Bridge Live-Load Models

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Abstract: Live load is an important load component for highway bridges. The paper summarizes the available data base and formulates the approach to calculating maximum moments and shears for various time periods. The live-load data base consists of truck-survey results. Moments and shear forces are calculated for surveyed trucks and various spans. The maximum load effects for time periods from one day to 75 years are derived by extrapolations and simulations. Calculations are performed for single-lane and two-lane bridges. For single lanes, the maximum moment and shear are caused by a single truck for spans up to about 100 ft (30 m). For longer spans, two trucks following behind each other govern. For two lanes, the maximum effect is obtained for two trucks side-by-side, with fully correlated weights. For the maximum 75-year moment or shear, each side-by-side truck is represented by the maximum 1.5-month truck. The effect of a 1.5-month truck is about 15% smaller than that of a 75-year truck.

Introduction

There is a growing interest in the development of probability-based rational criteria for the design and evaluation of bridges. The live-load model for load and resistance factor design (LRFD) is one of the most important part of these new developments. The objective of this paper is to formulate the procedure for calculation of live-load moments and shears for highway bridges. The proposed model is applied to girder bridges.

The major load components of highway bridges are dead load, live load (static and dynamic), environmental loads (temperature, wind, and earthquake), and other loads (collision or emergency braking). Each group includes several subcomponents. Load components can be treated as random variables. The basic load combination is a simultaneous occurrence of dead load, live load, and dynamic load. The combinations involving other load components (wind, earthquake, and collision forces) require a special approach.

Live load covers a range of forces produced by vehicles moving on the bridge. Traditionally, the static and dynamic effects are considered separately. The present study deals with the static component of live load. The derivation of the dynamic load model is described by Hwang and Nowak (1991).

The effect of live load depends on many parameters including truck weight, axle loads, axle configuration, span length, position of the vehicle on the bridge (transverse and longitudinal), number of vehicles on the bridge (multiple presence), stiffness of structural members (slab and girders), and future growth (Moses and Ghosn 1985). Because of complexity of the model, the load and load distribution properties are considered separately.

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Data Base

There are various sources of live-load data, including truck surveys and weight-in-motion (WIM) measurements. WIM measurement programs were carried out by many state departments of transportation. A major study to process the available information is in progress [National Cooperative Highway Research Program (NCHRP) Project 12-28 (11), unpublished]. However, the validity of some measurements is questioned, and the results require verification. Therefore, in this study the major source of data is truck surveys.

Truck Surveys

Extensive programs have been carried by the Ontario Ministry of Transportation since the early 1970s. The major study was performed in 1975 and covered about 10,000 heavy vehicles [only trucks that appeared to be heavily loaded were measured and included in the data base (Agarwal and Wolkow-

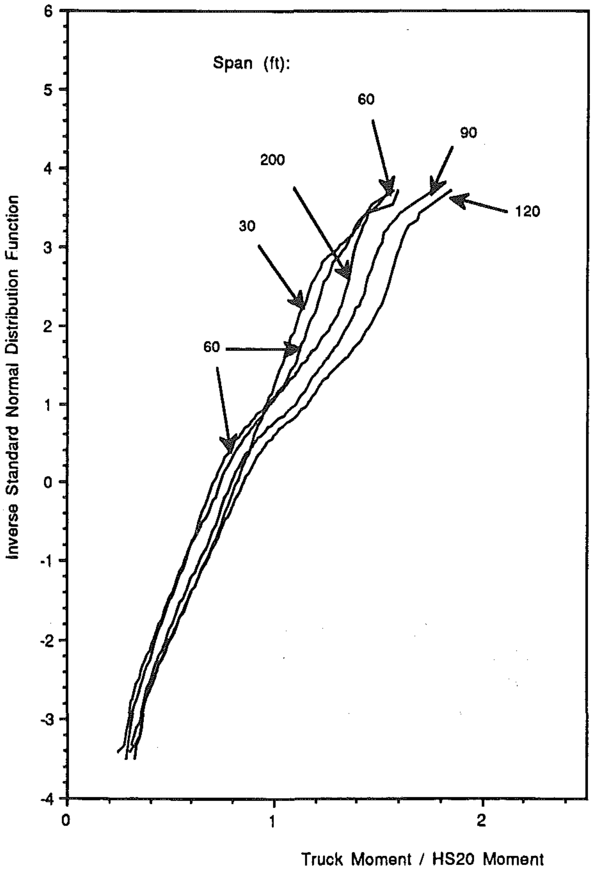

FIG. 1. Cumulative Distribution Functions for Moments due to Surveyed Trucks (1 ft = 0.305 m)

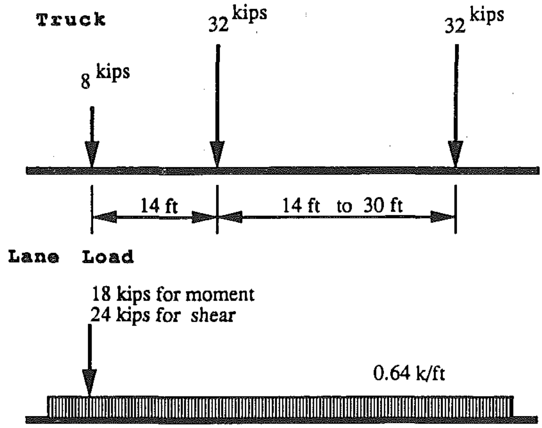

FIG. 2. HS20 Truck and Lane Load (*Standard Specifications*) (1 kip = 4.448 kN; 1 ft = 0.305 m)

icz 1976)]. Several other truck surveys were carried out to verify the results and to study the changes in live load over the years.

For truck, bending moments are calculated. The resulting cumulative distribution functions (CDFs) for simple spans 30–200 ft (9–60 m) are plotted on normal probability paper in Fig. 1. Construction and use of the normal probability paper are explained in several textbooks (e.g., Benjamin and Cornell 1970). The vertical scale in Fig. 1, z is

$$z = \phi^{-1}[F(M)] \qquad (1)$$

where M = moment; $F(M)$ = CDF of the moment M; and ϕ^{-1} = inverse standard normal distribution function.

The horizontal scale is in terms of the American Association of State Highway and Transportation Officials (AASHTO) HS20 live-load moment (*Standard Specifications* 1989) (truck or lane load, as shown in Fig. 2, whichever governs). Mean (average) values of the moments can be read directly from Fig. 1, at the intersection of the CDFs with level 0 on the vertical scale. They are about 0.7–0.85 of HS20 moments. The slope of the CDFs is an indication of the coefficient of variation; they are about 0.20–0.35. Maximum calculated moments are about 1.4–1.8 of HS20 moments.

The shear forces are also calculated for simple spans and the results are plotted on normal probability paper in Fig. 3. Mean values are about 0.7–0.85 of HS20 shears and the coefficients of variation are about 0.20–0.35, the same as for moments. Maximum calculated shears are 1.4–1.7 of HS20 shears.

Maximum Truck Moments and Shears

The maximum truck moments and shears were extrapolated from distributions shown in Figs. 1 and 3. Let N be the total number of trucks in period of time T. It is assumed that the surveyed trucks represent about two-week heavy traffic on an interstate highway. Therefore, in T = 75 years the num-

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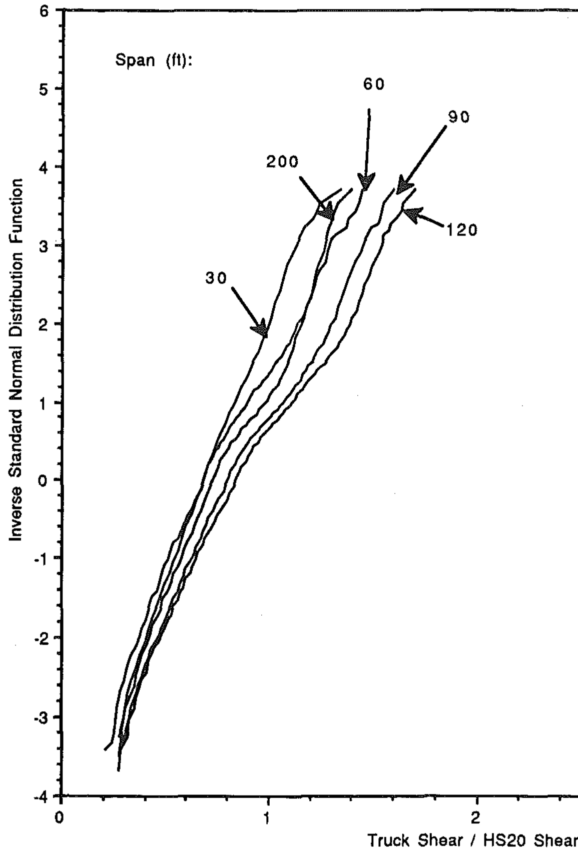

FIG. 3. Cumulative Distribution Functions for Shears due to Surveyed Trucks (1 ft = 0.305 m)

ber of trucks, N, will be about 1,500 larger than in the survey. This results in N = 15,000,000 trucks. The probability level corresponding to this N is $1/N = 7 \times 10^{-8}$ which corresponds to $z = 5.26$ [(1)] on the vertical scale in Figs. 1 and 3.

The number of trucks (N), probabilities ($1/N$), and inverse normal distribution values (z), corresponding to various time periods T from one day to 75 years, are shown in Table 1. The mean maximum moments and shears for time period T can be read from the extrapolated distributions.

The mean maximum moments and shears for various time periods are shown in Figs. 4 and 5. The coefficients of variation for the maximum truck moments and shears can be calculated by transformation of CDFs in Figs. 1 and 3. Each CDF can be raised to a certain power, depending on T, so that the calculated earlier mean maximum moment (or shear) becomes the mean value after transformation. The slope of the transformed CDF determines the coefficient of variation, V. Calculated V varies from 0.11 for 75 years to 0.2 for two days.

TABLE 1. Time Period, Number of Trucks, and Probability

Time period (T) (1)	Number of trucks (N) (2)	Probability ($1/N$) (3)	Inverse normal (z) (4)
75 years	15,000,000	7×10^{-8}	5.26
50 years	10,000,000	1×10^{-7}	5.19
7.5 years	1,500,000	7×10^{-7}	4.82
1.5 years	300,000	3×10^{-6}	4.53
Nine months	150,000	7×10^{-6}	4.34
Three months	50,000	2×10^{-5}	4.11
1.5 months	25,000	4×10^{-5}	3.94
Two weeks	10,000	1×10^{-4}	3.71
One day	1,000	1×10^{-3}	3.09

Single-Lane Moments and Shears

The maximum effect is caused by either a single truck or two (or more) trucks following behind each other. The mean maximum moments and shears due to a single truck are presented in Figs. 4 and 5. For a multiple-truck occurrence, the results depend on headway distance and degree of correlation between truck weights. Trucks can be similar (e.g., if they belong to the same owner, have an identical axle configuration, carry the same load, and were loaded by the same crew). In this case they are highly correlated with regard to weight. Correlated trucks can travel in groups, following behind each other or side-by-side.

The following assumptions are made based on observations and engineering judgment:

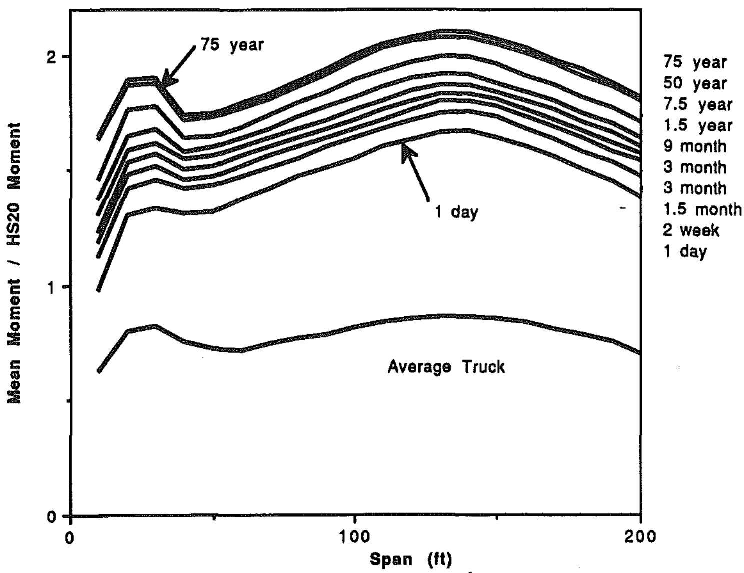

FIG. 4. Mean Maximum Moments versus Span Length (1 ft = 0.305 m)

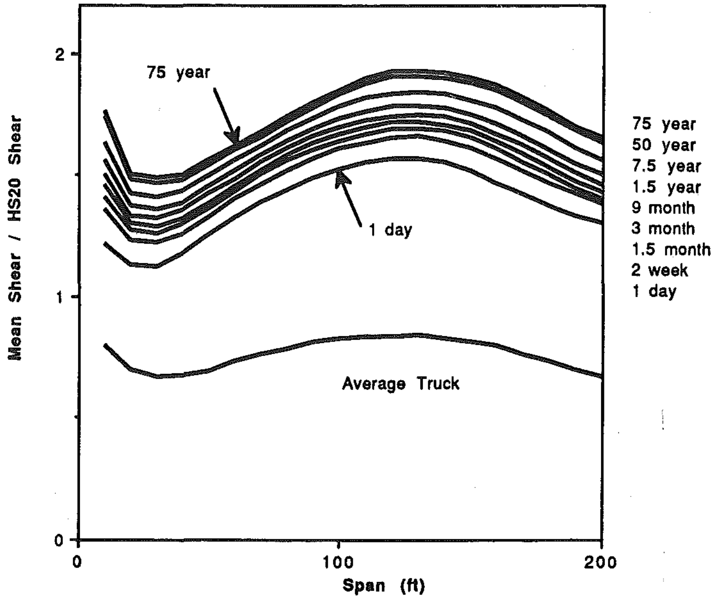

FIG. 5. Mean Maximum Shears versus Span Length (1 ft = 0.305 m)

1. Every 10th truck is followed by another truck with the headway distance less than 50 ft (15 m).
2. Every 50th truck is followed by a partially correlated trucks (with regard to weight).
3. Every 100th truck is followed by a fully correlated truck.

Let the two trucks be denoted by T_1 and T_2. The degree of correlation between T_1 and T_2 is expressed by coefficient of correlation, ρ. Three cases are considered.

1. $\rho = 0$: no correlation between T_1 and T_2; T_1 is the maximum 7.5-year truck (every 10th truck), and T_2 is the average truck.
2. $\rho = 0.5$: partial correlation between T_1 and T_2; T_1 is the maximum 1.5-year truck (every 50th truck), and T_2 is the maximum daily truck.
3. $\rho = 1$: full correlation between T_1 and T_2; T_1 and T_2 are both the maximum nine-month trucks (every 100th truck).

The results of calculations are presented in Figs. 6 and 7 for the moments and shears, respectively. Two headway distances are considered; 15 and 30 ft (4.5 and 9 m). It is clear that a single truck governs for spans up to about 100–120 ft (30–40 m) for the moments and up to about 90 ft (27 m) for shears. For longer spans, depending on headway distance, two fully correlated trucks govern.

The minimum headway distance is associated with nonmoving vehicles or trucks moving at reduced speeds. This is important in consideration of dy-

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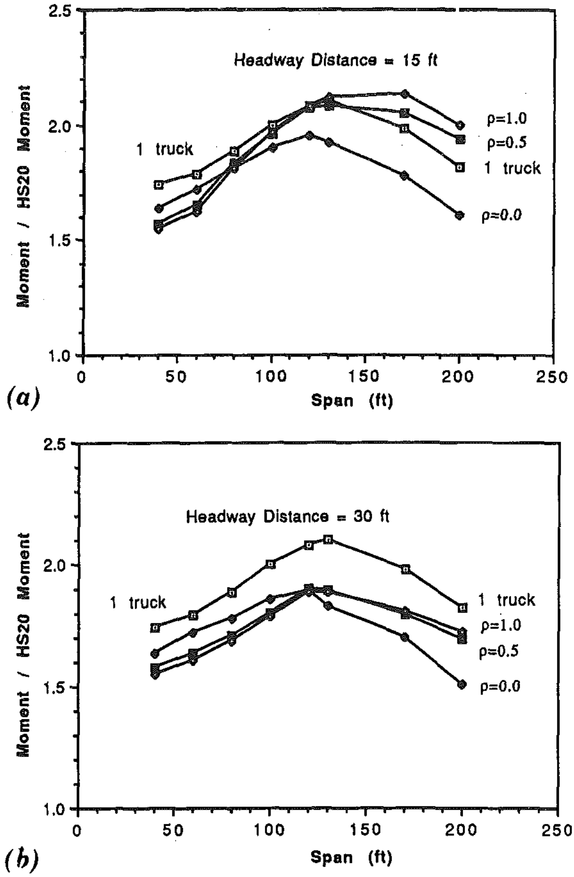

FIG. 6. Moments for Single Truck and Two Trucks with Various Degrees of Correlation versus Span Length (1 ft = 0.305 m): (*a*) Headway Distance = 15 ft; and (*b*) Headway Distance = 30 ft

namic loads. In further calculations it is assumed, conservatively, that the headway distance is 15 ft (5 m), even for normal speeds.

Two-Lane Moments and Shears

The analysis involves the determination of the load in each lane and load distribution to girders. The effect of multiple trucks is calculated by superposition. The maximum moments and shears are either due to the maximum load in one lane only or somewhat reduced loads in two lanes.

To determine the girder-distribution factors, a structural analysis was performed using the finite element method. The model is based on the linear behavior of girders and slabs. In the current AASHTO guidelines (*Standard Specifications* 1989), the girder-distribution factor is a function of girder spacing. For moments in interior steel or prestressed concrete girders it is $s/7$ for one lane and $s/5.5$ for two lanes, where s is the girder spacing. The

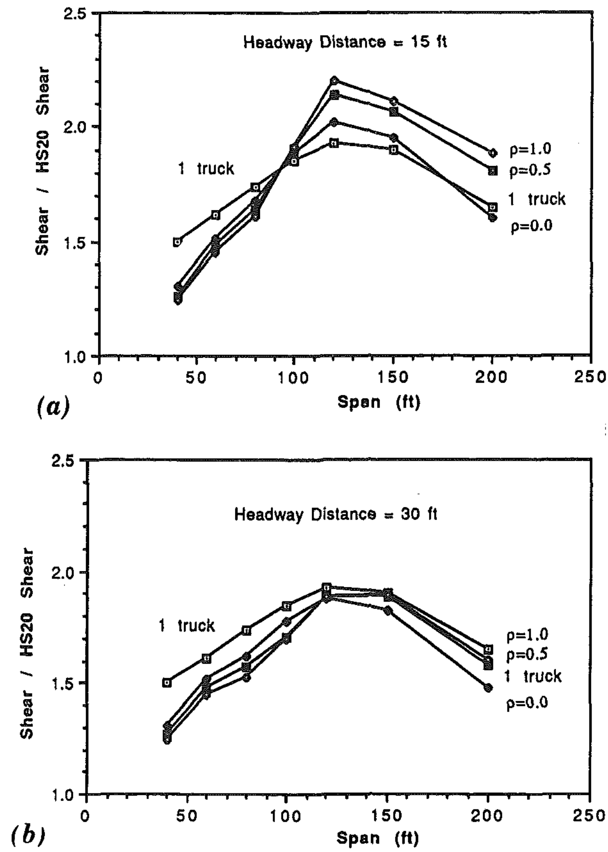

FIG. 7. Shears for Single Truck and Two Trucks with Various Degrees of Correlation versus Span Length (1 ft = 0.305 m): (*a*) Headway Distance = 15 ft; and (*b*) Headway Distance = 30 ft

calculated factors are compared to the specified AASHTO values in Fig. 8 for moments in two lanes.

It has been observed that, on average, every 50th to 100th truck is on the bridge simultaneously with another truck (side-by-side). In further calculations it is assumed, conservatively, that every 50th truck occurs on the bridge side-by-side with another truck. For each such a simultaneous occurrence, it is assumed that the two trucks are partially correlated every fifth time and fully correlated (with regard to weight) every 10th time. It is also assumed, conservatively, that the transverse distance between two side-by-side trucks is 4 ft (1.2 m) (wheel center-to-center).

Let the load effect in the first lane be denoted by L_1 and in the other lane by L_2. As in the case of T_1 and T_2, three values of the coefficient of correlation between L_1 and L_2 are considered.

1. $\rho = 0$: no correlation between L_1 and L_2; L_1 is calculated as the maximum 1.5-year lane load (every 50th truck), and L_2 is the average lane load.

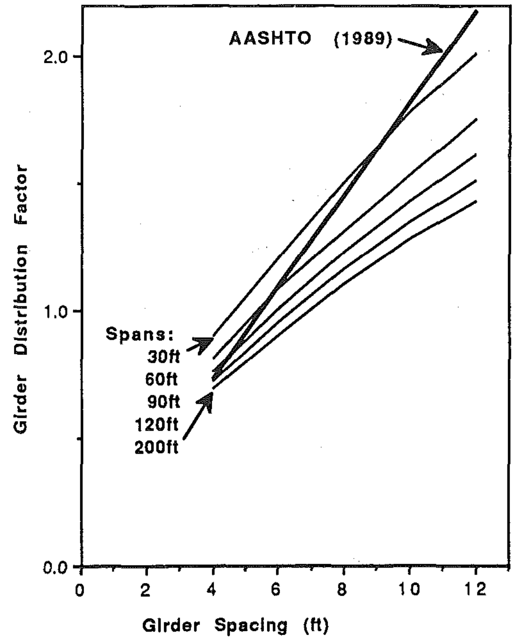

FIG. 8. Girder Moment Distribution Factors for AASHTO (*Standard Specifications* 1989) and Calculated (1 ft = 0.305 m)

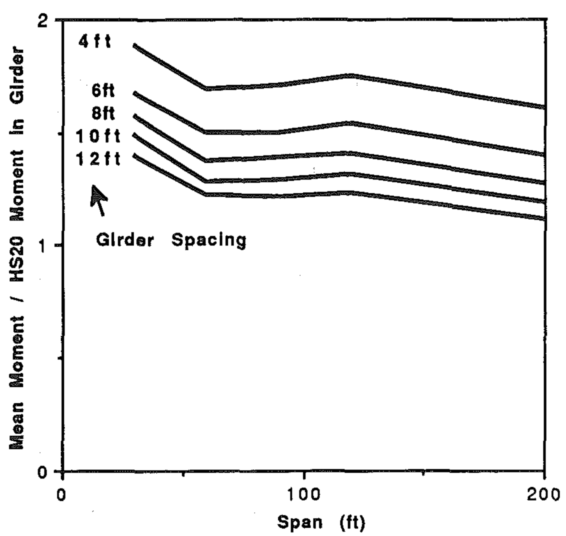

FIG. 9. Mean-to-Nominal Moment Ratios for Girders (1 ft = 0.305 m)

2. $\rho = 0.5$: partial correlation between L_1 and L_2; L_1 is taken as the maximum three-month lane load (every 250th truck), and L_2 is the maximum daily lane load.

3. $\rho = 1$: full correlation between L_1 and L_2; L_1 and L_2 are both taken as the maximum 1.5-month lane loads.

The results of simulations indicate that two side-by-side, perfectly correlated trucks govern (two perfectly correlated lane loads for longer spans). The ratio of the maximum 1.5-month truck load (or land load) and maximum 75-year truck load (or lane load) is equal to about 0.85.

AASHTO (*Standard Specifications* 1989) live load is calculated using HS20 load in each lane. There is no multiple-lane reduction factor for two lanes. Therefore, the mean-to-nominal live load per girder is different for single-lane and two-lane bridges. For single-lane bridges the mean-to-nominal values are as shown in Figs. 4 and 5. For two-lane bridges, the mean-to-nominal value is a combination of lane-load ratio, which is about 15° less than for a single lane (1.5-month load to 75-year load is 0.85) and girder-distribution factor (Fig. 8). The results are shown in Fig. 9.

Conclusions

A live-load model is developed for highway bridges. The data base consists of the results of truck surveys. Maximum moments and shears are calculated by extrapolations and simulations for time periods from 1 day to 75 years. Single-lane and two-lane bridges are considered.

The lane load is governed by a single truck for spans up to 100–120 ft (30–36 m) for moments and 90 ft (27 m) for shears. Two trucks following behind each other govern for longer spans.

For two-lane bridges, the maximum effects are obtained for two side-by-side trucks (or lane loads) with perfect correlation between truck (or lane load) weights. To calculate the maximum 75-year effect, each truck (or lane load) is taken as the maximum 1.5-month truck (or lane load). The ratio of the mean maximum 1.5-month load and the maximum 75-year load is almost constant and equal to 0.85.

Girder-moment–distribution factors in the current AASHTO guidelines (*Standard Specifications* 1989) are conservative for larger spacings of girders.

The ratio of the mean maximum 75-year moment to HS20 moment 1989 (AASHTO) per girder varies. It is larger for shorter spans and girder spacing.

Acknowledgments

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The conclusions are those of the writers and not necessarily of the sponsoring institutions. Thanks are due to Hani Abi-Nassif for his assistance in processing the truck survey data and Tadeusz Alberski for plotting some of the results.

Appendix I. References

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Appendix II. Notation

The following symbols are used in this paper:

F = cumulative distribution function (CDF);
L_1L_2 = lane load effects in two adjacent lanes;
M = moment due to live load;
N = number of trucks;
T_1T_2 = trucks following behind each other;
z = value of inverse normal distribution function;
ϕ = standard normal distribution function;
ϕ^{-1} = inverse standard normal distribution function; and
ρ = coefficient of correlation.

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