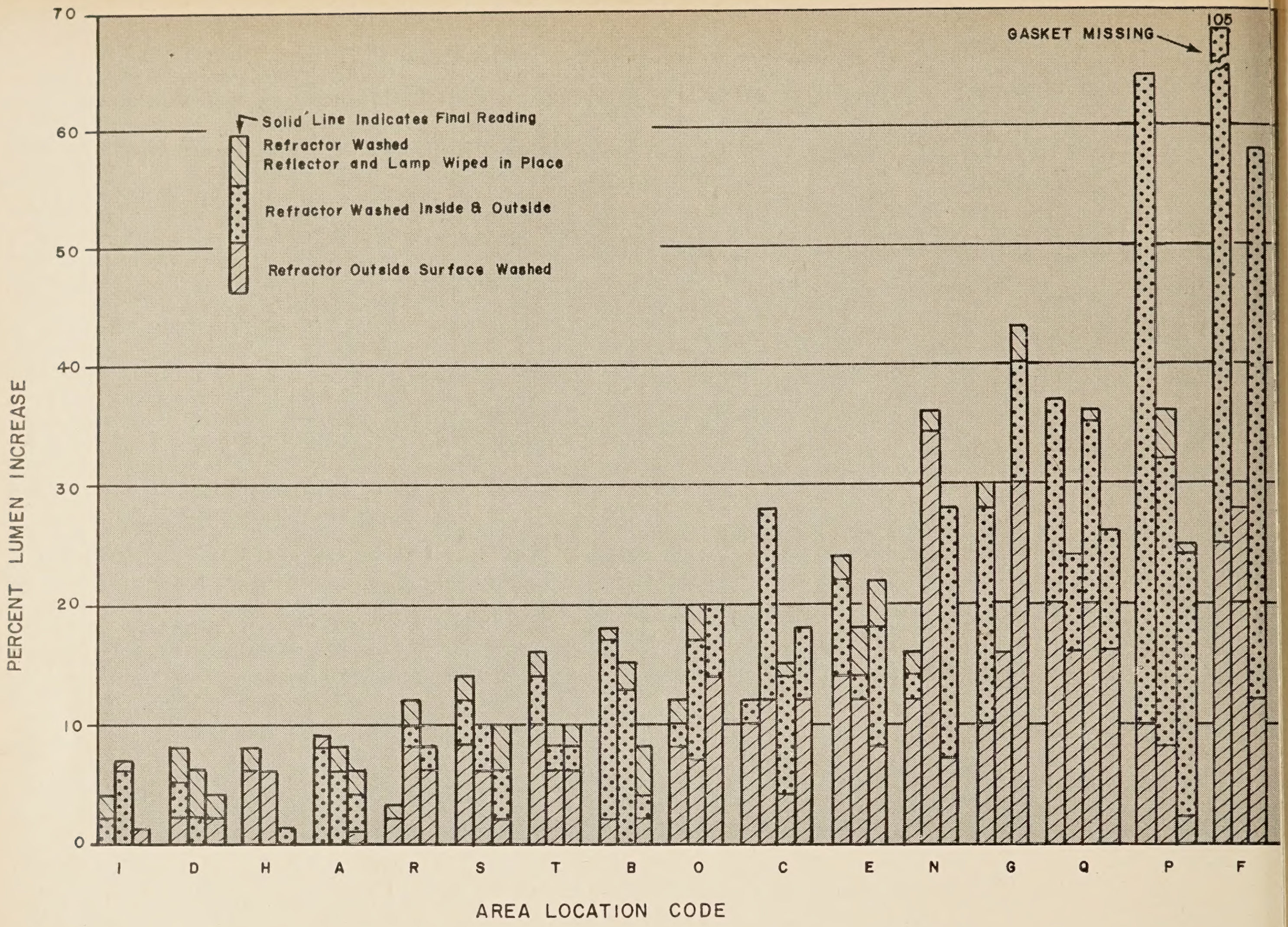


*Figure 3.—Percent lumen increase after luminaire washing (4).*

## *Review of Literature*

Very little research has been done in the field of highway lighting maintenance. A few isolated studies have attempted to correlate the effect of maintenance on lighting cost and on lighting effectiveness. Others have attempted to evaluate actual maintenance factors of lighting installations and correlate these to the maintenance factors used in design.

### Economic considerations

Clark (*2*) developed a procedure for estimating the costs of various mercury street lighting maintenance programs and their resulting effects on light output. The estimated annual costs for various luminaire cleaning and relamping cycles are presented in table 3. The percent of initial light output and the total annual cost are also presented, making it possible to estimate the increased light output of the various cycles. A comparison of a 3-year cleaning and relamping cycle versus a 1-year cleaning and 3-year relamping cycle is illustrated in table 3. By cleaning annually, the light output is increased from 53.3 percent to 70 percent of initial output at an increased total annual cost of $0.83 ($27.00—$26.17). This increase represents only 0.7 to 3.2 percent of the total annual cost, depending on the energy and plant costs used, and results in a 16.7 percent increase in light output.

### Luminaire dirt depreciation

Clark (*3*) proposes the following step-by-step procedure for calculations in roadway lighting design:

Objectives and specifications
1. Seeing task requirements.
2. Quality of illumination.
3. Quantity of illumination.
4. Atmosphere environment.
5. Area dimensions.
6. Luminaire selection.

Light loss factors not to be recovered
7. Luminaire ambient temperature.
8. Voltage.
9. Ballast efficiency.
10. Luminaire component depreciation.
11. Change in physical surroundings.
12. Burnouts.

Light loss factors to be recovered
13. Lamp lumen depreciation.
14. Luminaire dirt depreciation.
15. Accurate light loss factors.

Calculations
16.1 Determine average minimum foo candles.
16.1.1 Obtain coefficient of utilizati table.
16.1.2 Select proper CU value.
16.1.3 Use standard horizontal footcand formula to determine avera minimum footcandle level.
16.2 Determine average minimum at point.
16.2.1 Obtain appropriate isofootcand table.
16.2.2 Select proper values from source
16.2.3 Use standard point formula.
16.3 Check uniformity ratio.
16.4 Disability veiling brightness value
16.5 Make layout.
17.0 Review for compliance with spec fications.

Details of only those portions of the pro cedure that relate to luminaire depreciatio are presented here.

Step 4. *Atmosphere environment.*—Next t be considered is the environment throug which the system will operate. Dirt in th surrounding atmosphere will come from tw sources.

One, the area classification, which is the source of adjacent atmosphere. The adjacent atmosphere is the product of the effect of the contributions from the neighborhood, such as an asphalt plant, open dirt areas, heavy or light industry—in fact any source that can supply contamination to the air that will get to the luminaire.

Roadway classification, the second source of dirt, is the surrounding atmosphere that comes from the roadway itself. This surrounding atmosphere, as well as the area atmosphere, may be intermittent, but being the roadway, it is more critical. Careful analysis of the roadway, what dirt may be on it, and what vehicles use it, are very important. Inert, adhesive, and attracted dirt generated by small to large moving objects and other air movement can make it difficult to evaluate conditions under which the lighting system will operate.

Step 10. *Luminaire component depreciation.*—Luminaire surface depreciation results from adverse changes in aluminum, paint, and plastic components, which reduce light output. Clearly this is an important consideration in design calculations.

Step 14. *Luminaire dirt depreciation.*—Luminaire dirt depreciation is determined by first learning the dirt category of the environment, referring to data learned in Step 4. Using the exterior luminaire dirt depreciation curve (fig. 2), select the appropriate curve, of the five presented, and the elapsed time between cleanings. From information gathered in Steps 12 and 13, a realistic cycle can be chosen to find a luminaire dirt depreciation factor.

The luminaire dirt depreciation factors presented in figure 2 are average values to which the designer of the lighting system must apply his experience and judgment.

Oerkvitz (*4*) studied the actual luminaire dirt depreciation factors of luminaires located in different areas of Philadelphia. Each area environment was classified according to the following system proposed by the IES Roadway Lighting Committee Maintenance Subcommittee:

1. Very clean—tight luminaires, clean atmosphere, paved streets, no open dirt areas in vicinity, slow-moving traffic, residential, rural, outlying areas.
2. Clean—local minor residential intermediate area.
3. Average—expressways, freeways, downtown open areas.
4. Dirty—expressways, freeways, downtown confined areas.
5. Very dirty—open, loose luminaires, heavy traffic, industrial park atmosphere, business, heavy trucks, open dirt areas, confined streets, major downtown streets.

Three identical luminaires were photometered in each of 16 different locations. Each of the luminaires had been in service approximately 12 months since its last washing. Four separate photometer readings were taken of each luminaire.

1. Before reading—lamp-lit luminaire untouched.
2. Outside of glassware washed.
3. Outside and inside of glassware washed.
4. Outside and inside of glassware washed and reflector and lamp wiped in place.

Figure 3 shows the percent lumen increase of each luminaire resulting from the three successive cleaning stages. Figure 3 also shows that there is wide variation in the percent of lumen increase between individual luminaires in the same area location at each cleaning stage. Table 4 gives the average percent lumen increase for each area location and the corresponding luminaire dirt depreciation factors, which range from 0.70 to 0.97.

A more limited testing of reflector efficiency was also conducted in Philadelphia. The measured efficiency after washing averaged 92 percent for reflectors over 10 years old and 96 percent for reflectors from 2 to 10 years old. Cleaning and polishing the reflectors with a liquid metal cleaner increased the average efficiency approximately 5 percent. This was not considered significant in view of the labor time and costs involved.

Davison (*5*) presented data supporting the need for regular lighting maintenance, based on testing by the Georgia Power Company. Figure 4 shows a lamp lumen depreciation curve for an average mercury vapor lamp, and the combined lamp lumen depreciation and luminaire depreciation curves of average luminaires installed in normal dirt conditions and in extra dirty conditions. For a commonly used 4-year relamping the luminaire light output has reduced to 48 percent under typical conditions and 31 percent under severe conditions when no

**Table 4.—Tabulation of luminaire dirt depreciation factors (*4*)**

| Area location code | Luminaire age (years) | Percent lumen increase after washing [1] | Luminaire dirt depreciation factor | Initial area classification estimate [2] | Comments on area environment | |
|---|---|---|---|---|---|---|
| | | | | | Environment | Traffic |
| F | 3½ | 43 | 70 | 5 | Heavy industrial—depressed roadway. | Heavy truck. |
| P | 4 | 41 | 71 | 4 | Heavy industrial—confined area | Heavy truck. |
| Q | 10 | 30 | 77 | 5 | Heavy industrial—oil refinery | Very heavy—mixed. |
| G | 16 | 30 | 77 | 4 | Heavy industrial—open area | Heavy truck. |
| N | 7 | 23 | 81 | 3 | Medium industrial—near river | Medium truck. |
| E | 8 | 21 | 83 | 5 | Heavy industrial—near river | Medium—mixed. |
| C | 6 | 18 | 85 | 4 | Medium industrial—near railroad yard. | Heavy—mixed. |
| O | 8 | 16 | 86 | 3 | Medium industrial—near river | Heavy truck. |
| B | 10 | 14 | 88 | 4 | Medium industrial | Expressway ramp—heavy truck. |
| T | 6 | 11 | 89 | 2 | Medium industrial | Medium—mixed. |
| S | 6 | 11 | 89 | 4 | Medium industrial—residential | Medium—mixed. |
| R | 7 | 07 | 93 | 3 | Light industrial—open area | Light—mixed. |
| A | 5 | 07 | 93 | 3 | Commercial—light industrial | Heavy—mixed. |
| H | 7 | 04 | 96 | 1 | Residential | Medium—mixed. |
| D | 6 | 03 | 97 | 2 | Medium industrial—open terrain | Medium—heavy truck. |
| I | 7 | 03 | 97 | 2 | Residential—heavy tree foliage | Light—local traffic. |

[1] Average of luminaires tested in each area.
[2] Observation before testing.

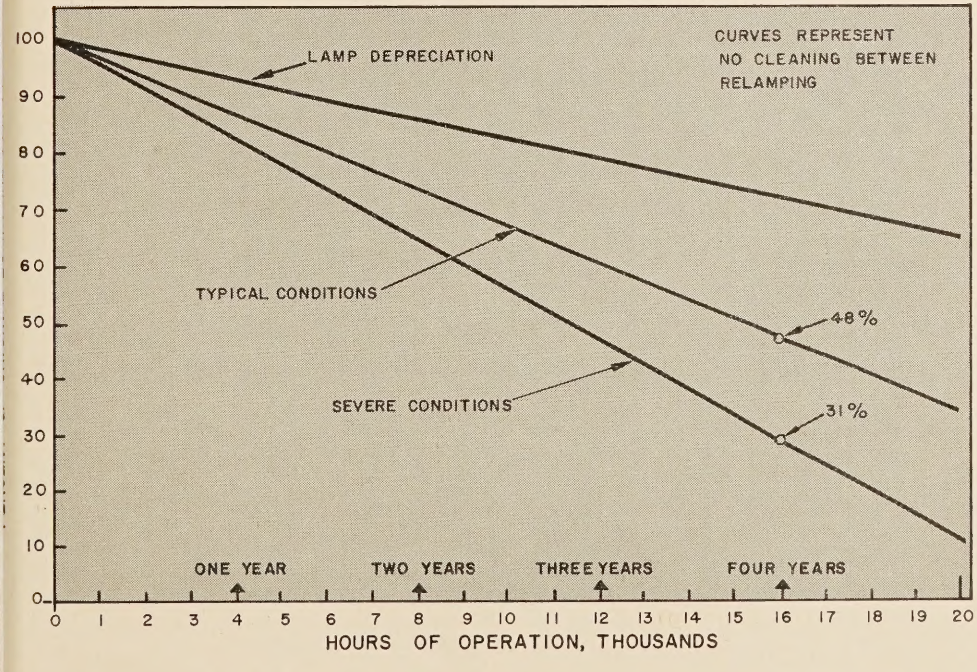


*Figure 4.—Lumen depreciation—no cleaning (5).*

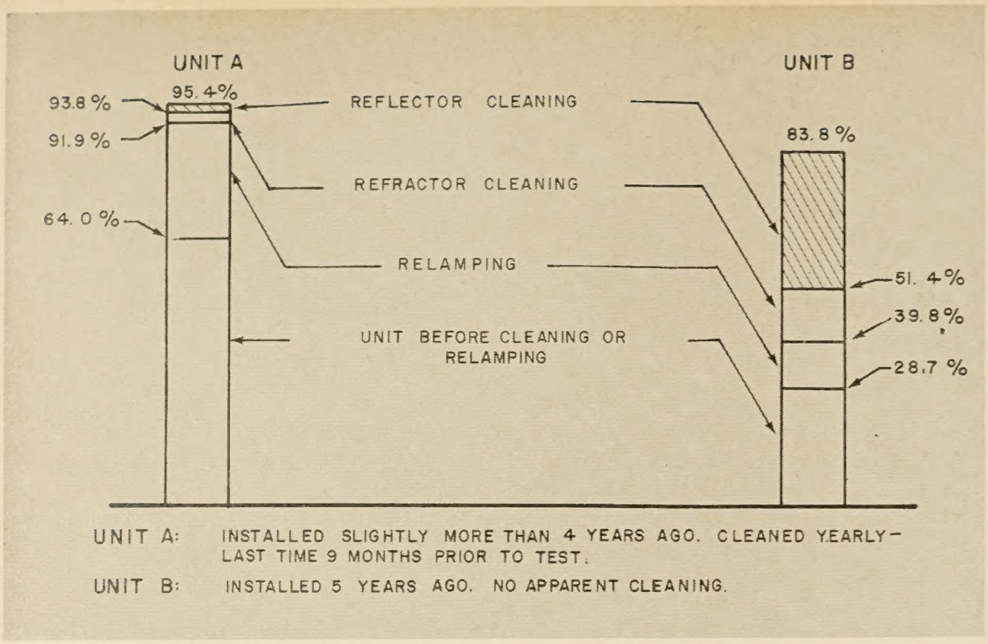


*Figure 5.—400 watt luminaire cleaning analysis (5). (Units 4–5 years old and tested with clear mercury lamps.)*

washing is performed between relamping. Figure 5 shows test results on two similar luminaires that had been in service approximately 4 years. Unit A had been cleaned annually but unit B had never been cleaned. Unit A was operating at 64 percent of initial light output before relamping and cleaning and unit B at 28.7 percent. Following relamping and cleaning, unit A was restored to 95.4 percent of its theoretical maximum light output. The refractor of unit B was so badly stained that it had to be replaced. Even with the new refractor and intensive reflector cleaning, unit B could only be restored to 83.8 percent of its theoretical maximum light output.

Figure 6 shows the total luminaire depreciation of a typical luminaire when a 1-year cleaning schedule is used. Following cleaning, the light loss resulting from dirt accumulation is virtually eliminated, resulting in a reduction in light output due almost entirely to lamp depreciation.

Van Dusen (*6*) studied the luminaire dirt depreciation of 15 horizontal mercury-type luminaires located in an industrial area in Milwaukee. The luminaire dirt depreciation was divided into three general measurement categories: external, internal, and permanent.

External depreciation was defined as that caused by the deposit of contaminants on the outside of the glassware. The amount of external contamination increases with time and then tends to level off at a relatively constant value, depending on the rate of accumulation and the rate of washing by rain.

Internal depreciation was defined as that caused by the deposit of contaminants on optical surfaces not directly exposed to weather. The internal contamination increases with time and can only be removed y washing the luminaire components. Since te internal components of the luminaire are rt exposed to weather, they are not washed y rain.

Permanent depreciation was defined s a loss of light output not recoverable by nmal washing. It represents the change ltween luminaire efficiency when new and afr cleaning. The causes of permanent depreation include corrosion and abrasion of te reflector, discoloring or etching of the glass r plastic ware, and incomplete removal f external and internal contaminants by wasing.

As a result of observations and tests i Milwaukee, procedures were developed fr estimating the luminaire dirt depreciati factor for different ambient contaminat densities and luminaire types. The lumina type determines the amount of outside r containing contaminants that enter the lunnaire over a given time as a result of wind prsure and luminaire breathing. The study ccluded that the amount of outside air enteri the luminaire because of wind pressure s generally significantly greater than th resulting from luminaire breathing. T

**Table 5.—Ambient category (*6*)**

| Ambient category No. J | Suspended particulates $\mu g./m.^3$ | Ambient sampler change/week | External maintenance $M_E$ | Time to reach constant value (years) |
|---|---|---|---|---|
| 1 | 0–150 | 0–2.0 | 0.984 | 2 |
| 2 | 150–300 | 2.0–4.0 | .967 | 1 |
| 4 | 300–600 | 4.0–8.0 | .934 | 0.5 |
| 8 | 600–1200 | 8.0–16.0 | .868 | .25 |
| 16 | 1200–2400 | 16–32 | .736 | .25 |
| 32 | over 2400 | over 32 | .480 | .25 |

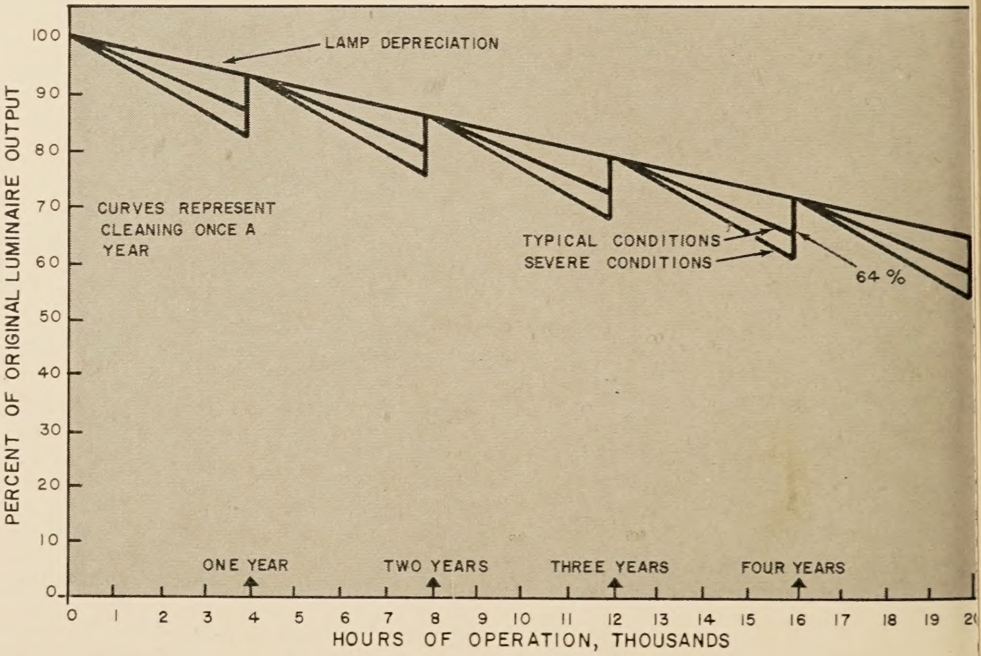


*Figure 6.—Lumen depreciation—1-year cleaning intervals (5).*

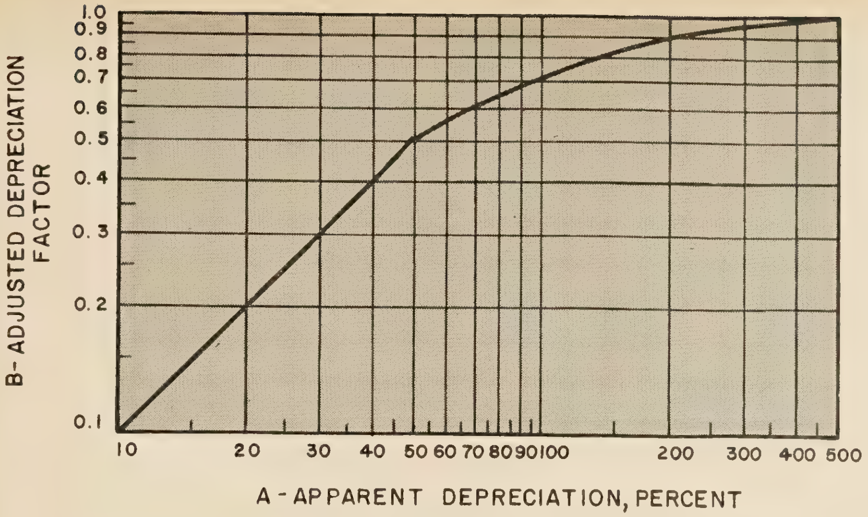


*Figure 7.—Correction for layering effect. Based on tests where the effect of light transmission due to varying the weight of deposited artificial contaminant dust was measured. Dusts used were lamp black and powdered clay (6).*

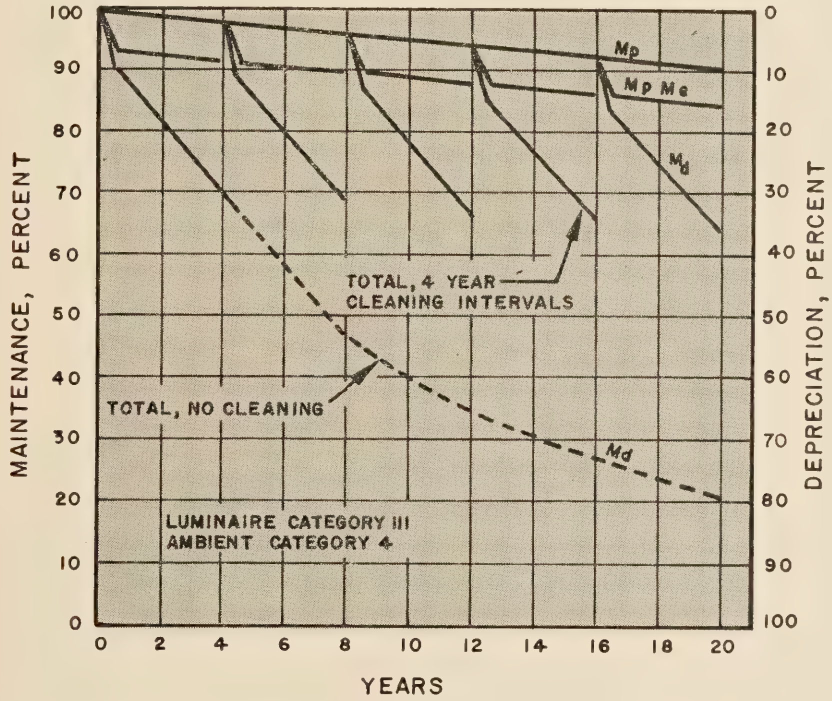


*Figure 8.—Luminaire dirt maintenance calculated by the formula procedure (6).*

luminaire dirt depreciation factor ($M_D$) is the product of the internal ($M_I$), external ($M_E$), and permanent ($M_P$) depreciation factors.

Table 5 includes external depreciation factors for ambient contamination densities from 0–150 to greater than 2,400$\mu$g./m.$^3$ (micrograms per cubic meter). An average urban ambient contamination density not in close proximity to pollution sources was 100 $\mu$g./m.$^3$. Wide variations existed, however, within a limited area, with values of 1,000 $\mu$g./m.$^3$ or more common in industrial areas. The external depreciation factor will have the value of 1.0 initially and will decrease linearly to the constant value at the time interval shown in table 5 for the ambient category.

The internal depreciation is determined from the formula:

$$A = (T_1)(K)(J)$$

Where,

$A$ = apparent internal depreciation, percent.

$T_1$ = time since last washing, years.

$K$ = depreciation constant for luminaire, table 6.

$J$ = ambient category number, table 5.

The adjusted internal depreciation ($B$) is then determined from figure 7 for the calculated value of $A$. Figure 7 accounts for the layering effect of dirt accumulation; that is, depreciation is not proportional to quantity of dirt accumulation beyond a depreciation of 48 percent. The internal depreciation factor ($M_I$) is equal to 1.0 minus the adjusted internal depreciation ($B$).

The permanent depreciation factor ($M_P$) is determined by the formula:

$$(M_P) = 1.0 - (P)(T_2)$$

Where,

$P$ = permanent depreciation per year.

$T_2$ = luminaire age, years.

Values between 0.003 and 0.009 for $P$ were observed in the Milwaukee area.

Figure 8 shows an example of luminaire dirt depreciation as calculated by the Van Dusen procedure.

General Electric (7) presents photometric test data showing the gain in light output after each step of cleaning of luminaires that had been in service several years. Figure 9 shows typical results of this testing on a luminaire that had no maintenance for 4 years. Lamp lumen depreciation was not a factor in these tests because new lamps of known lumen output were used. By completely cleaning both the reflector and refractor, the luminaire's efficiency was increased from 67 to 96 percent of original light output. Contaminants on the outside of the refractor accounted for only 1 percent of the light loss.

Box (8) studied the relationship between illumination and accidents on freeways. The study primarily consisted of analyzing accident rates on freeways with different illumination levels and uniformity ratios at several locations in the United States and Canada. Although the study was primarily concerned with the effect of illumination on accident rates, actual field measurements of existing freeway lighting were made at 14 locations. A comparison of these field measurements with calculated initial illumination levels provided a general indication of the extent of illumination depreciation.

Table 7 shows some examples of the illumination depreciation as determined by these field measurements. Actual horizontal footcandles of illumination ranged from 0.28 to 0.82 of calculated initial values. Table 7 also indicates a significant reduction of illumination uniformity. Actual uniformity ratios ranged from 0.29 to 2.15 of calculated initial values. The study recommended additional research on the effects of differing maintenance practices on illumination depreciation and suggests using a luminaire depreciation factor in the area of 0.50 for typical conditions.

**Table 6.—Luminaire category. The depreciation constant represents annual depreciation in 100 $\mu$g./m.$^3$ ambient (6)**

| Luminaire category number | Description | Internal depreciation constant K |
|---|---|---|
| | | *Percent* |
| I | Open bottom | 4.0 |
| II | Ventilated | 2.0 |
| III | Semi-sealed | 1.5 |
| IV | Gasket sealed | 0.5 |

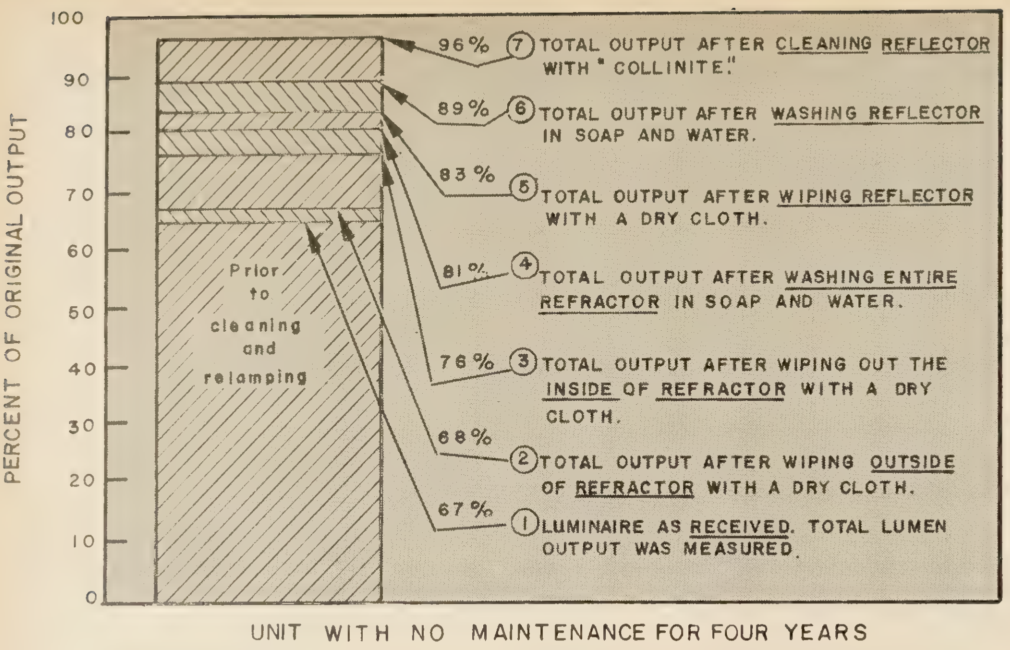


*Figure 9.—Typical increase in light output resulting from step-by-step luminaire cleaning (7).*

The following are principal findings of the study:

"Latitude, longitude, local DST practice, or metropolitan area size, appear to cause no significant variation in the 25 percent of urban freeway traffic consistently occurring at night.

"Lighted urban freeways have a significantly lower night accident potential than unlighted ones. An average reduction of 40 percent in night accidents can be predicted as a result of lighting.

"A great variation was found in luminaire output in the field. In eight different freeway sections, readings were taken below several adjacent luminaires, and approximate illumination values were calculated between more than 60 pairs of adjacent units. When compared with the 'average' from the point-by-point area measurements within each test location, HFC variations were found as low as 67 percent below the average, to as high as 60 percent above it.

"HFC variations within sections of routes where maintenance was by replacement of lamps only after burnout were checked against the variations of sections having group-replacement maintenance. No significant difference was found in the extreme range average under either type of maintenance. A separate check of systems having different types of maintenance found an average depreciation of 54 percent for burnout (spot) replacement versus only 36 percent for group replacement methods. This suggests that the variation problem is due to inconsistent lamp output more than the maintenance procedure.

"Data were analyzed from over 800 mercury lamps taken from the field after lengths of service ranging between a few months and 10 years. The illumination output was checked as a percent of control lamps (used to simulate 'initial' lamp performance). Wide variation was found, with lamps less than 2 years old producing 54 percent to 98 percent of nominal output, those between 2 and 3 years old producing 46 percent to 94 percent and those 3 to 4 years old producing 40 percent to 9 percent. The average output was 67 percent of nominal.

"Due to the inconsistent depreciation rates of 400-watt mercury lamps as found unde actual field conditions, the commonly accepted roadway lighting system design elements o 'average HFC' and 'uniformity' appear to be nearly meaningless. The driver is typically exposed to wide ranges in both of these values These variations are in addition to the undulating illumination and glare that he visually experiences in driving between one luminaire and the next."

Luminaire dirt depreciation can result from conditions other than ambient contaminants Figure 10 shows several examples of broken or defective luminaires with excessive amounts of light loss. While problems with squirrels or birds are no doubt more common to residential street lighting, highway lighting installations are by no means immune to such occurrences. Light loss resulting from insect accumulation inside the refractor is certainly not unique to residential street lights alone.

## Review of Current Practice

For an effective highway lighting program it is essential that design values used for the components of the maintenance factor correspond to the actual lighting maintenance practice.

### State highway departments

The current lighting maintenance policies and practices of State highway departments were determined through a questionnaire sent to the highway departments of each State and the District of Columbia. Basic information was sought regarding the following aspects of lighting installation:

Table 7.—Examples of lighting depreciation—urban freeways, burnout lamp replacement, no washings, mainline sections, 400-watt mercury (*8*)

| Route data | | | Equipment | | | Illumination | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Calculated initial | | Measured in service[3] | | Depreciation factor[4] | |
| Total lanes both directions | ADT | Area in U.S. | Mounting height | Luminaire overhang from edge of traffic lane | Replacement age | H.F.C.[1] | U.R.[2] | H.F.C.[1] | U.R.[2] | H.F.C.[1] | U.R.[2] |
| | *Thousands* | | *Feet* | *Feet* | *Years* | | | | | | |
| 4 | 75 | South | 28 | 6 | 12.0 | 1.29 | 5.6 | 0.38 | 2.6 | 0.29 | 2.15 |
| 4 | 80 | Southwest | 33 | 0 | 4.3 | 2.13 | 2.2 | 1.37 | 2.7 | .64 | .81 |
| 4 | 80 | do | 33 | 0 | 4.3 | 1.87 | 2.3 | .87 | 3.8 | .47 | .61 |
| 4 | 75 | do | 33 | 0 | 12.4 | .75 | 2.5 | .50 | 3.6 | .66 | .69 |
| 6 | 60 | South | 28 | 3 | 5.1 | 1.22 | 8.3 | 1.00 | 20.0 | .82 | .41 |
| 6 | 90 | Southwest | 33 | 6 | 14.2 | .67 | 7.8 | .28 | 7.3 | .42 | 1.04 |
| 6 | 50 | do | 30 | 3 | 5.7 | 1.62 | | .45 | 9.0 | .28 | |
| | | | (5) | (5) | (5) | (5) | (5) | [5] .50 | [5] 10.0 | .31 | (5) |
| | | | (6) | (6) | (6) | (6) | (6) | [6] 1.18 | [6] 6.0 | [6] .73 | (6) |
| 6 | 50 | Southwest | 30 | 3 | 5.7 | 1.25 | 6.3 | .44 | 22.0 | .35 | .29 |
| 8 | 75 | do | 33 | 0 | 4.7 | 1.38 | 2.6 | .80 | 3.5 | .58 | .74 |
| 10 | 110 | do | 33 | 0 | 6.1 | 1.43 | 3.6 | .87 | 5.1 | .61 | .71 |

[1] Horizontal footcandle average (travel lanes only).
[2] Uniformity ratio (average to minimum).
[3] Measured ¼-point mid-area average (travel lanes).
[4] In-service value divided by calculated initial value.
[5] Same location, luminaire washed.
[6] Same location, luminaire washed plus new lamp.

- Responsibility for maintenance.
- Schedule of maintenance.
- Design values used for maintenance factor.

Forty-three of the 51 highway departments responded to the questionnaire. But not all of the responding departments completely furnished the information requested.

Responsibility for lighting maintenance as reported by the State highway departments included State forces, local jurisdictions, utility companies, maintenance contractors, and combinations of these. Maintenance by State forces was reported by only 15 highway departments, and in most cases this was limited to lighting outside of municipalities. Since the vast majority of highway lighting installations are located within municipalities, the rural lighting maintained by State forces constitutes only a small portion of the total highway lighting in these States. The prevailing highway lighting maintenance practice, as reported, placed responsibility with the local jurisdiction. The local jurisdiction generally did not perform the maintenance but contracted with a utility company or a maintenance contractor.

**Table 8.—Total maintenance factor, group replacement schedule, and luminaire cleaning schedule**

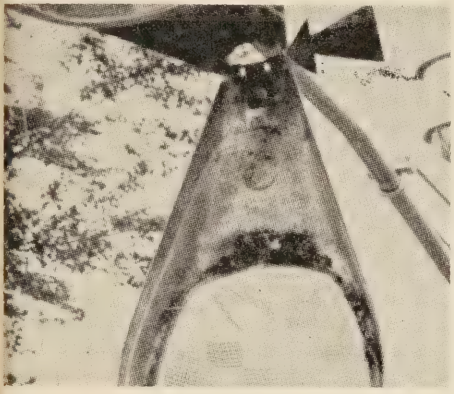
| Maintenance factor | Group replacement schedule | Luminaire cleaning schedule |
|---|---|---|
| | *Years* | *Years* |
| [1] 0.60 | 1 | 1 |
| .60 | 5 | 5 |
| .65 | 3 | (2) |
| .65 | (3) | (3) |
| .68 | (3) | (3) |
| .70 | [4] 4 | [4] 1 |
| .70 | (3) | (3) |
| .80 | 5 | (2) |

[1] 0.60 for 400-w. and 0.70 for 700-w. luminaires.
[2] None reported.
[3] No established schedule.
[4] Urban installations only. Remainder on outage basis.

**Table 9.—Luminaire dirt depreciation factor and luminaire cleaning schedule**

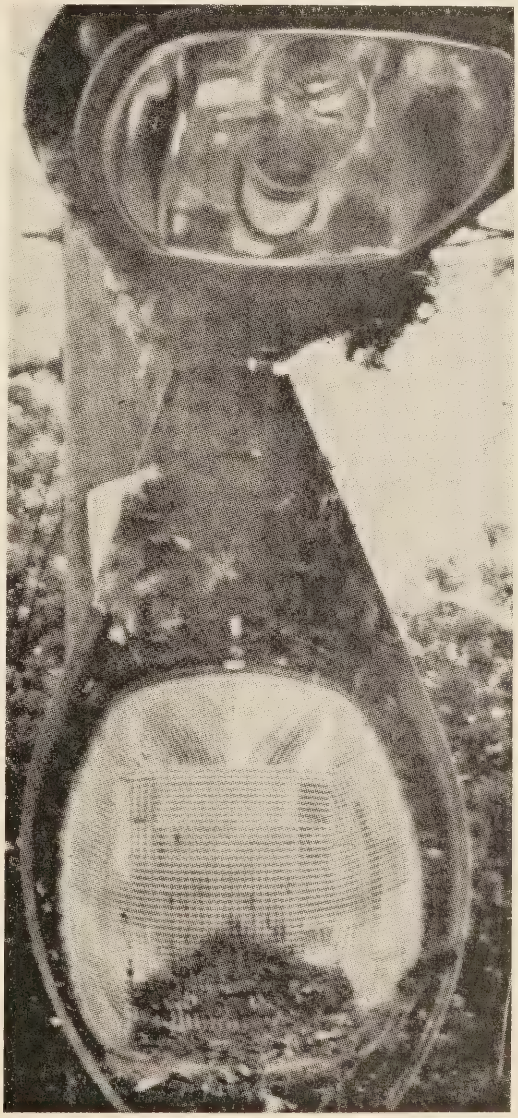
| Luminaire dirt depreciation factor | Luminaire cleaning schedule |
|---|---|
| [1] 0.68 | No established schedule. |
| .70 | Do. |
| .70 | Do. |
| .70-.85 | Mercury vapor—4 years.[3] |
| .75 | 4 years [3]. |
| .75 | Mercury vapor—3½ years.[3] |
| .80 | 1 year. |
| .80 | Do. |
| .80 | No established schedule. |
| .80 | At relamping (80 percent rated life). |
| .80 | No established schedule. |
| [2] .85 | Do. |
| .85 | Do. |
| .85 | Do. |
| .85 | At relamping.[3] |
| .85 | 4 years.[3] |
| .85 | No established schedule. |
| .85 | 1 year. |
| .85 | No established schedule. |
| .85 | At relamping (3½ years and mid-point of relamping period). |
| .85 | 4 years.[3] |
| .90 | Mercury vapor—4 years.[3] |
| .90-.92 | Do. |

[1] Mounting height 30 feet.
[2] 0.65 used for high mast.
[3] Luminaire cleaning schedule not reported. Assumed cleaning performed at time of reported relamping.



Arrow points to missing guard which has permitted the entrance of squirrels into the fixture. The dead space behind the glassware has become a bathroom.

Glassware of this optical assembly has been broken through thermal shock (a condition directly resultant from accumulations of dirt). The fixture has become a haven for birds, rendering the street light totally useless.



In the fixture above, the dead spaces have been filled with the debris of birds and the prisms of the glassware are clogged with the dead and decaying bodies of insects.

*Figure 10.—Excessive luminaire dirt depreciation (13).*

Lighting maintenance schedules varied from a fixed program of group replacement and luminaire cleaning at specified intervals to complete reliance on the municipality or utility company for establishing and complying with programs. The State highway departments generally reported fixed schedules for maintenance performed by their own forces. In many cases where the maintenance is the responsibility of a municipality or utility, the maintenance schedule is at the option of the municipality or utility company and the highway department is not always aware of the schedule being used.

Maintenance responsibility of highway lighting within a municipality is generally transferred by the State highway department to the municipality through a maintenance agreement. While these maintenance agreements clearly establish both the physical and financial maintenance responsibility, a schedule for maintenance other than burnout or major outages is not always included.

Highway departments exercise a greater control over lighting maintenance schedules when the maintenance is performed by their own forces. Although the amount of lighting maintained by State forces is small in relation to the total lighting installations, many States have established specific schedules.

Values of the maintenance factor used in lighting design were reported by 30 highway departments. The combined total maintenance factor used was reported by eight highway departments. The remaining highway departments reported one or both of the components of the maintenance factor—lamp lumen depreciation factor and luminaire dirt depreciation factor—used in lighting design. These values are summarized in tables 8 and 9.

Tables 8 and 9 indicate that there is little correlation between the design values used for the maintenance factor or its components and the group replacement and luminaire cleaning schedules assumed or reported by the State highway departments. Table 8 shows a maintenance factor of 0.60 reported by a department with an annual group replacement and luminaire cleaning schedule. The same 0.60 maintenance factor was reported by a department with a 5-year group replacement and luminaire cleaning schedule. A portion of this variation in group replacement schedules can probably be explained by the differences in rated life of the lamps used by individual highway departments. The same wide variation is evident from table 9. Luminaire cleaning schedules of annual and every 4 years were reported for the same luminaire dirt depreciation factor of 0.85.

Only one highway department reported using a different luminaire dirt depreciation factor depending on the local conditions at the lighting installation. This department's design values for the luminaire dirt depreciation factor are dependent on the luminaire cleaning schedule and differentiate between medium and dirty conditions. As reported by the remaining departments, the same maintenance factor is used for all locations without regard to local conditions.

Texas Transportation Institute (TTI) (*9*) conducted a survey by questionnaire as part of their state-of-the-art study of roadway lighting. Two items in the TTI questionnaire related to maintenance responsibility and cleaning and relamping intervals. These items and the response to them are summarized in tables 10 and 11. Table 11 shows that of the 35 State highway departments responding to the TTI survey, only four perform their own maintenance. In 24 departments all lighting maintenance was done by local companies; the remaining departments reported most of their lighting maintenance done by local companies.

Cleaning and relamping intervals shown in table 11 range from 6 months to more than 48 months, with many of the State highway departments reporting no schedule.

**Table 10.—Responsibility for maintenance of State highway lighting (*9*)**

| Responsible for maintenance | Percentage of total installations | Number of States responding |
|---|---|---|
| State highway department | 100 | 4 |
| Local companies | 100 | 24 |
| Do | 90 | 2 |
| Do | 85 | 1 |
| Do | 75 | 2 |
| Do | 50 | 1 |
| Do | 10 | 1 |

### Cities

The TTI study also included a questionnaire to 50 cities. Two items in this questionnaire also related to maintenance responsibility and cleaning and relamping intervals. These items and the responses by the cities are summarized in tables 12 and 13.

## *Summary*

An important variable in the design of highway lighting is the maintenance factor. The individual components of the maintenance factor—the lamp lumen depreciation factor and the luminaire dirt depreciation factor—should be based on the local conditions of each lighting installation and the maintenance schedule used.

The survey of State highway departments revealed that highway lighting maintenance is generally the responsibility of local jurisdictions or utility companies. However, many highway departments did not specify any schedule for maintenance. Some departments were not aware of the group lamp replacement and luminaire cleaning schedules being used by the local jurisdiction or utility company performing the lighting maintenance. Highway departments exercise a greater control over the schedule of lighting maintenance performed by their own forces. However, only a very small portion of all highway lighting installations are maintained by State forces.

The survey also revealed that there is no significant amount of correlation of the maintenance factor used in design and actual lighting maintenance schedules. Further, most States reported using an average value for the luminaire dirt depreciation component of the maintenance factor regardless of the local conditions of the lighting installation. The research clearly indicates a wide variation in luminaire dirt depreciation, depending on ambient contaminant density. Investigation has also shown the low relative cost of adequate lighting maintenance program and the resulting substantial increase in light output.

The illumination levels established at the time a lighting system is designed are minimum acceptable values. Failure to correlate the lighting design assumptions with actual maintenance practices can result in the lighting system producing considerably less than the minimum acceptable illumination levels and becoming both an economic and safety concern.

**Table 11.—Cleaning and relamping maintenance—State highway departments (*9*)**

| Lighting type | Time interval (months) | | | | | |
|---|---|---|---|---|---|---|
| | 6–12 | 12–24 | 24–36 | 36–48 | >48 | No schedule |
| Continuous freeway | 8 | 4 | 3 | 7 | 3 | 19 |
| Continuous arterial | 5 | 3 | 6 | 8 | 1 | 22 |
| Full interchange | 6 | 4 | 3 | 11 | 4 | 17 |
| Safety | 6 | 5 | 2 | 8 | 1 | 20 |

## *Conclusions*

Until recent years there was little need fo luminaire cleaning other than at the time o lamp replacement. The life of incandescen lamps and the early versions of the mercur vapor lamps was generally 1 to 1½ years. A a result at least a minimal amount of luminair cleaning could be done at little additiona cost or effort when the burned out lamps wer replaced at 1 to 2 year intervals.

The rated life of modern lamps used in highway lighting however is substantially longe Mercury vapor lamps now ususally last years or more, and metal halide and sodiu vapor lamps are rapidly approaching a 4- o 5-year rated life. Consequently, luminair cleaning at the time of relamping will generally mean an interval of 4 or 5 years or more In most cases luminaire dirt depreciation wi be extensive and result in excessive loss o light output when such a long interval between luminaire cleaning is used. The economics of effecting the continued performance o a lighting installation must also be considered The cost of an adequate maintenance progra is relatively small when compared to th capital investment represented by a lightin installation.

The questionnaire sent to each State highway department specifically asked if th lighting maintenance schedules currentl being used were satisfactory. A few of th departments responding to this question indicated their schedules were not completel satisfactory, but lack of personnel and fund prevented any changes.

Highway lighting maintenance is anothe responsibility for highway departments tha are generally without the corresponding increase in funds and personnel with which t accomplish it. Because of this situation, it i unlikely that State highway departments wil assume a greater amount of lighting maintenance with their own forces in the nea future. But it is relatively certain that th practice of highway lighting maintenance b local jurisdictions or utility companies wil continue.

Highway lighting maintenance by loca jurisdictions or utility companies need no preclude an adequate maintenance program. Certain steps can be taken to assure a maintenance program compatible with the lightin design. To accomplish this it is essential tha components of the maintenance factor used in lighting design correspond to the environmental conditions of the lighting installatio and the relamping and luminaire cleanin schedules actually used.

The designer of a highway lighting syste must be aware of the prevailing ambien conditions and the resulting expected luminaire dirt depreciation, and the maintenanc schedule which will be followed. Without thi information the maintained level and uniformity of illumination cannot be predicte with reasonable accuracy.

If the maintenance schedule at a particula location cannot be changed, the design value for the components of the maintenanc factor should be selected to fit the condition at that location. The lamp lumen depreciation factor and the luminaire dirt depreciation factor should represent the lamp replacement and luminaire cleaning schedules actually used and the prevailing ambient conditions. The use of an average value for the maintenance factor throughout a State can only result in overdesign of some lighting installations and underdesign of others.

A better solution would be the selection of the group lamp replacement schedule and luminaire cleaning schedule to be used when a lighting system is designed. This schedule would be based on an economic evaluation and the existing and expected ambient conditions at the particular location. The maintenance agreement with the local jurisdiction or utility company would include these group lamp replacement and luminaire cleaning schedules, assuring correlation with the lighting design assumptions. There is wide variation in the ambient conditions and resulting luminaire dirt depreciation between a lighting installation located in an industrial area and one located in a rural area. The use of a standard luminaire cleaning schedule for all lighting installations will result in those installations located in areas with high ambient contaminant densities rapidly falling below their desired illumination levels. Because of the variation in rated life of lamps being used, a group lamp replacement schedule based on years of service is not advantageous. A schedule based on percent of rated life or minimum lumen output could be uniformly used at all locations.

**Table 12.—Responsibility for maintenance of city lighting (*9*)**

| Maintenance responsibility | Percentage of total installations | Number of cities responding |
|---|---|---|
| City | 100 | 6 |
| Do | 20 | 1 |
| Local utilities | 100 | 13 |
| Do | 80 | 1 |
| Private contractor | 100 | 2 |

Highway lighting represents a significant portion of the total highway investment in this country. The number of highway lighting installations will continue to increase in future years. It is only reasonable that this investment and the benefits which it provides be protected by developing an adequate program of highway lighting maintenance.

## ACKNOWLEDGMENTS

The author wishes to express his appreciation to each of the State highway departments who took the time and effort to respond to the questionnaire.

Special thanks are extended to Mr. James A. Thompson, Regional Traffic Operations Engineer, Federal Highway Administration, Kansas City, Mo., for his encouragement and assistance.

**Table 13.—Cleaning and relamping maintenance—cities (*9*)**

| | Time interval (months) | | | | | |
|---|---|---|---|---|---|---|
| | 6–12 | 12–24 | 24–36 | 36–48 | >48 | No schedule |
| Freeways | 8 | 3 | 2 | 5 | 3 | 6 |
| Arterials | 9 | 3 | 2 | 5 | 3 | 5 |
| Collectors and locals | 9 | 3 | 2 | 5 | 3 | 5 |
| Interchanges and intersections | 9 | 3 | 2 | 5 | 3 | 5 |

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# New Publications

The Federal Highway Administration has recently published two documents. These publications may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, prepaid. The following paragraphs give a brief description of each publication and its purchase price.

### *Hydraulic Flow Resistance Factors for Corrugated Metal Conduits*

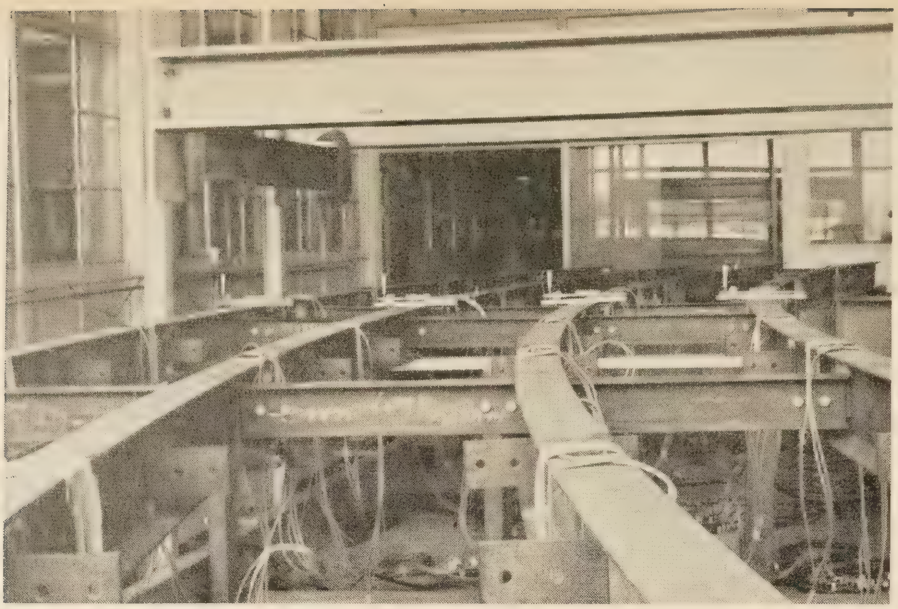
*Hydraulic Flow Resistance Factors for Corrugated Metal Conduits*, 1970 (55¢ a copy), will be of interest to design engineers and those concerned with problems involving hydraulic resistance factors of drainage structures. The full range of currently available data is drawn upon to assemble and present hydraulic resistance factors for corrugated metal conduits of a variety of sizes, shapes, and corrugation forms. Resistance factors and aids for dealing with the geometry of various shapes of corrugated conduits are presented together with *procedure guides* in tabular and graphic form.

The magnitudes of the errors inherent in applying a single resistance factor to corrugated pipes of all sizes, shapes, flow rates, and corrugation forms are pointed out, and parameters influencing corrugated pipe resistance, including relative roughness, Reynolds number, corrugation form, and method of manufacture, are discussed. Resistance factors are presented in terms of both Darcy f and Manning n values, permitting them to be easily incorporated into most design procedures.

### *Emergency Application Systems for Power Brake Mechanisms of Highway Trailer Combinations*

*Emergency Application Systems for Power Brake Mechanisms of Highway Trailer Combinations*, 1970 ($1 a copy), presents the results of a research effort to compare the performance of axle-by-axle brake protection systems with vehicle-by-vehicle brake protection systems.

The report presents data obtained in the laboratory on simulated vehicles. Also, of much greater importance is the data obtained in the field tests. Different types of motor vehicles were tested on the highways with various defects introduced in the brake system and distance required to stop obtained.



*One of the three curved bridge models at the University of Maryland used in the tests reported in this article.*

# Behavior of Curved Bridge Models

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**Reported by CONRAD P. HEINS, JR., Associate Professor, and BIJAN BONAKDARPOUR, Research Faculty Assistant, Civil Engineering Department, University of Maryland**

## *Introduction*

THE design and analysis of curved bridge systems has been reported in various research and technical reports (*1, 2, 3, 4, 5*).[1] The use of these techniques by the designer, with some degree of confidence, can be assured only by experimental verification. It is therefore the purpose of this paper to present such verification from the testing of curved bridge models (*6*).

The primary objectives for testing three curved bridge models are the following:

- Determine the load distribution characteristics of radial diaphragms spaced at various intervals when subjected to dead and concentrated loads.
- Investigate the load deformation characteristics of a steel girder system in noncomposite and composite action with a reinforced concrete slab.
- Determine the validity of the *slope deflection* technique in predicting the behavior of a one-, two-, or three-span system of varying stiffness.

## *Definitions*

Special abbreviations and mathematical terms used by the author are defined in the following list:

Z/L —Fraction of span length.
$\mu$ —Units of strain in $10^{-6}$ in./in.
B.S.F—Bare steel frame structure.
N.C. —Noncomposite structure.
C. —Composite structure.
$\sigma_w$ —Warping stress, k.s.i.
$\sigma_{max}$ —Maximum normal stress, k.s.i.
$E_s$ —Modulus of elasticity of steel, k.s.i.
$E_c$ —Modulus of elasticity of concrete, k.s.i.
E —Modulus of elasticity, k.s.i.
G —Modulus of rigidity, k.s.i.
$I_x$ —Bending stiffness of girder, in.$^4$
$I_w$ —Warping stiffness of girder, in.$^6$
$K_T$ —St. Venant Stiffness, in.$^4$

## *Experimental Tests*

### Structural models

The experimental program consisted of building and testing three structural models. Each model consisted of four cold bent 7 I 15.3 steel girders spaced at 2.0 feet, with an interior radius of 50.0 feet and length of 30.0 feet. Fourteen 4 I 7.7 steel diaphragms located between each girder provided radial stiffness. One model consisted of only these steel I girders and diaphragms. The other two models used the same steel structure, but in addition had a 3-inch noncomposite and composite reinforced concrete slab placed on top of the girders. Figure 1 describes the general plan of the model and pertinent dimensions.

Diaphragms and girders were connected by 5-inch by 5-inch by ⅜-inch by 2¾-inch structural angles. These angles were welded to the girder webs, with the outer leg containing bolt holes. The diaphragms were then placed between the angles and bolted into position (fig. 2). This connection permitted easy removal of the diaphragms, thus various structural diaphragm configurations could be tested.

Not including the structural slab, the basic model consisted of curved steel I girders with radial stiffening diaphragms. To examine the structural interaction of the girders and diaphragms, various diaphragm spacings were incorporated into the test program. Series I consisted of radial diaphragms spaced at

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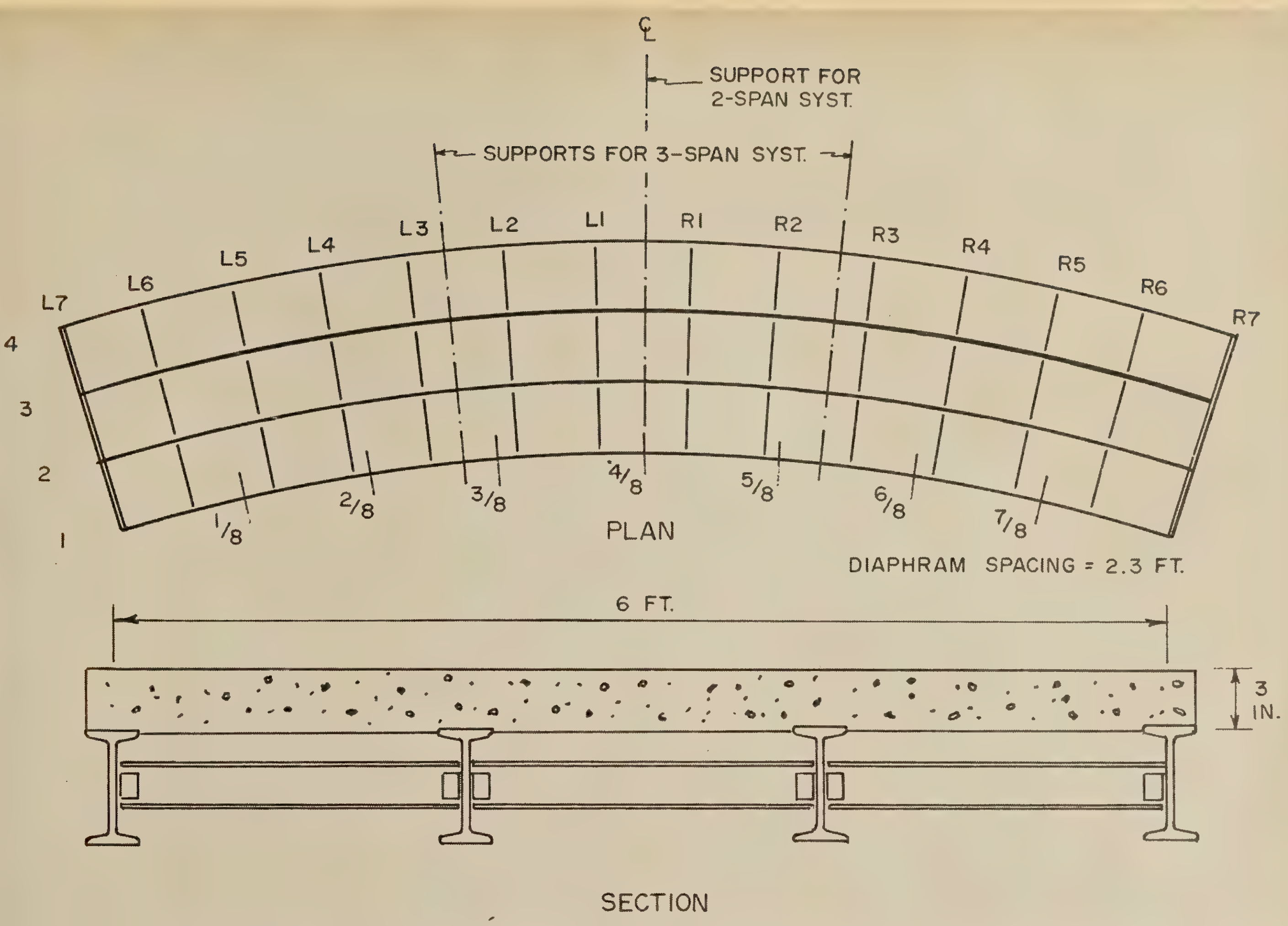
[1] Italic numbers in parentheses identify the references listed on p. 251.



| NAME | SIZE OF MEMBER | ARC LENGTH | RADIUS |
|---|---|---|---|
| GIRDER 4 | 7 I 15.3 | 33.6' | 56.0' |
| GIRDER 3 | 7 I 15.3 | 32.4' | 54.0' |
| GIRDER 2 | 7 I 15.3 | 31.2' | 52.0' |
| GIRDER 1 | 7 I 15.3 | 30.0' | 50.0' |
| DIAPHRAGM | 4 I 7.7 | — | — |

*Figure 1.—Dimension of model.*

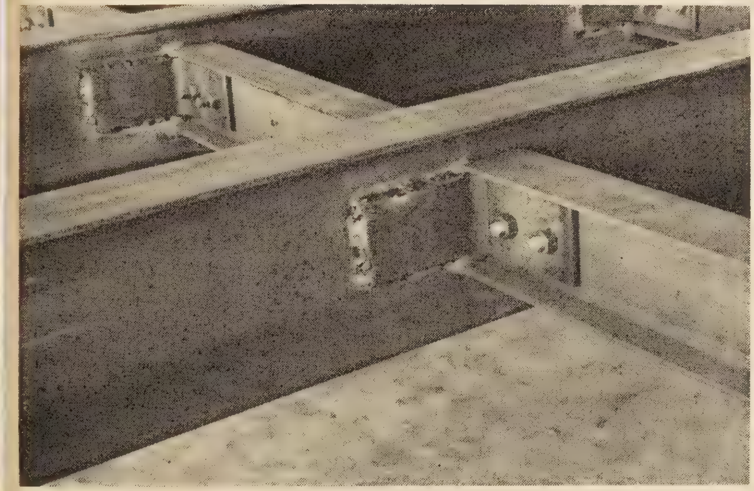


*Figure 2.—Diaphragm and girder connection.*

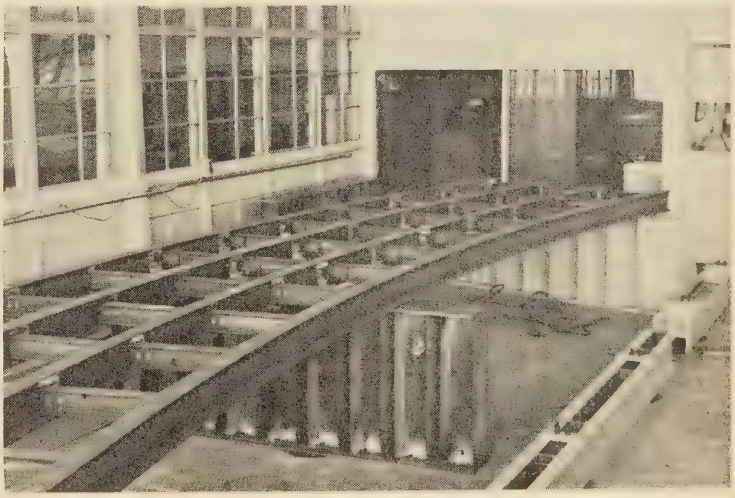


*Figure 3.—Assembled structure.*

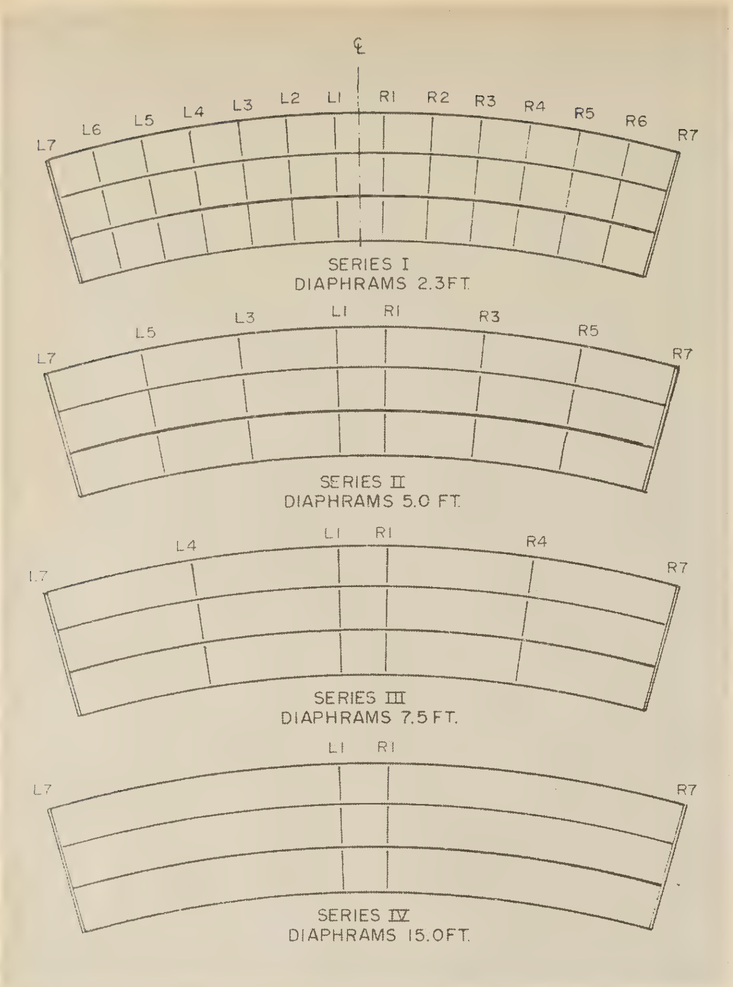


*Figure 4.—Diaphragm series.*

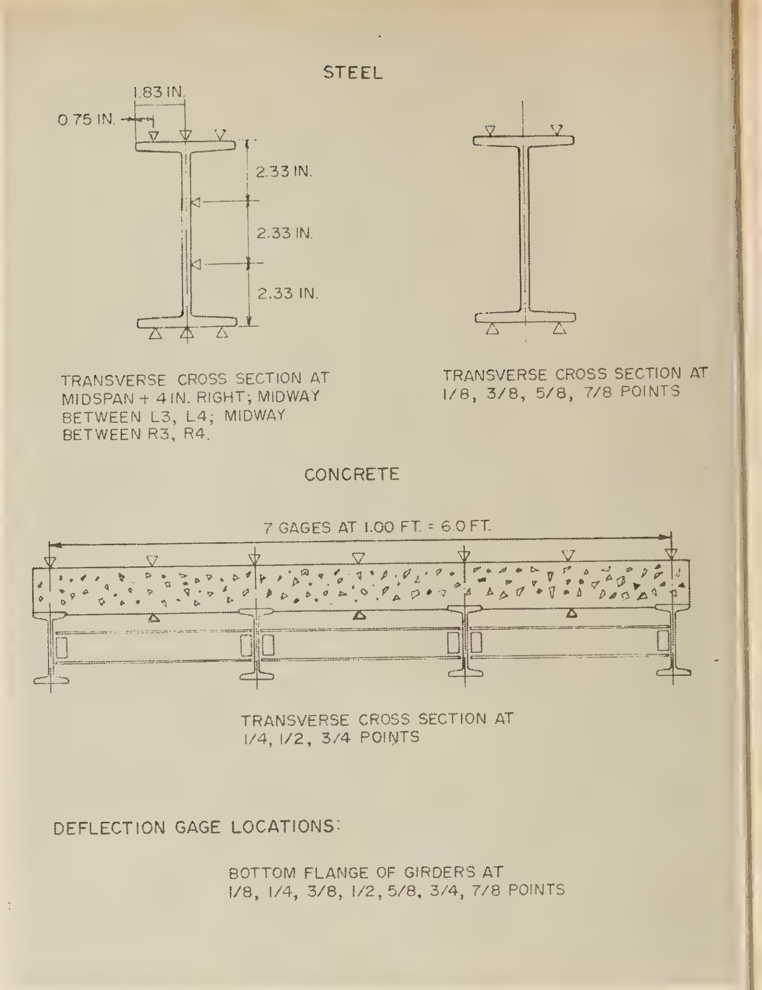


*Figure 5.—Gage locations.*

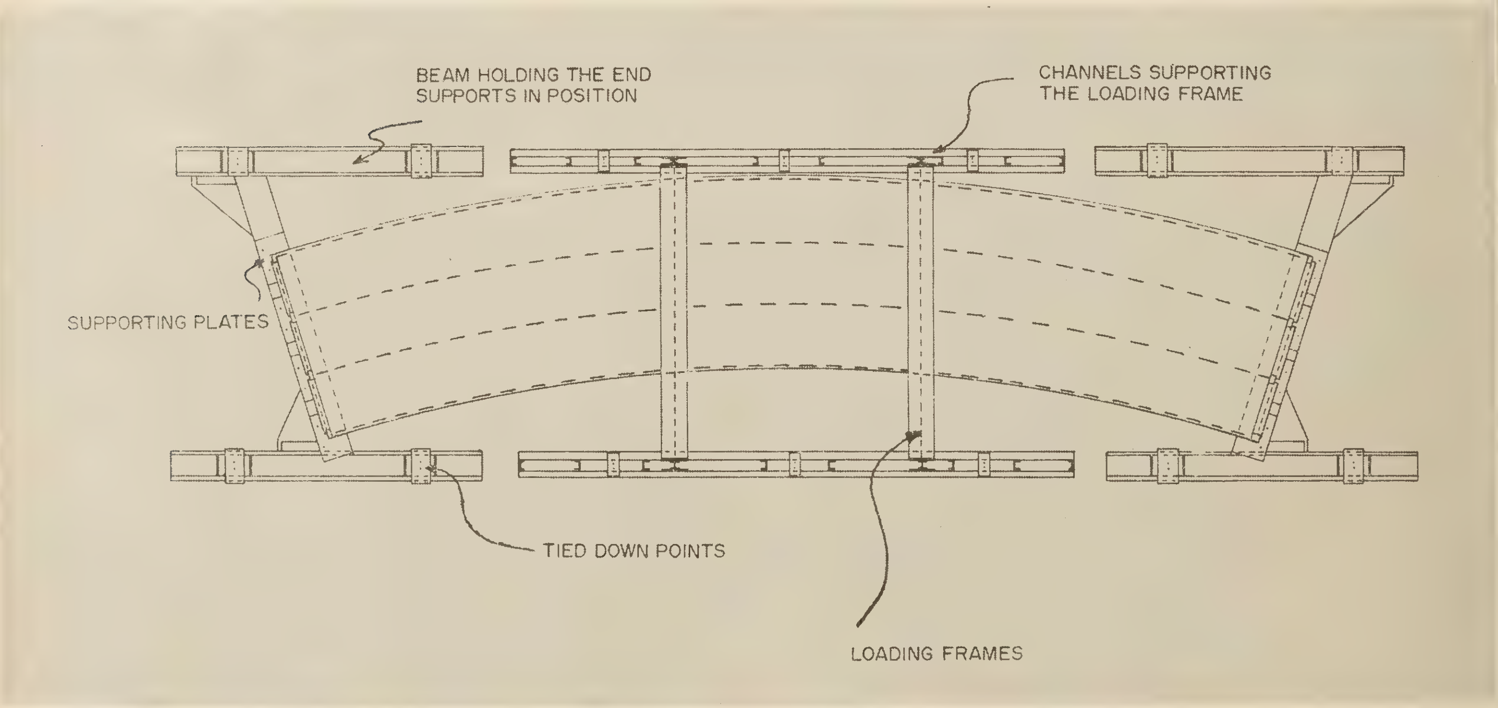


*Figure 6.—General plan of loading frame.*

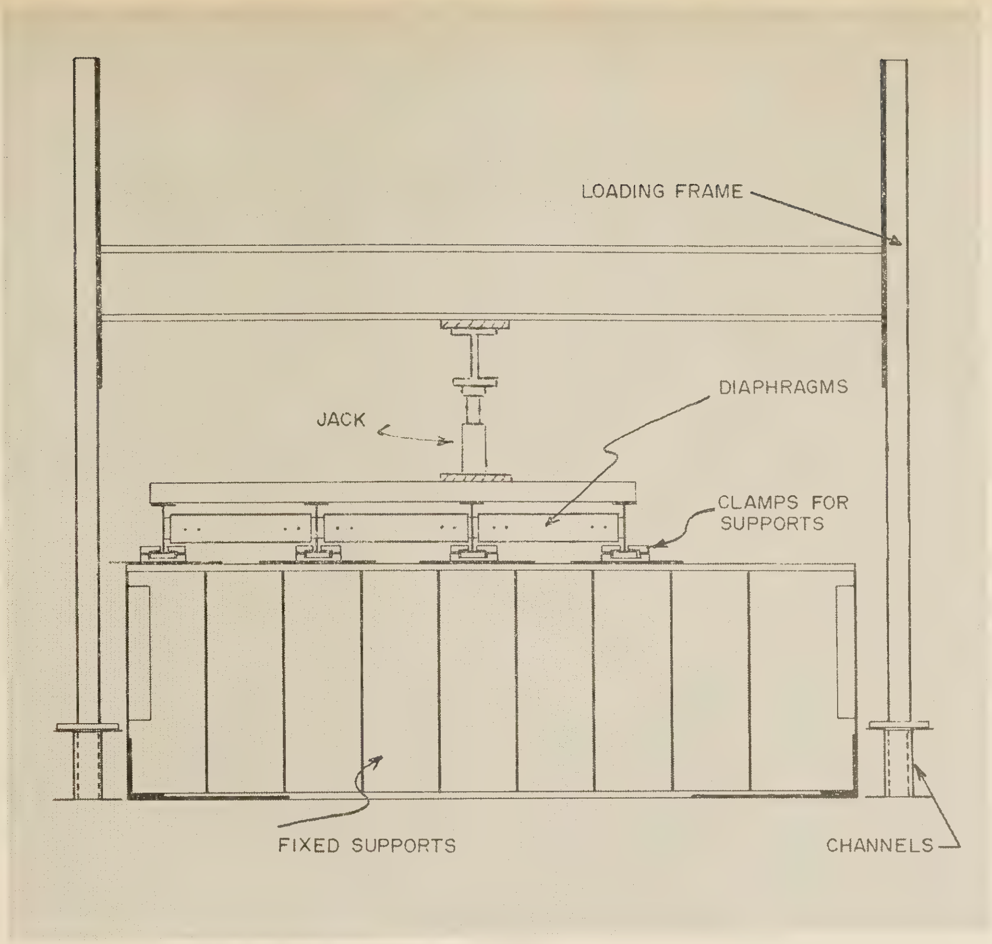


*Figure 7.—Elevation view of loading frame.*

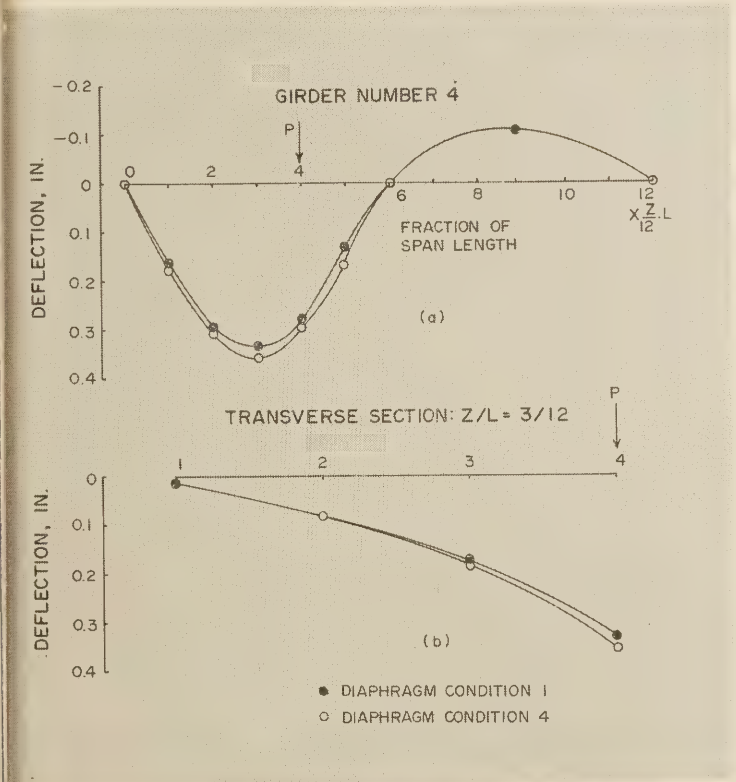


*Figure 8.—Diaphragm effects—noncomposite model.*

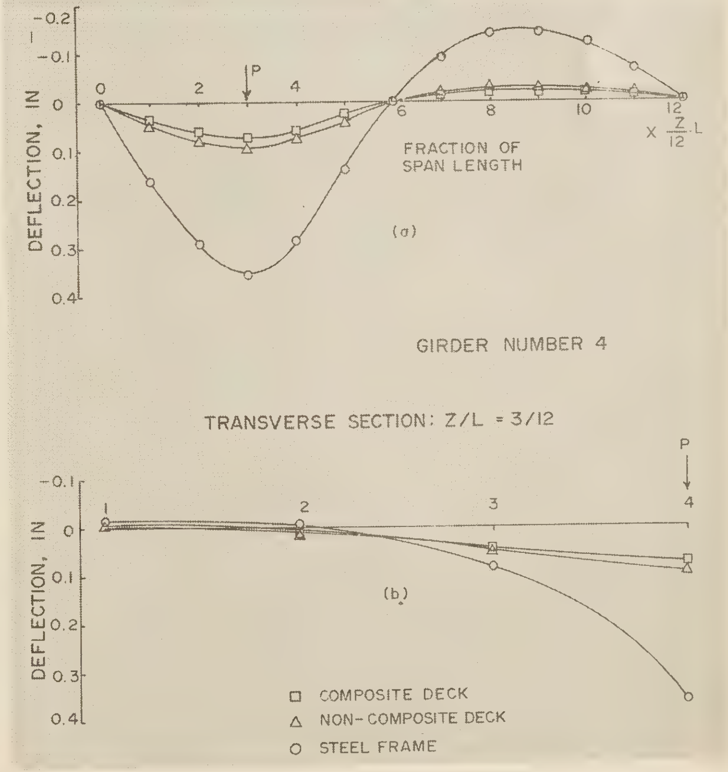


*Figure 9.—Diaphragm series I—all models.*

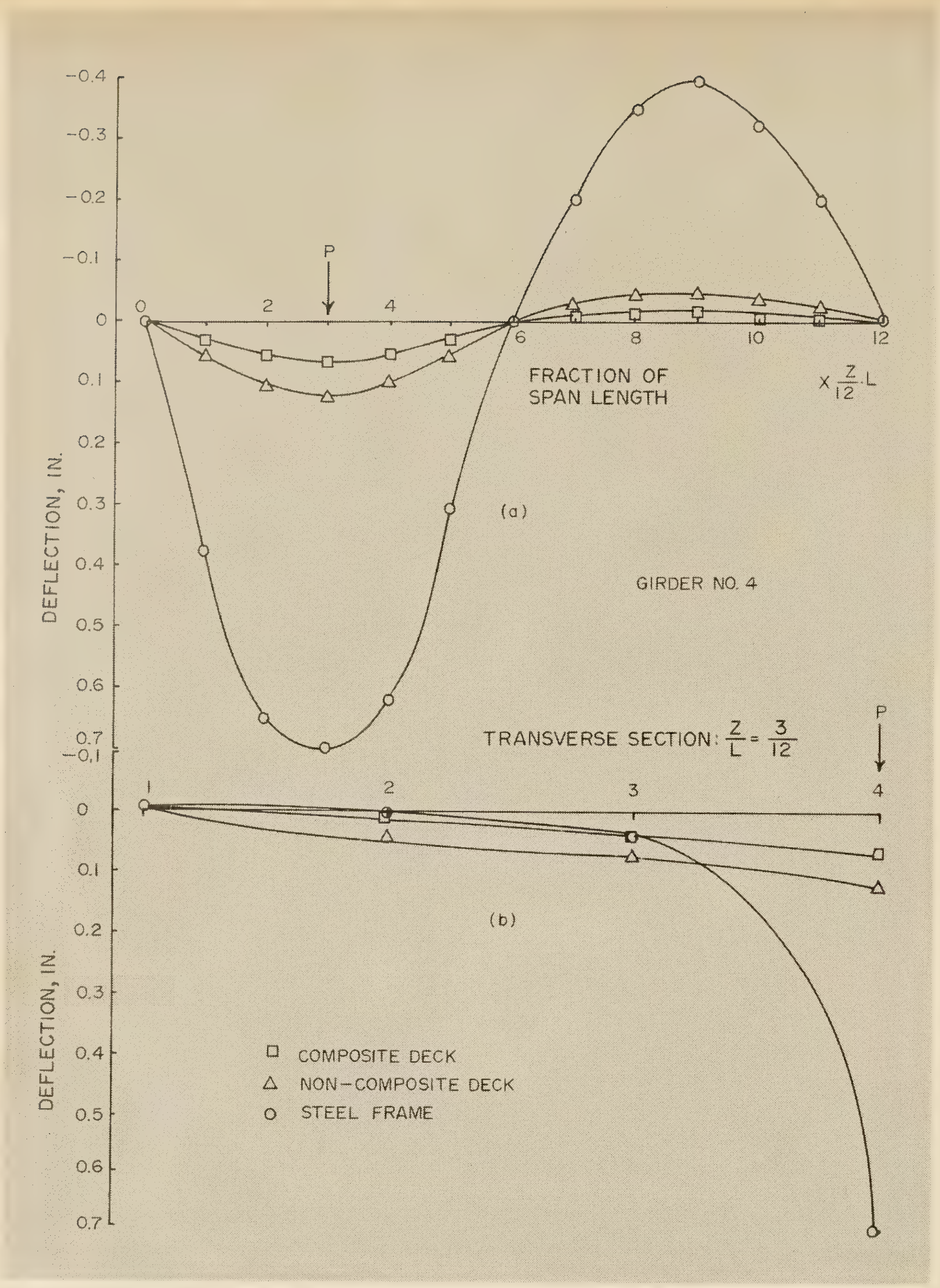


*Figure 10.—Diaphragm series IV—all models.*

longitudinal intervals of 2.3 feet or one-thirteenth of the span lengths. Figure 4 shows this arrangement. The diaphragms are labeled at L1 through L7 and R1 through R7—representing the diaphragms to the left and right of the centerline. Series II had radial diaphragms spaced at intervals of 5.0 feet, beginning at the left of the center (L1) and right of the center (R1) diaphragms. This spacing is approximately one-sixth of the span length. Series III had center diaphragms spaced at intervals of 7.5 feet from the center diaphragms (L1) and (R1). This represents approximately one-fourth of the span length. Series IV consisted of only diaphragms to the left (L1) and right (R1) of the centerline (fig. 4). The spacing of the diaphragm is therefore approximately one-half of the span length. These diaphragm spacings were used to provide some insight into the effects of load transfer by the diaphragms and interaction of the top slab.

### Model details and span configurations

*Bare steel frame structure.*—The basic model was first tested as a single-span structure with simple supports along radial lines (L7) and (R7). Then a roller support was positioned at the centerline between radial lines (L1) and (R1), and the structure was tested as a two-span continuous system. A three-span continuous system was the last structure tested. Interior supports were positioned one-third to the right of radial line (L3) and one-third to the left of radial line (R3). These supports consisted of roller devices, which permitte development of vertical forces but not later forces. Figure 1 describes the location of the supports and figure 3 shows the assemble model.

*Noncomposite structure.*—The noncomposi structure consisted of the bare steel frame an a 3-inch reinforced concrete slab placed on to of the I-girder flanges. The concrete was rei forced by a 6-inch by 6-inch by ¼-inch wi mesh positioned 1 inch from the bottom of th slab. All mill scale was removed from the to of the girder flanges and oil was then applie to ensure no composite action between th slab and girders. Figure 1 describes the gener cross section of the system. The structure wa tested in the single-span, two-span, and three span configurations.

*Composite structure.*—The composite stru ture also consisted of a bare steel frame an 3-inch reinforced concrete; however, th concrete was in composite action with th steel structure by ½-inch round by 2-inc welded studs. These studs were welded alon the centerline of each girder at 10-inc intervals. This structure was also teste in a single-span, two-span, and three-spa configuration.

*Instrumentation.*—Deflection, strain, an rotation data were collected during th testing of all structural models. Deflectio data were obtained by Ames dial deflectio gages located along the bottom flange each girder. These gages were placed a intervals equal to one-eighth of the girde length.

Induced strains on the steel girders an concrete slab were collected by monitorin SR–4 wire strain gages. These gages wer applied to the steel girders (fig. 5). Thre longitudinal gages on both the top an bottom flanges were applied to all four girde located at a midspan section plus 4 inches t the right. Two longitudinal gages were als applied to the web at this section. Figure describes the same gage arrangement applie to girder cross sections midway betwee radial lines (L3) and (L4) and (R3) and (R4)

Additional gages were applied to othe cross sections of the system, but not a extensively. Figure 5 shows two gages applie to the top and bottom flanges of the girder The gages were located at transverse section given in figure 1 as ⅛, ⅜, ⅝, and ⅞ of th span length.

Figure 5 describes the longitudinal strai gages applied to the concrete slab. These gage were positioned on top of the concrete sla over each girder and midway between girder Gages were also applied to the bottom of th slab between girders. These 10 gages wer located at transverse sections at 2/8, 4/8, an ⅞ of the span length (fig. 1). All strain gage were monitored by an automatic digita strain recording machine. The transvers rotations, at various girder sections, wer obtained by a series of level bar-micromete control devices.

*Material Properties.*—Six coupons fro the web and flanges of the I girders wer tested to obtain the modulus of elasticity (E and modulus of rigidity (G). These test

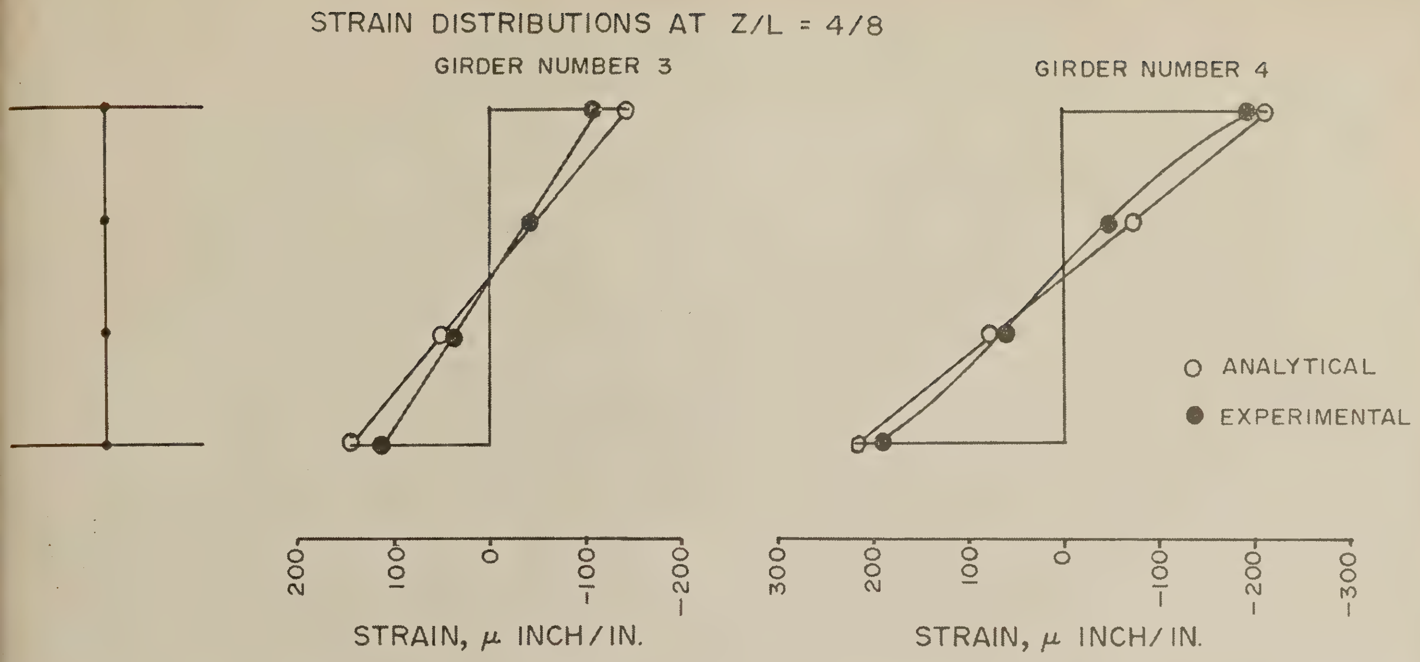


*Figure 11.—Longitudinal strain distribution—bare steel frame model.*

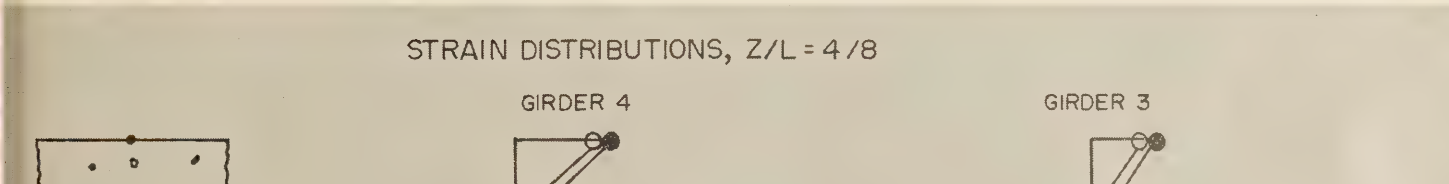


*Figure 12.—Longitudinal strain distribution—noncomposite model.*

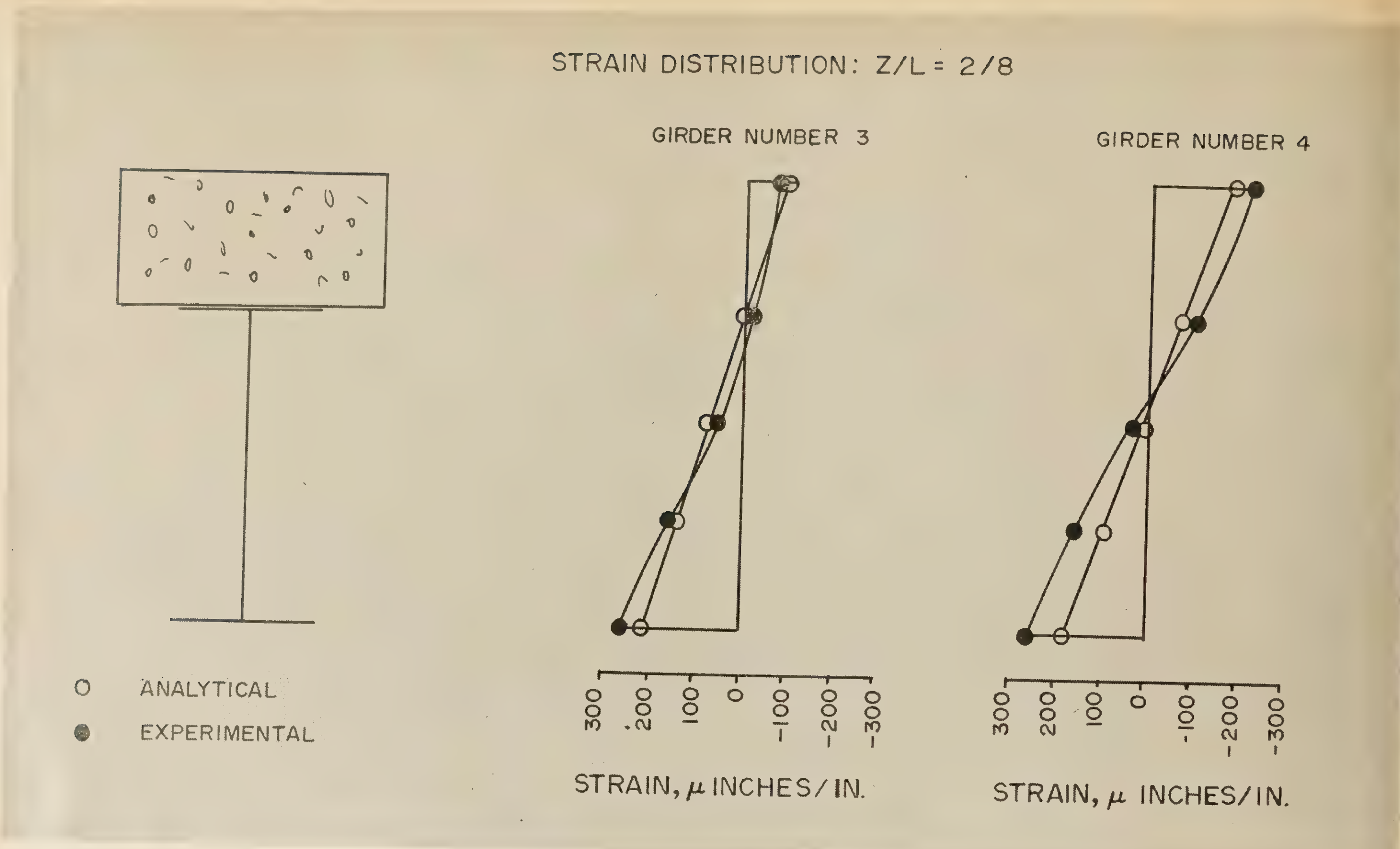


*Figure 13.—Longitudinal strain distribution—composite model.*

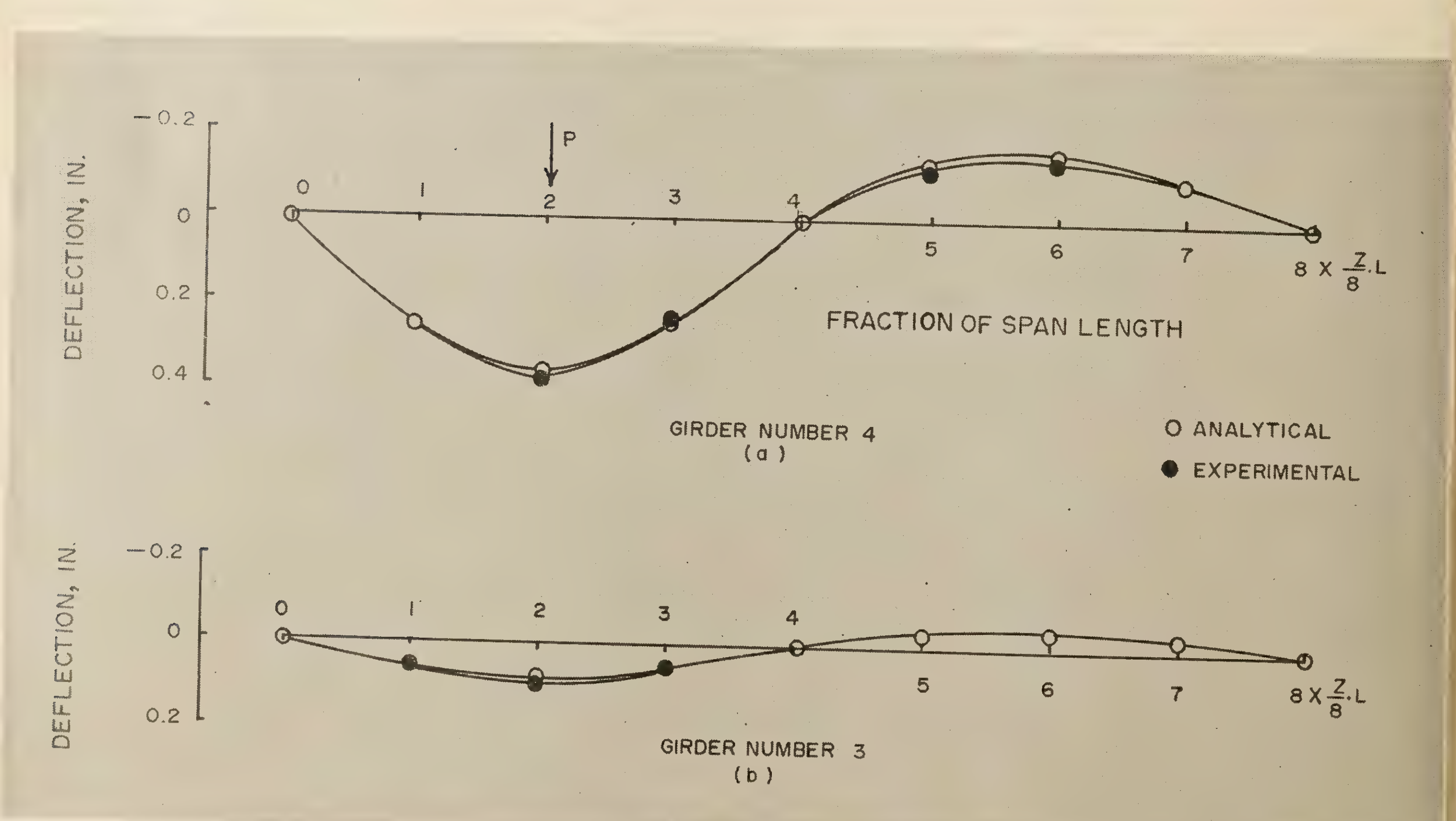


*Figure 14.—Girder deflections—bare steel frame model.*

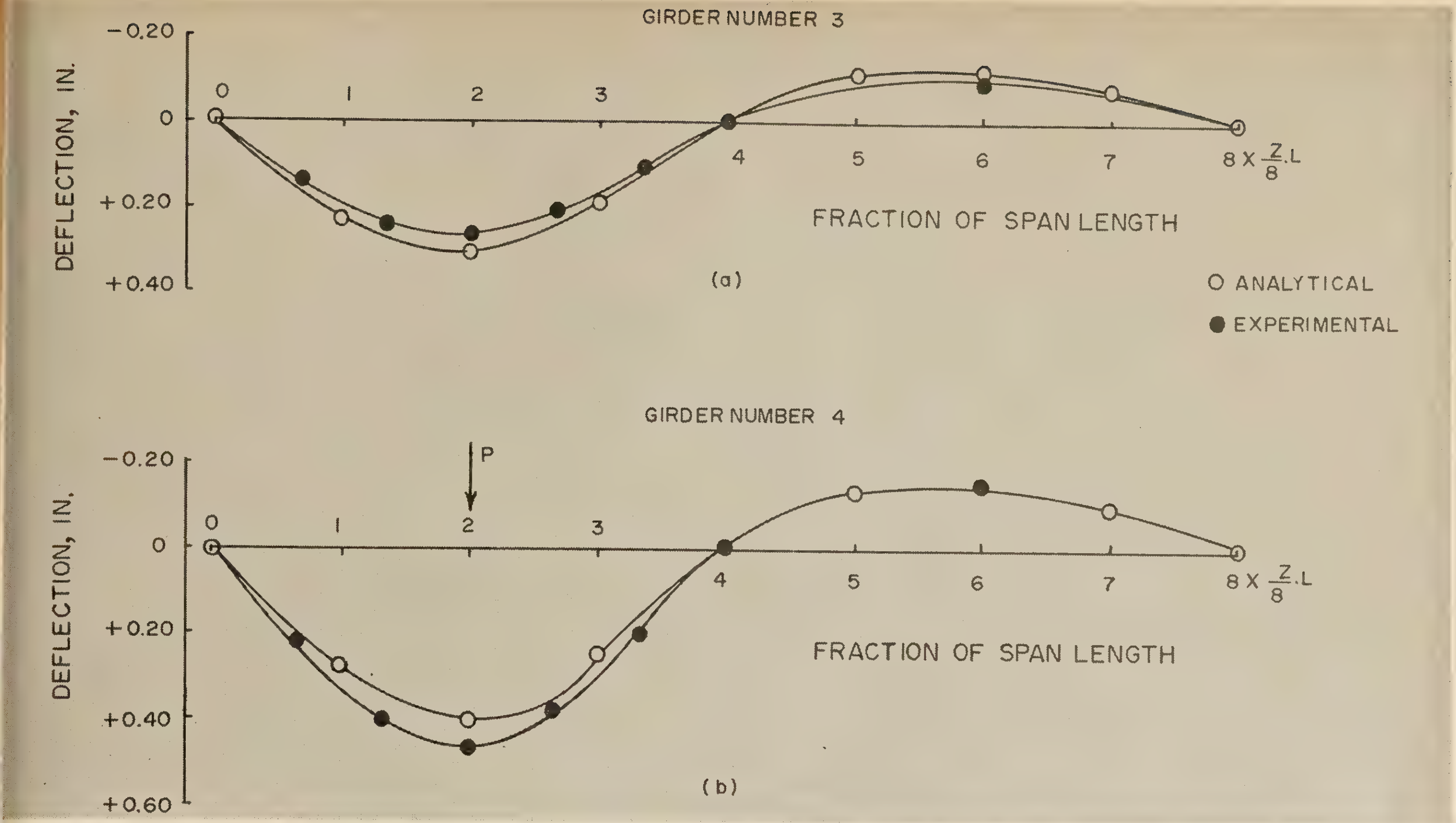


*Figure 15.—Girder deflections—noncomposite model.*

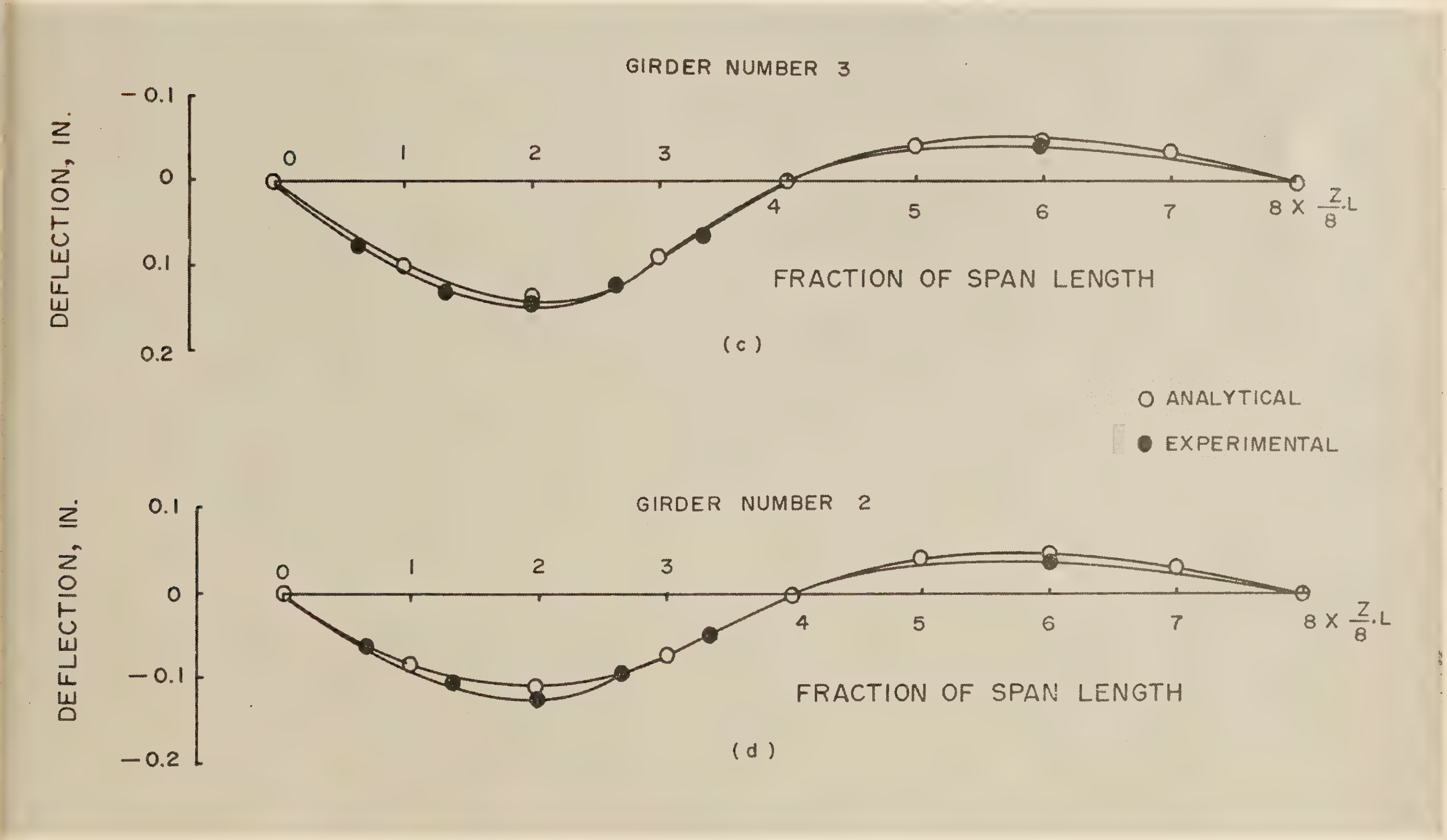


*Figure 16.—Girder deflections—composite model.*

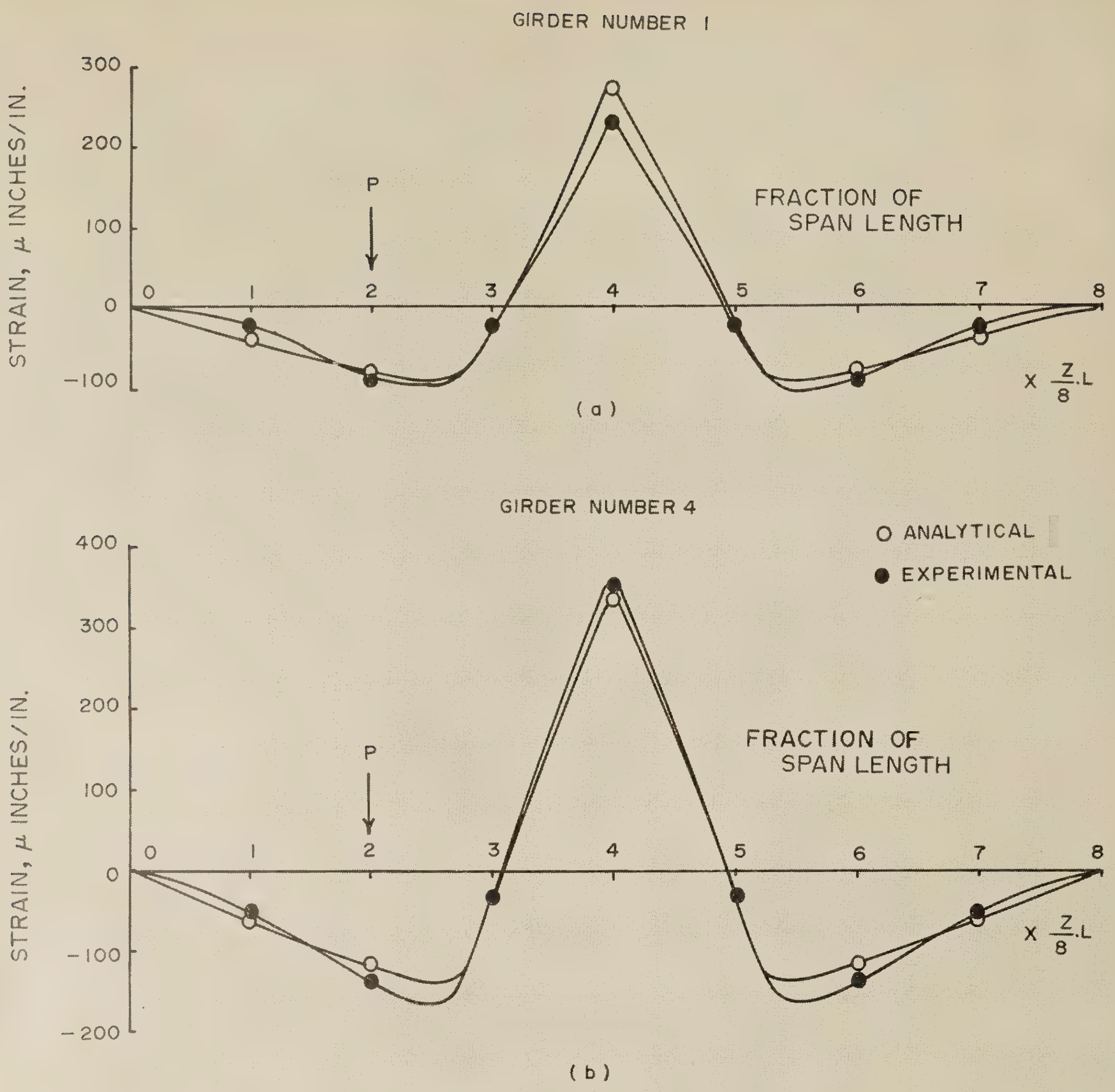


*Figure 17.—Longitudinal strain distribution—bare steel frame model.*

yielded average values of E=27.6×10³ k.s.i. and G=11.2×10³ k.s.i., values which were then used in evaluating the theoretical girder and slab stiffness properties. The material properties of the noncomposite and composite concrete slabs were obtained from compression tests of concrete cylinders. The results from these tests gave an average elastic modulus E=3.7×10³ k.s.i. and G=1.6×10³ k.s.i.

*Loadings.*—Calibrated hydraulic jacks were used to apply concentrated loadings to all models. These jacks were positioned over a loading frame (figs. 6 and 7) and jacked against the frame and model. The cross beam of the loading frame was movable, thus the loads could be applied at various positions. Generally the cross beams were located at positions where the applied loads would create the maximum deformations and strains.

In addition to applied concentrated loads, the effect of the dead load of the structure was examined. This required supporting the systems, zeroing all gages, and then releasing all supports.

The types and ranges of loads applied to each of the models were as follows:

- Bare steel frame structure (32 loading conditions)—dead load, concentrated load 2.5 to 4.0 kips.
- Noncomposite structure (26 loading conditions)—dead load, concentrated load 2.5 t 8.0 kips.
- Composite structure (29 loading conditions)—dead load, concentrated load 2.5 t 10.0 kips.

The number of loading conditions for eacl model represents those loads applied to th single, two, and three-span structures. Also the magnitude of the concentrated loads tha would induce reasonable deformations increased as the model stiffness increased. Som of the locations and magnitudes of the load were duplicated for each model in order t examine the effect of the stiffnesses of th various models.

## Theory

*The Slope Deflection Fourier Series Tech-ique* (*1, 2*) has been developed to analyze urved girder bridge systems. From this evelopment the resulting equations were omputerized (*3*) and a series of preliminary esign equations developed (*4, 5*). The advantages of this technique over the stiffness matrix method presently employed are (*1*) the deck slab is considered as a plate element and not an equivalent beam element; and (*2*) warping stiffnesses of the girders are included. That girder supports are radial and a constant stiffness throughout the girder length must be maintained are primary restrictions of this technique.

**Table 1.—Stiffness properties of bridge models**[1]

| Model | $I_X$ | $K_T$ | $I_W$ | EI | $GK_T$ | $EI_W$ |
|---|---|---|---|---|---|---|
| Interior girder | | | | | | |
| | *In.*$^4$ | *In.*$^4$ | *In.*$^6$ | *K-in.*$^2$ | *K-in.*$^2$ | *K-in.*$^4$ |
| Bare steel frame | 36. 2 | 0. 240 | 29. 5 | $998.0 \times 10^3$ | $2.68 \times 10^3$ | $815.0 \times 10^3$ |
| Noncomposite | 36. 2 | . 240 | 29. 5 | $998.0 \times 10^3$ | $2.68 \times 10^3$ | $815.0 \times 10^3$ |
| Composite | 119. 0 | 31. 14 | 117. 6 | $3{,}280.0 \times 10^3$ | $348.0 \times 10^3$ | $3{,}240.0 \times 10^3$ |
| Exterior girder | | | | | | |
| Bare steel frame | 36. 2 | . 240 | 29. 5 | $998.0 \times 10^3$ | $2.68 \times 10^3$ | $815.0 \times 10^3$ |
| Noncomposite | 36. 2 | . 240 | 29. 5 | $998.0 \times 10^3$ | $2.68 \times 10^3$ | $815.0 \times 10^3$ |
| composite | 72. 5 | 15. 70 | 66. 2 | $2{,}000.0 \times 10^3$ | $176.0 \times 10^3$ | $1{,}830.0 \times 10^3$ |

[1] Where: $E_S=27.6 \times 10^3$ k.s.i.
$G_S=11.2 \times 10^3$ k.s.i.

To use this technique, girder, diaphragm, and slab stiffness properties must be computed. The bending and torsional properties of the steel members are available from references (*7, 8*). Table 1 gives the primary girder properties and their resulting stiffnesses. Torsional properties of the composite girders require modification of the general equations (*9*).

Bending properties are obtained from the conventional equivalent area technique; the resulting stiffnesses are listed in table 1. Note that the effective exterior girder of the composite system is not symmetrical. The evaluation of the neutral axis of this girder indicates that part of the slab is in tension. This tension area of concrete (8 by 3 inches) was therefore neglected in evaluating the bending and warping stiffness properties. The remaining effective slab was 5.83 by 3 inches referenced from the edge of the girder flange. This assumption was verified from strain gage data located near the computed neutral axis location. A modular ratio $E_s$

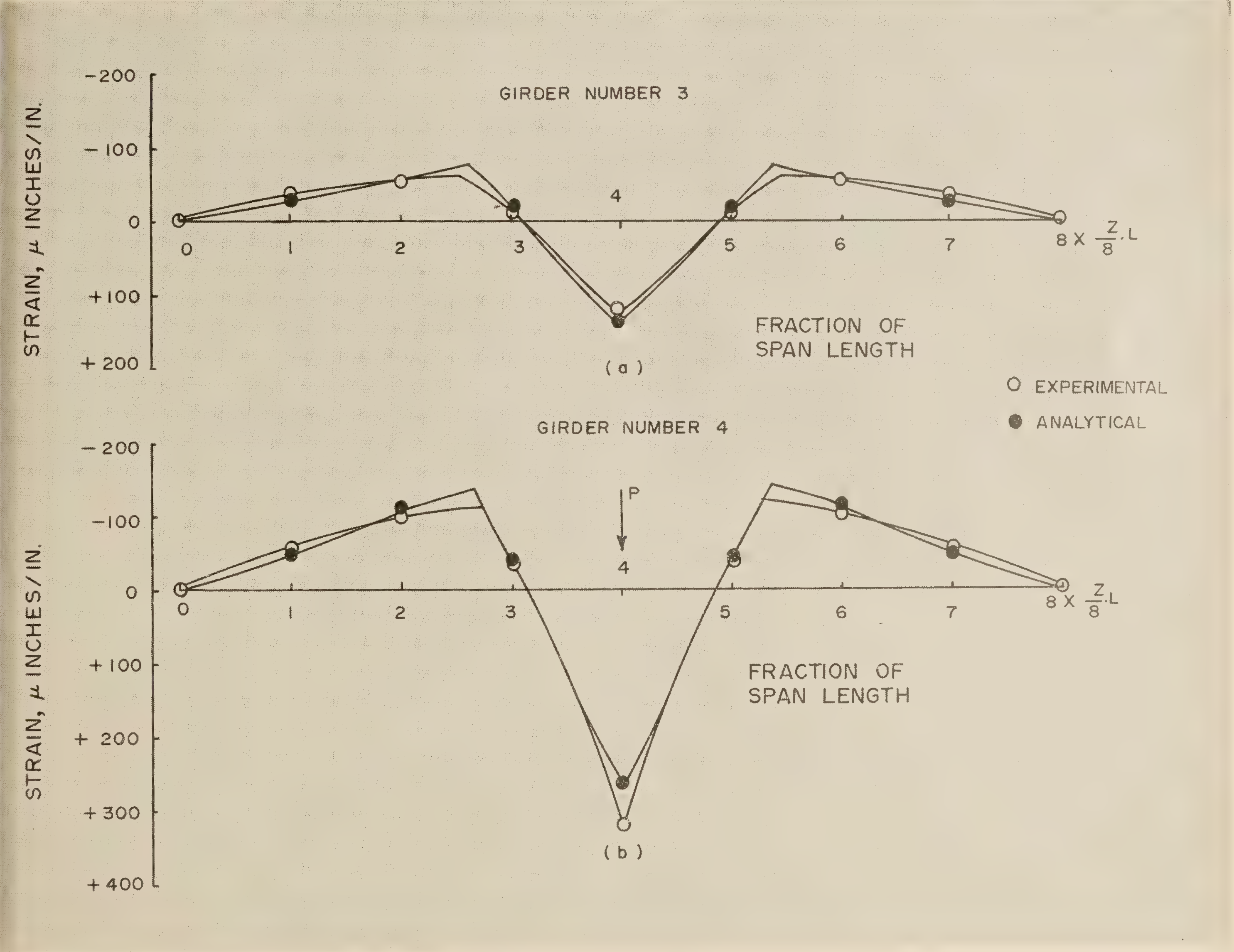


*Figure 18.—Longitudinal strain distribution—noncomposite model.*

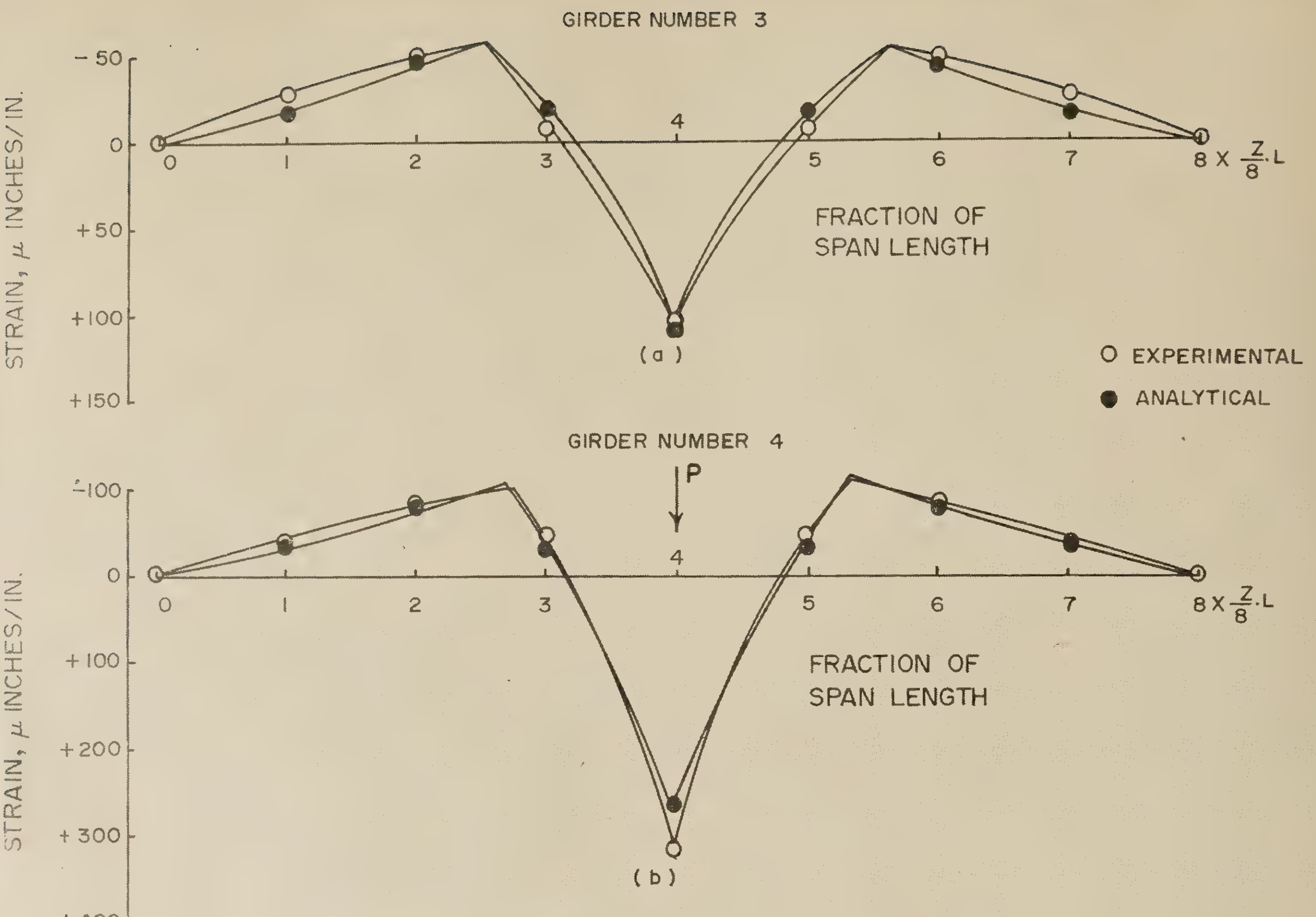


*Figure 19.—Longitudinal strain distribution—composite model.*

$E_c$=7.5 ($E_s$=modulus of elasticity of steel, k.s.i. and $E_c$=modulus of elasticity of concrete, k.s.i.) was used in these calculations.

Using the appropriate girder stiffnesses for the model under investigation and the magnitude and location of the loads applied to the laboratory models, the analysis of the model was performed by the various computer programs (*3, 6*). The resulting data from programs: deflections, rotations, and strains were then compared to the laboratory data.

## *Results of Model Tests*

A total of 87 loading tests were performed. Each test required collecting strain, deflection, and rotation data of the respective models. Because of the voluminous amount of data, only a limited amount will be presented here. The complete set of data and comparative results with theory are in reference (*6*), but the results presented here are representative of all data collected.

### Diaphragm effects

One of the objectives in testing these models was to determine the effect of the radial diaphragms on the load distribution.

Figure 8 shows the influence of the diaphragms on the noncomposite models behavior. The results are for a concentrated load of 6.0 kips applied to outside girder 4 at two-eighths of the model length for the two-span model. Including all diaphragms (series I) and retaining only six diaphragms (series IV) yields negligible results on the deformation of the structure.

This is also true for the composite girder model. However, the behavior of the bare steel frame model is dependent on the number of diaphragms in the system. Figures 9 and 10 describe the deformation of all three models when subjected to a concentrated load on girder 4 at two-eighths of the span length. Figure 9 represents data for series I, with a load P=2.5$^k$. Figure 10 represents the deformation of the system for series IV, with a load P=2.0$^k$.

The difference in deformations (figs. 9, 10) is due to the diaphragms and loads. However, the primary influence on the deformations is caused by the diaphragms (table 2). Table 2 lists the maximum deformations (figs. 9, 10) of girders 3 and 4 for the two-diaphragm series. The ratio of these girder displacements shows that the diaphragms have negligible effec on loading distribution capacity of the noncomposite and composite models. However the influence on the bare steel frame i significant.

### Theory versus experiment

Using the stiffness properties (table 1) the theoretical deflections and strains were evaluated.

Table 3 describes the positions and magnitude of the loads applied to the various laboratory models. A wide variation in loads model configurations, and functions (stresses deflections) were selected to demonstrate the general behavior and comparisons of the theory and test data. The location of the loads was given according to the girder number, where the load was applied, and fraction of span length (Z/L) along the girder (fig. 1).

Figures 6, 11, 12, and 13 show the longitudinal girder strains through the mid-line of the girders. Girder strains, computed analytically and obtained experimentally, are caused by the dead load of the system. Tranverse cross sections are located at midspan or center or centerline (Z/L=4/8) of the single-span configuration for the bare steel frame

**Table 2.—Effect of diaphragms on load distribution**

| Model | Girder 3 deflection | Girder 4 deflection | Ratio of girder displacement [1] |
|---|---|---|---|
| Diaphragm series I [2] | | | |
| | *Inches* | *Inches* | *Percent* |
| Bare steel frame | 0.080 | 0.355 | 22.4 |
| Noncomposite | .050 | .095 | 52.8 |
| Composite | .040 | .070 | 57.0 |
| Diaphragm series IV [3] | | | |
| Bare steel frame | .040 | .700 | 5.7 |
| Noncomposite | .070 | .125 | 56.0 |
| Composite | .040 | .070 | 58.0 |

[1] Girder 3 deflection/girder 4 deflection×100.
[2] Loading for series I--2.5$^k$ on girder 4 at (2/8) L.
[3] Loading for series IV—2.0$^k$ on girder 4 at (2/8) L;

model and noncomposite beam model. The strain data obtained from the composite beam model (fig. 13) is for a transverse section at quarter span (Z/L=2/8).

Figures 14, 15, and 16 describe the experimental and analytical deflections along the span lengths of various girders for the two-span bare steel, noncomposite and composite models. Figure 14 describes the deformations for the bare steel frame models when subjected to a 2.5 kip concentrated load on the outside girder (No. 4) at ¼ of the entire model length. The deformations are plotted along girders 4 and 3. Figure 15 describes the vertical displacements along girders 3 and 4 of the noncomposite model. These deformations are due to concentrated loads (7.0 kips) applied to the inside (No. 1) and outside (No. 4) girders at one-fourth of the model length.

Figure 16 also describes vertical girder displacement resulting from the same loading but applied to the composite model. The displacements are described along interior girders 2 and 3.

Figures 17, 18, and 19 show the maximum strains on the bottom flange of various girders for the three-span structure. Figure 17 shows strains along girders 1 and 4 resulting from a concentrated load (4.5$^k$) applied at one-fourth of the model length. These data are for the bare steel frame model.

Figure 18 describes the strains along girders 3 and 4 of the noncomposite model. The concentrated load (8.0$^k$) was applied on girder 4 at one-half length or midspan.

Figure 19 describes similar strain data on girders 3 and 4, but represents the behavior of the composite model. The load is the same as for the noncomposite model.

**Warping stresses**

A design technique was proposed several years ago (*10*), which accounted for the action of the diaphragms in distributing live load as well as dead load and neglected the slab effects. Results from these laboratory studies indicate that the effect of the diaphragm on live-load distribution is negligible. Therefore, the diaphragms should only be designed for dead-load effects and erection considerations. Possibly a temporary system should be utilized until the concrete slab has been placed and cured.

In analyzing all the laboratory data the following information was obtained relating the maximum normal stresses ($\sigma_{max}$) and the warping stresses ($\sigma_w$) for the various structures:

- Bare steel frame model $\sigma_w = (20-25\%)\ \sigma_{max}$
- Noncomposite model $\sigma_w - (10=15\%)\ \sigma_{max}$
- Composite model $\sigma_w - (10=12\%)\ \sigma_{max}$

**Table 3.—Location and magnitude of applied loads for data presented**

| Figure No. | Location of load | | Magnitude of load | Plot | System | Diaphragm series | Span configuration |
|---|---|---|---|---|---|---|---|
| | Girder No. | Z/L [1] | | | | | |
| | | | (*Kips*) | | | | |
| 11 | 1, 2, 3, 4 | | Dead load | Strain | B.S.F.[2] | 1 | 1 |
| 12 | 1, 2, 3, 4 | | do | do | N.C.[3] | 1 | 1 |
| 13 | 1, 2, 3, 4 | | do | do | C.[4] | 1 | 1 |
| 14 | 4 | 2/8 | 2.5 | Deflection | B.S.F.[2] | 1 | 2 |
| 15 | 1, 4 | 2/8 | 7.0 | do | N.C.[3] | 1 | 2 |
| 16 | 1, 4 | 2/8 | 7.0 | do | C.[4] | 1 | 2 |
| 17 | 1, 4 | 4/8 | 4.5 | Strain | B.S.F.[2] | 1 | 3 |
| 18 | 4 | 4/8 | 8.0 | do | N.C.[3] | 1 | 3 |
| 19 | 4 | 4/8 | 8.0 | do | C.[4] | 1 | 3 |

[1] Z/L—Fraction of span length.
[2] B.S.F.—Bare steel frame structure.
[3] N.C.—Noncomposite structure.
[4] C.—Composite structure.

## *Conclusions*

Results from testing a curved model of varying structural configurations—steel frame, noncomposite concrete deck, and composite concrete deck—can be predicted by a proposed slope deflection technique. The analytical technique accommodates a single-span, two-span or three-span structure.

Analytical techniques may be used to evaluate the behavior of actual curved highway bridges. Thus, by using the preliminary design equation (*5*) and the general computer programs (*3*), the bridge engineer can accurately evaluate the forces and deformations in curved bridge systems.

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(*6*) *Analytical and Experimental Study of a Curved Bridge Model*, by B. Bonakdarpour and L. C. Bell, Research Report No. 34, Civil Engineering Department, University of Maryland, June 1970.

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(*8*) *Manual of Steel Construction*, 7th ed., AISC, New York, 1970.

(*9*) *Torsional Properties of Composite Steel Bridge Members*, by J. T. C. Kuo and C. P. Heins, Research Report No. 37, Civil Engineering Department, University of Maryland, June 1970.

(*10*) *U.S.S. Highway Structures Design Handbook*, Pittsburgh, Pa., 1965.

*Analytical plotter with a photo of building wall that served as an imaginary retaining wall for the reported research.*

# Determination of Motion and Deflection of Retaining Walls

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**Reported by[1] S. A. VERESS,**
**Associate Professor of Civil Engineering,**
**University of Washington**

THE MOTION and deflection of many retaining walls, dams, and bridges must be determined or kept under constant surveillance.

Terrestrial photogrammetry could be used effectively and economically to determine these motions and deflections because it provides information about the whole surface instead of one point at a time. Further, photographs can be kept as permanent records and can be reevaluated at any time.

If photogrammetry is used for determining the motion and deflection of retaining walls, it is necessary to use the method which provides the utmost accuracy because the maximum deflection of these structures seldom exceeds 4 inches. An elaborate investigation was conducted to find the optimum geometry and computational procedure to provide the highest degree of accuracy.

The theoretical findings were justified by practical experimentation. A simulated retaining wall consisting of an array of targets mounted on a building was used for this experiment. The targets were movable so that any deformation could be introduced and measured. Such a target is shown in figure 1.

Target positions were determined precisely with a Wild T-2 theodolite from a base line. Photogrammetric target positions were determined from photographs using two different cameras—a Galileo Santoni Verostat terrestrial camera (fig. 2) and a standard 6-inch focal length aerial camera modified for terrestrial use (fig. 3). Data obtained with these cameras were evaluated by two different instruments—the Galileo Santoni Stereosimplex IIc, shown in figure 4, and the O.M.I. Analytical Plotter (AP/C) shown in figure 5.

Besides the instrumentation, the evaluation methods consisted of three basic approaches: Analogical or instrumental, semi-analytical, and analytical. A solution was found by which errors inherent in the photogrammetric method can be largely corrected. This solution is equally applicable to analytical and semi-analytical methods.

The best accuracy was obtained by the analytical method using the AP/C as a comparator. The residual standard error of the photogrammetric process was ±0.04 inches when photographs were taken at 175 feet from the retaining wall. A lesser degree of accuracy resulted from using the semi-analytical method which produced ±0.05–0.06 inch standard residual error. The analogical method is not recommended for practical use.

The first phase of the research project was concluded by establishing a photogrammetric method capable of providing the required accuracy. The second phase consisted of experimentation designed to determine the minimum deflection of the wall detectable by photogrammetric methods. Two types of

---

[1] Based on *Determination of Motion and Deflection of Retaining Walls*, Final Technical Report, Part II—Technical Applications, by S. A. Veress, Principal Investigator, and G. E. DeGross, Research Assistant, Department of Civil Engineering, University of Washington, Seattle, Wash., 1971.

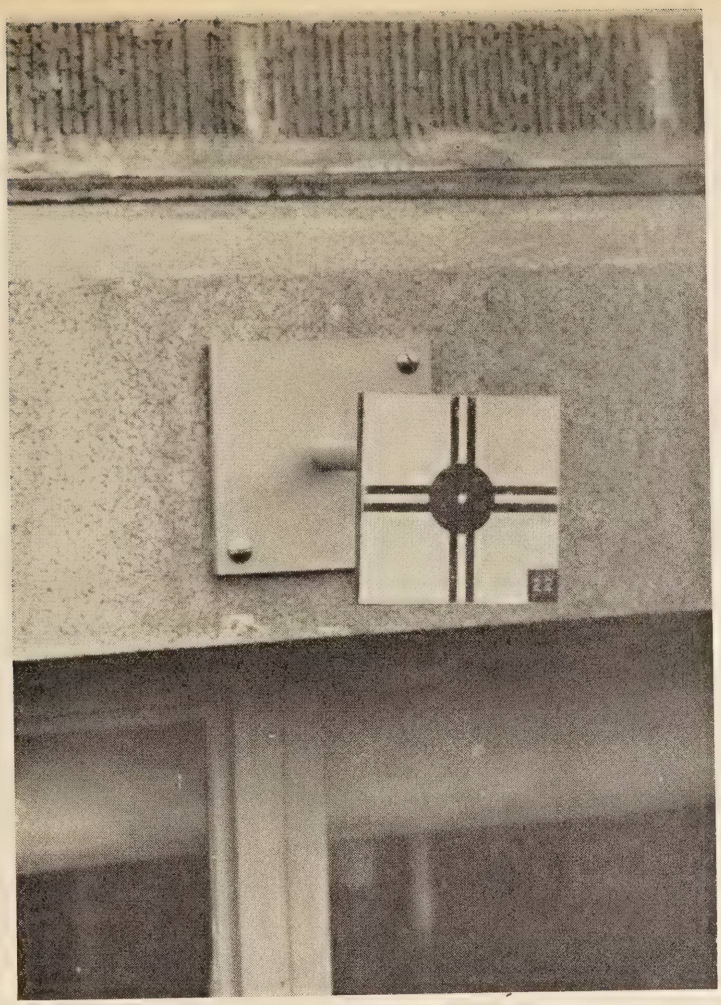

*Figure 1.—Target mounted on simulated retaining wall.*

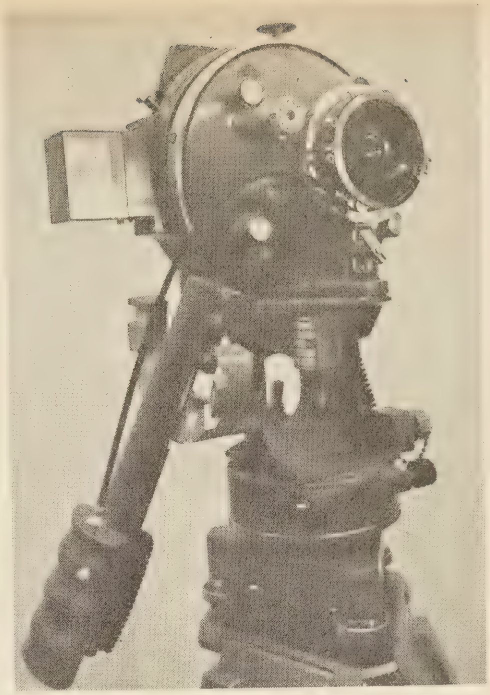

*Figure 2.—Galileo Santoni Verostat terrestrial camera.*

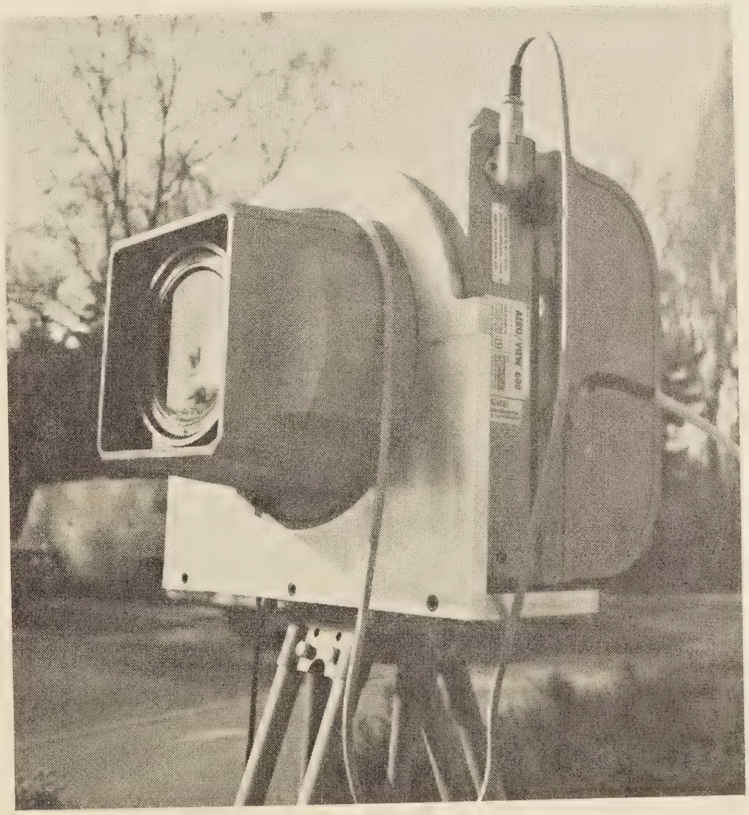

*Figure 3.—6-inch focal length aerial camera.*

deflection were determined—the absolute deflection and the relative deflection.

In the absolute deflection it was assumed that four control points were located on but independent of the wall because they were anchored behind the stability slope of the soil. The photogrammetric models were adjusted to fit these control points. As the relative deflection studies assumed no such points, the control points were also deflected.

It was found that the minimum photogrammetrically detectable deflection of a retaining wall is about 0.15 inch in either the absolute or relative deflection, or about three times the standard residual photogrammetric error.

Research results proved that a photogrammetric method was capable of providing for monitoring purposes continuous data from retaining walls, potential slide areas, dams, and bridges. The economical feasibility study incorporated into the research shows that the method is about 50 percent more economical than the conventional method currently used.

A modified version of the method developed during this research project has been implemented for bridge survey by the U.S. Army Corps of Engineers, Seattle District, since March 1971. They are using a Wild P30 phototheodolite to obtain the required photographs and a Wild A-7 autograph as a comparator for photo-coordinate measurements.

In the State of Washington three bridges—the Wynoochee, the Mud Mountain, and the Tacoma Reservoir—are being surveyed using terrestrial photogrammetry. All these bridges are about 300 feet long. Photogrammetry will also be used to supplement conventional survey techniques on four longer bridges in the Columbia River area.

The photogrammetric residual error obtained by the U.S. Army Corps of Engineers in routine practice is about ±0.02–0.04 inch. This corresponds to or is slightly better than that obtained during this research project.

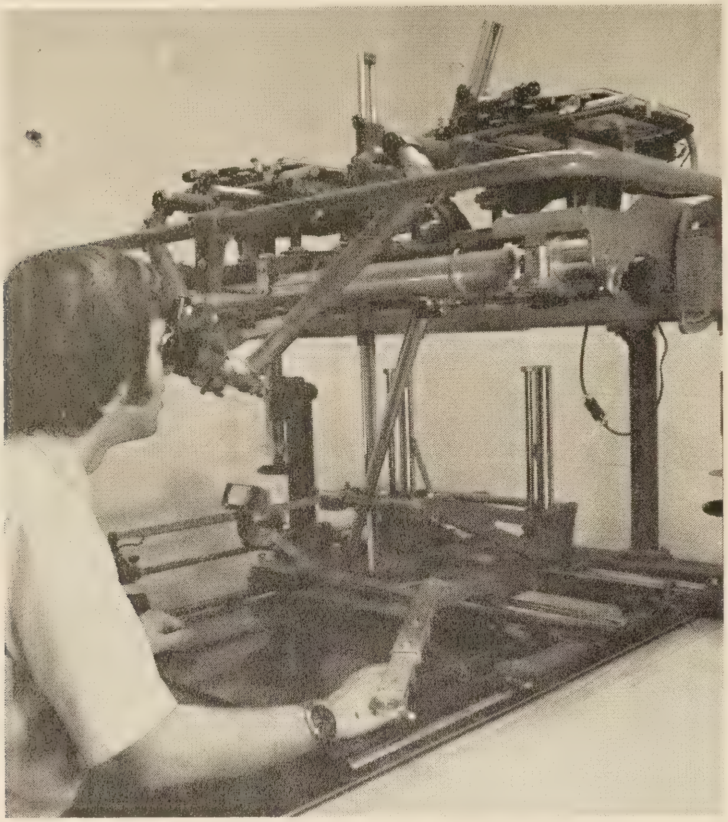

*Figure 4.—Galileo Santoni Stereosimplex IIc.*

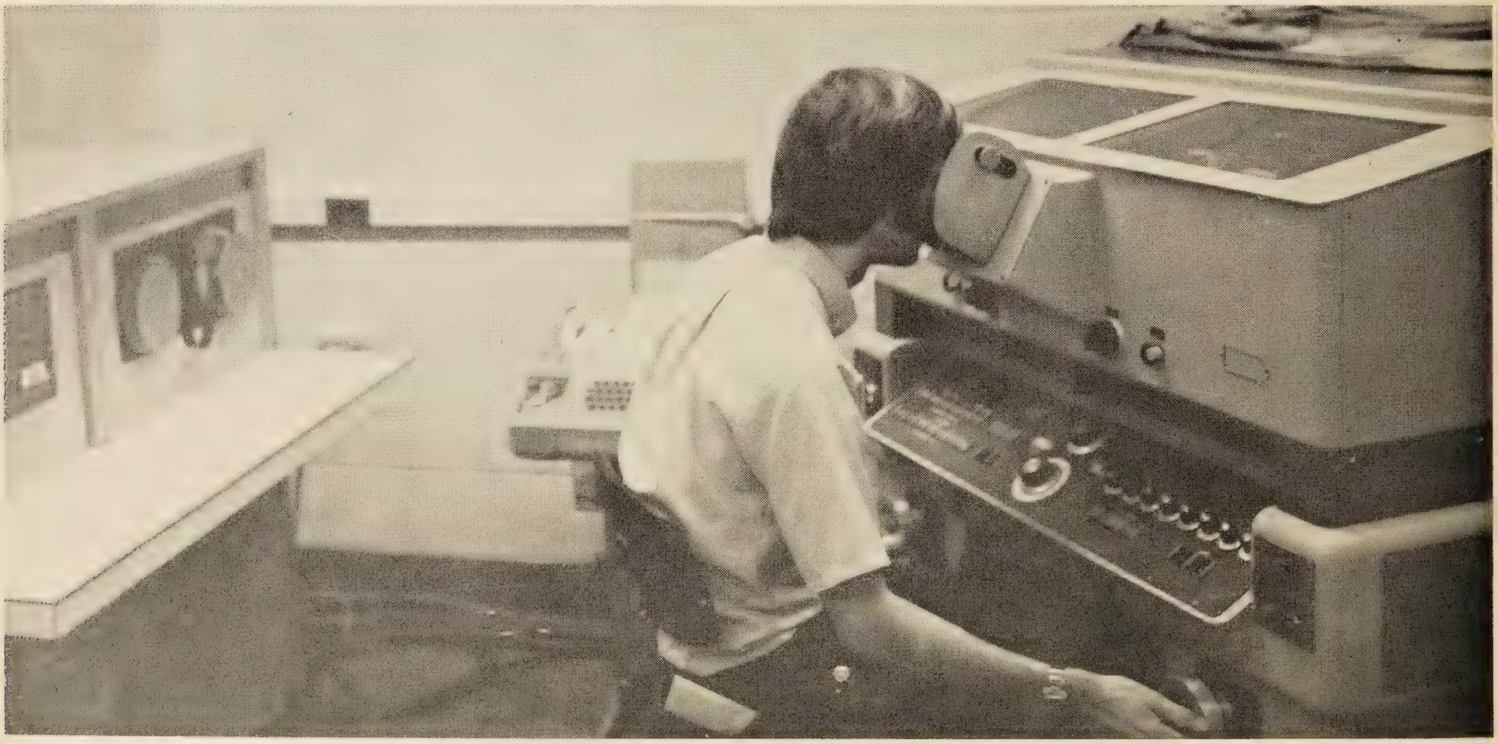

*Figure 5.—O.M.I. Analytical Plotter (AP/C).*

# Digest of Recent Research and Development Results

**Reported by the Implementation Division, Office of Development**

*The items reported here have been condensed from highway research and developement reports, predominantly of Federally aided studies. Not necessarily endorsed or approved by the Federal Highway Administration, the items have been selected both for their relevancy to highway problems and for their potential for early effective application.*

*Each item is followed by source or reference information. Reports with an "NTIS" reference number are available in microfiche (microfilm) at 95 cents each or in paper facsimile at $3 each from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Va. 22151.*

## ORGANIC-ZINC PRIMER IMPROVES STEEL BRIDGE COATING

An *organic-zinc-rich* primer is more economical and time-saving for prime coating of steel bridges than is the present *basic lead silico chromate* coating frequently used. Life expectancy is considered equal or better, and there are other protective advantages according to accelerated exposure tests (salt fog and weatherometer) in Louisiana on five generic types of the new primer with their respective topcoats. The organic-zinc system is considered most advantageous for maintenance.

*Evaluation of Organic-Zinc Coatings*, Louisiana Department of Highways, Study No. 69-1Ch(B).

## LIME STABILIZATION OF SWELLING SOILS

Lime treatment of swelling subgrade soils in South Dakota during construction reduces the expected heaving and thus provides better rideability. A 6-year evaluation study of 16 projects provides proof that the benefits of lime stabilization are permanent with respect to reduced road roughness and increased stability. Supporting data for these conclusions were obtained from high-speed roughometer tests, swell measurements from CBR tests, modified field CBR and plate load tests, pH tests, and Atterberg limit tests.

*Lime Research Study, South Dakota Interstate Routes—Final Report.* South Dakota Department of Highways, Study No. 622(65).

## DESIGNING FOR SAFER HIGHWAYS

Structural concepts for reducing highway vehicle exposure to roadside obstructions are featured in a 3-volume report which embodies the highway engineering approach to safer highways. A product of the 4S program, *Structural Systems in Support of Highway Safety,* sponsored by the Federal Highway Administration, the report is a solid technical response to the objectives of the accelerated program. It identifies bridge concepts and sign and lighting system concepts that are responsive to safety-related design criteria—either eliminating solid obstructions in the vicinity of the traveled way, or using energy-absorbing devices and structural arrangements which minimize the severity of impact with such obstacles as cannot be eliminated. The report was recently distributed nationally to all State highway departments.

*New Structures Concepts for Highway Safety.* Three volumes. Study by Southwest Research Institute, NTIS Nos. for the three volumes are PB 187781, 187782, and 187783 respectively.

## CANTILEVERED SIGNS AID SAFETY

A notable example of highway safety implementation is described in a recent report on design, evaluation, and application of a unique sign structure consisting of a cable-tensioned cantilever-type A-frame with curved center-section members and straight end section. The study included evaluation of in-service performance of a full-scale prototype sign structure with a setback of 36 feet, 9 inches, at the base. The sign end closest to the pavement has a 3-foot offset from the pavement and a 16-foot vertical clearance. The study, by the New York Department of Transportation, was entirely supported by the State. The report was recently distributed nationally to all State highway departments.

*Field Testing of an Experimental Sign Structure.* New York Department of Transportation Research Report 69-7. NTIS No. PB 189302.

## NEW DESIGN PROCEDURE FOR DRILLLED SHAFT FOOTINGS

A new design procedure for drilled shaft footings supporting signs, light standards, strain poles, and other minor service structures has been field tested. It promises to moderate the general design practice of using a highly conservative factor of safety to compensate for lack of knowledge. The new design theory, significantly more sophisticated than the old, is based specifically on static lateral loads of short duration, but also relates performance to dynamic and long-term loads. (Footing resistance to single dynamic loads exceeded the static pullover resistance predicted by the theory for 5 degrees rotation.)

Sophistication notwithstanding, the new design procedure is extremely easy to apply, since it is based on using design curves rather than applying cumbersome equations. Specific information on parameters of soil characteristics, if lacking, will probably dictate some conservatism by the designer, but will still represent a considerable improvement over present methods. The published report presents an example problem, including a section on estimating the soil parameters necessary for the footing design.

*Design Procedure Compared to Full-Scale Tests of Drilled Shaft Footings; Dynamic Overturning Loads on Drilled Shaft Footings; and Long Term Overturning Loads on Drilled Shaft Footings.* January 1970. Texas Highway Department Study No. 2-5-67-105. Research Reports Nos. 105-3, 105-4, and 105-5F respectively. NTIS No. PB 194953.

## PAVEMENT JOINTS ARE PUMPING AGAIN

California investigators have found that violent pumping action of water under increasingly heavy and more frequent truck loadings has eroded stabilized base and redeposited the material to cause slab joint faulting, occasionally up to almost ¼ inch.

Eliminating the problem means taking positive steps to:

1. Keep the water out of the pavement system.
2. Remove quickly any water that does enter.
3. Build dense stabilized erosion-resistant base courses.
4. Utilize fully stabilized erosion-resistant shoulders adjacent to slabs.
5. Maximize the bond between the slab and its base course.

The alternative may mean many sections of prematurely rough riding pavements.

*California Pavement Faulting Study.* Interim Report. Study No. D-3-32. Available from Department of Public Works, Division of Highways, P.O. Box 1499, Sacramento, Calif. 95807.

# Highway Research and Development Reports Available from the National Technical Information Service

*The following highway research and development reports are available from the National Technical Information Service (formerly the Clearinghouse for Federal Scientific and Technical Information), Sills Building, 5285 Port Royal Road, Springfield, Va. 22151. Paper copies are priced at $3 each and microfiche copies at 95 cents each. To order, send the stock number of each report desired and a check or money order to the National Technical Information Service. Prepayment is required.*

*Other highway research and development reports available from the National Technical Information Service will be announced in future issues.*

### *STRUCTURES*

| *Stock No.* | |
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| PB 190626 | Consolidation Practices in Concrete Pavement Construction. |
| PB 198326 | A study of Untreated, Emulsion-Treated, and Asphaltic-Cement-Treated Bases, Experimental Ring No. 3. |
| PB 199359 | An Experimental Self-Stressing Pavement, Route 2, Glastonbury (Final Report). |
| PB 199419 | Operation and Installation Instructions for an Energy-Absorbing Bridge Rail System. |
| PB 199420 | Energy-Absorbing Bridge Rail—Fragmenting Tube. |
| PB 200664 | Prestressed Concrete Bridge Girder Design Program. |
| PB 200666 | An Experimental Study of Cross-Bending of Curved Compression Flanges in Fish-Belly Haunched Plate Girders. |
| PB 200668 | Relaxation Losses in Stress-Relieved Special Grade Prestressing Strands. |
| PB 200671 | Experimental Evaluation of Subgrade Modulus and Its Application in Small-Dimension Slab Studies. |
| PB 200672 | An Element for Anisotropic Skew Plates and Grids. |
| PB 200718 | Behavior of Composite Beams Subjected to Torsion. |
| PB 200961 | Structural Behavior of the South Road Curved Girder Bridge. |
| PB 201059 | Maintenance Management System Implementation. |
| PB 201062 | The Whitewater Experimental Project—an Instrumented Roadway Test Section to Study Hydrogenesis (Final Report). |
| PB 201098 | A Study of I-Section Prestressed Concrete Girders Subject to Torsion, Shear, and Bending. |
| PB 201150 | A Study of Pavement Skid Resistance at High Speeds and at Locations Shown to be Focal Points of Accidents, Phase I Report. |
| PB 201153 | Field Testing of Horizontally Curved Steel Girder Bridges. |
| PB 201155 | Landslide Studies in South Dakota. |
| PB 201297 | Final Report on Riveted and Bolted Structural Joints. |
| PB 201959 | Recharge Basins for Disposal of Highway Storm Drainage—Theory, Design Procedure, and Recommended Engineering Practices (Final Report). |
| PB 201960 | Static Test of an Indiana Standard Guardrail (Final Report). |
| PB 201965 | Tests of Composite Beams Under Negative Moment. |
| PB 201977 | A Method for Separately Evaluating the Structural Performance of Subgrade and the Overlying Flexible Pavements. |

### *MATERIALS*

| *Stock No.* | |
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| PB 197148 | Quantitative Cold Differential Thermal Analysis. |
| PB 197151 | Characteristics of Various Aggregate Producing Bedrock Formations in New York State. |
| PB 200462 | Highway-Problem-Oriented Photo Interpretation Using Panchromatic, Normal Color, and Infrared Color Air Photos. |
| PB 200662 | The relative Effect of Dew on Three Reflective Sign Materials. |
| PB 200667 | The Moisture Mechanism that Causes Asphalt Stripping in Asphaltic Pavement Mixtures. |
| PB 200670 | Study of Specific Gravity as a Criterion of Aggregate Quality (Final Report). |
| PB 200872 | Reflective Traffic Bead Study (Final Report). |
| PB 201061 | Continuously Reinforced Concrete Pavement (Final Report). |
| PB 201154 | Prediction of Swelling in Expansive Clays. |
| PB 201220 | Computer Simulation for Quality Assurance in Asphaltic Concrete Production: Program & Technical Considerations. |
| PB 201955 | Synthetic Aggregate from Soil Cement. |
| PB 201962 | Traffic Marking Materials Experiment (Final Report). |
| PB 201974 | Polymer Concrete Applications Development. |
| PB 201976 | Deicer Scaling Mechanisms in Concrete. |

### *TRAFFIC*

| *Stock No.* | |
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| PB 197606 | GHD Research Assistance Project No. 1-70—Development of a Procedure to Estimate Parking Demand in Urban Areas. |
| PB 198270 | Some Effects of Pavement Edge Lines on Driver Behavior. |
| PB 198505 | Automatic Data Telemetering for Michigan's Permanent Traffic Recording System. |
| PB 200669 | Effectiveness of Statistical Control Chart Techniques in Selective Enforcement Applications. |
| PB 200998 | The Development of a Digital Simulator for the Analysis of Freeway Traffic Phenomena. |
| PB 201060 | Alcohol Level and Driving Performance. |
| PB 201151 | The Degree of Influence of Certain Factors Pertaining to the Vehicle and the Pavement on Traffic Accidents Under Wet Conditions. |
| PB 201221 | Analytical Models of Unidirectional Multi-Lane Traffic Flow (Final Report):<br>Volume I |
| PB 201222 | Volume II |
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| PB 200870 | Drainage Correlation Research (Final Re port):<br>Volume I |
| PB 200871 | Volume II |
| PB 201099 | The Toxicity of 2,4-D, and Picloram Herbi cides to Fish. |
| PB 201883 | Analysis of Alternative Solutions to th Motor Vehicle Air Pollution Problem— Study Design Phase. |
| PB 201954 | A Routing Methodology for Snow Plows an Cindering Trucks—Cost Effectivenes Studies of Antiskid and Deicing Program in Pennsylvania (Interim Technical Re port). |
| PB 201961 | Interaction between Fixed and Vehicula Illumination Systems. |
| PB 201973 | Cost of Hauling Antiskid Materials in Commonwealth Vehicles—Cost-Effectivenes Studies of Antiskid and Deicing Program in Pennsylvania (Interim Technical Re port). |

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| PB 201152 | Acceptance Sampling Plans for Rigid Pave ment Thickness. |
| PB 201156 | Nuclear Moisture Density Gauges. |
| PB 201157 | Nuclear Test Equipment Investigation Portable Moisture/Density Gauges—Par II. |
| PB 201220 | Computer Simulation for Quality Assurance in Asphaltic Concrete Production: Pro gram and Technical Considerations. |

### *RESEARCH IMPLEMENTATION*

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| PB 201975 | Photogrammetry Research Study No. 1. |

### *PLANNING*

| *Stock No.* | |
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| PB 196807 | Connecticut Master Transportation Plan, 1971. |
| PB 198506 | Trip Generation, Regression Analysis—Procedural Manual. |
| PB 200661 | Procedures for Estimating the Total Load Experience of a Highway as Contributed by Cargo Vehicles. |
| PB 200663 | Traffic Circulation Study, National Airport. |
| PB 200673 | Airport Access Signing (Report on Immediate Action Improvements). |
| PB 200686 | Marketing Access Services, Report No. 1 (Report on Immediate Action Improvements). |
| PB 200691 | Transportation Network Evaluation: Costable Criteria. |
| PB 201963 | Factors Influencing Land Development—Subdivision Development Study, Interstate 71, Franklin County. |

# PUBLICATIONS of the Federal Highway Administration

*A list of articles in past issues of* Public Roads *and title sheets for volumes 24–35 are available upon request from the Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 20590.*

*The following publications are sold by the Superintendent of Documents, Government Printing Office, Washington, D.C. 20402. Orders should be sent direct to the Superintendent of Documents. Prepayment is required.*

Accidents on Main Rural Highways—Related to Speed, Driver, and Vehicle (1964). 35 cents.

Aggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.

America's Lifelines—Federal Aid for Highways (1969). 35 cents.

Analysis and Modeling of Relationships between Accidents and the Geometric and Traffic Characteristics of the Interstate System (1969). $1.00.

A Book About Space (1968). 75 cents.

Bridge Inspector's Training Manual (1970). $2.50.

Calibrating & Testing a Gravity Model for Any Size Urban Area (1968). $1.00.

Capacity Analysis Techniques for Design of Signalized Intersections (Reprint of August and October 1967 issues of PUBLIC ROADS, a Journal of Highway Research). 45 cents.

Construction Safety Requirements, Federal Highway Projects (1967). 50 cents.

Corrugated Metal Pipe (1970). 35 cents.

Creating, Organizing, & Reporting Highway Needs Studies (Highway Planning Technical Report No. 1) (1963). 15 cents.

Emergency Application Systems for Power Brake Mechanisms of Highway Trailer Combinations (1970). $1.00.

Fatal and Injury Accident Rates on Federal-Aid and Other Highway Systems, 1968. 45 cents.

Federal-Aid Highway Map (42x65 inches) (1970). $1.50.

Federal Assistance Available (1971). 10 cents.

Federal Laws, Regulations, and Other Material Relating to Highways (1970). $2.50.

The Freeway in the City (1968). $3.00.

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

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

Handbook on Highway Safety Design and Operating Practices (1968). 40 cents.
  Supplement No. 1 (Nov. 1968). 35 cents.
  Supplement No. 2 (Nov. 1969). 40 cents.

The Highway and its Environment, 3d Annual Awards Competition (1970). 60 cents.

Highway Beautification Program. Senate Document No. 6, 90th Cong., 1st sess. (1967). 25 cents.

Highway Condemnation Law and Litigation in the United States (1968):
  Vol. 1—A Survey and Critique. 70 cents.
  Vol. 2—State by State Statistical Summary of Reported Highway Condemnation Cases from 1946 through 1961. $1.75.

Highway Cost Allocation Study: Supplementary Report, House Document No. 124, 89th Cong., 1st sess. (1965). $1.00.

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

Highway Joint Development and Multiple Use (1970). $1.50.

Highway Planning Map Manual (1963). $1.00.

Highway Research and Development Studies Using Federal-Aid Research and Planning Funds (1969). $1.50.

Highway Statistics (published annually since 1945):
  1966, $1.25; 1967, $1.75; 1968, $1.75; 1969, $1.75.
  (Other years out of print.)

Highway Statistics, Summary to 1965 (1967). $1.25.

Highway Transportation (November 1970) 65 cents, (Spring 1971), 60 cents.

Highways and Human Values (Annual Report for Bureau of Public Roads) (1966). 75 cents.
  Supplement (1966). 25 cents.

Highways to Beauty (1966). 20 cents.

Highways and Economic and Social Changes (1964). $1.25.

Hydraulic Engineering Circulars:
  No. 5—Hydraulic Charts for the Selection of Highway Culverts (1965). 55 cents.
  No. 10—Capacity Charts for the Hydraulic Design of Highway Culverts (1965). $1.00.
  No. 11—Use of Riprap for Bank Protection (1967). 40 cents.
  No. 12—Drainage of Highway Pavements (1969). $1.00.

Hydraulic Design Series:
  No. 1—Hydraulics of Bridge Waterways, 2d ed. (1970). $1.25.
  No. 3—Design Charts for Open-Channel Flow (1961). $1.50.
  No. 4—Design of Roadside Drainage Channels (1965). 65 cents.

Hydraulic Flow Resistance Factors for Corrugated Metal Conduits (1970). 55 cents.

Identification of Rock Types (1960). 20 cents.

Increasing the Traffic-Carrying Capability of Urban Arterial Streets: The Wisconsin Avenue Study (1962). Out of print—(Request from Federal Highway Administration).

Interstate System Accident Research Study–1 (1970). $1.00.

Interstate System Route Log and Finder List (1971). 25 cents.

Joint Development and Multiple Use (1970). $1.50.

Labor Compliance Manual for Direct Federal and Federal-Aid Construction, 3d ed. (1970). $3.75.

Landslide Investigations (1961). 30 cents.

Manual for Highway Severance Damage Studies (1961). $1.00.

Manual of Instructions for Construction of Roads and Bridges on Federal Highway Projects (1970). $3.25.

Manual on Uniform Traffic Control Devices for Streets and Highways (1971). $3.50.

Maximum Safe Speed for Motor Vehicles (1969). $1.00.

Modal Split—Documentation of Nine Methods for Estimating Transit Usage (1966). 70 cents.

Motor Carrier Safety Regulations (1968). 45 cents.

National Highway Needs Report, H. Comm. Print 90–22 90th Cong. 2d sess. (1968). 25 cents. Supplement 10 cents.

The National System of Interstate and Defense Highways (1970). 15 cents.

Overtaking and Passing on Two-Lane Rural Highways—a Literature Review (1967). 20 cents.

Park & Recreational Facilities (1971). 45 cents.

Presplitting. A Controlled Blasting Technique for Rock Cuts (1966). 30 cents.

Proposed Program for Scenic Roads & Parkways (prepared for the President's Council on Recreation and Natural Beauty), 1966. $2.75.

Quality Assurance in Highway Construction. (Reprinted from PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 35 Nos. 6–11, 1969). 50 cents.

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Road-User and Personal Property Taxes on Selected Motor Vehicles (1970). 65 cents.
Role of Economic Studies in Urban Transportation Planning (1965). 65 cents.
The Role of Third Structure Taxes in the Highway User Tax Family (1968). $2.25.
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Standard Land Use Coding Manual (1965). 50 cents.
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  Vol. III—Timber Bridges (1969). 75 cents.
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Study of Airspace Utilization (1968). 75 cents.
Transition Curves for Highways (1940). $2.50.
Transportation Planning Data for Urbanized Areas (1970). $9.2
Ultrasonic Testing Inspection for Butt Welds in Highway an Railway Bridges (1968). 40 cents.