Modeling Live Load and Dynamic Load for Bridges

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Live load and dynamic load are important load components for highway bridges. Rational load models are needed for the development of LRFD design codes. The paper summarizes the available data base and calculation procedure.

Live load model is based on the truck surveys. Maximum 75 year load effects are derived by extrapolation and simulations. Calculations are performed for single lanes and two lane bridges. 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 approach to selection of the design live load is formulated. The acceptance criteria is uniformity of the mean-to-nominal ratio for various spans.

Dynamic load is based on limited test data and special simulations. The major factors influencing dynamic load are the road roughness, bridge dynamics (frequency of vibrations) and vehicle dynamics (suspension system). Tests and analysis indicate that dynamic load (as a fraction of live load) is reduced for heavier trucks. It is also lower for two trucks compared to a single truck. It is recommended to use a uniform dynamic load for all the span lengths larger than 20 ft.

INTRODUCTION

Load model is an important part of the design code development procedure. Calculation of load and resistance factors in LRFD (load and resistance factor design) requires the knowledge of statistical distributions for the considered load components and resistance parameters. Load components for highway bridges include dead load, live load, dynamic load, environmental loads (wind, earthquake, temperature) and special loads (collision). The basic load combination is a simultaneous occurrence of dead load, live load and dynamic load.

Dead load, D, is the gravity load due to the self weight of the structural and nonstructural elements permanently connected to the bridge. Live load covers a range of forces produced by vehicles moving on the bridge. An example of bridge girder deflection under truck loading is shown in Fig. 1. The deflection is plotted as a function of time. Traditionally, the static and dynamic effects are considered separately (D_{sts} and D_{dyn} in Fig. 1). In this study, L covers the static component and the dynamic component is denoted by I.

The objective of this paper is to present the development of static and dynamic load for highway bridges. The developed models can serve as a basis for design code provisions.

DATA BASE FOR LIVE LOAD

The development of live load and dynamic load is based on truck surveys, bridge tests and analytical simulations. There is a need for more data, in particular, for reliable WIM (weigh-in-motion) results.

Extensive truck survey studies have been carried out by the Ontario Ministry of Transportation since early 1970's. The major data base includes 10,000 heavy trucks (only heavily loaded vehicles were measured). Each truck and axle configuration was run on the influence lines to calculate the moments and shears. For shears, for simple spans from 10 to 100 ft, the results are plotted on normal probability paper in Fig. 2 for moments and Fig. 3 for shears (1). Construction and use of the normal probability paper is described in ref. (2). Any normal distribution function is represented by a straight line on normal probability paper and any straight line represents a normal distribution function. In Fig. 2 and 3, the vertical scale, z, is the inverse standard normal distribution. The horizontal scale is the moment (or shear) divided by the HS20 design moment (or shear) specified by AASHTO (3). The maximum values of moments are 1.25 to 1.6 of HS20 moments, and the maximum shears are 1.15 to 1.7 of HS20 shears.

Police citation files provide information about overweight vehicles. Michigan State Police files were reviewed (4). The study covered one year period and 2511 vehicles. According to the Police estimates, these trucks were taken out of a population of 3 million trucks passing through the scales annually. The total

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annual population of trucks is estimated at 15 million. Moments calculated for these trucks are plotted in Fig. 4. These results can be considered as an indication of the upper tail of the moment distribution.

Processing of the available WIM data is the subject of an ongoing NCHRP Project 12-28(11). However, the validity of some measurements has been recently questioned and the results of final reviews are not published yet. Therefore, in this study, the live load calculations are based on the truck survey data.

DATA BASE FOR DYNAMIC LOAD

Dynamic load model is based on test results and special simulations (6,7). The tests covered 22 bridges and 30 spans, including prestressed concrete girders and slabs, steel girders, trusses and frames. The measurements were taken for four test vehicles (54 to 130 kips) and a normal traffic. The results are summarized in Table 1. Dynamic load is measured as a fraction of the mean live load.

Interpretation of these results is difficult because the observed dynamic loads are separated from the static live loads. It has been observed that the dynamic load, as a fraction of live load, decreases for heavier trucks. It is expected that the largest dynamic load fractions in the tests correspond to light-weight trucks.

To verify these observations, a computer procedure was developed for simulation of the dynamic bridge behavior (6,7). The dynamic load is function of three major parameters: road surface roughness, bridge dynamics (frequency of vibration) and vehicle dynamics (suspension system). The developed numerical procedure includes the effect of these three parameters.

Road surface roughness is one of the major parameters. The quantification of the degree of roughness is very difficult. Road profile is simulated using a Fourier transform of the power spectral density (PSD) function. The PSD function of the road profile has, in general, an exponential form.

The bridge is modeled as a prismatic beam. Modal equations of motion are formulated. Three fundamental modes of vibration are considered. It is assumed that the load is a mixture of 3 axle single trucks and 5 axle tractor-trailers. The axle configurations and weight distributions are shown in Fig. 5. Each truck is composed of a body, suspension system and tires. The body is subjected to a rigid body motion including the vertical displacement and pitching rotation. Suspensions are assumed to be of multi-leaf type springs. In the simulations a nonlinear hysteretic force-deflection equation was used. Tires are assumed as linear elastic springs.

Dynamic load is measured as the maximum dynamic deflection, D_{dyn}, divided by the maximum static deflection, D_{sta}, as shown in Fig. 1. Extensive simulations were carried out using a wide spectrum of parameters (road roughness, truck weight, axle configuration, speed and span length). The obtained dynamic load vs. truck weights is plotted in Fig. 6. Dynamic load turned out to be practically independent of the truck weight.

The simulations were also performed for a simultaneous occurrence of two trucks. For heavily loaded trucks (maximum 75 year load), the mean dynamic loads are plotted vs. span length in Fig. 7. For comparison, the means due to a single truck are also shown. The simulations showed that the dynamic load is lower for two trucks than for a single truck. In general, dynamic load is lower for a larger number of axles. For very heavy trucks, the results are summarized in Table 2. The means and standard deviations are given in terms of the mean live load.

MAXIMUM LIVE LOAD

Let N be the total number of trucks in period of time T. It is assumed that the surveyed trucks represent a two week traffic. Therefore, in T = 75 years the number of trucks, N, will be about 1,500 times larger. This will result in N = 150 million heavy trucks and axle configurations. The probability level corresponding to N is $1/N = 10^{-8}$, which corresponds to $z = 5.67$ on the vertical scale in Fig. 2 and 3. The distributions can be extrapolated for longer time periods (or larger numbers of trucks) as shown in Fig. 2 and 3. Numbers N, probabilities, 1/N, and inverse normal distribution values, z, corresponding to various time periods T

Table 1 Dynamic Load Factors from Test Results

Type of Structure	Mean	Standard deviation		
	Range	Average	Range	Average
P/C AASHTO girders	0.05-0.10	0.09	0.03-0.07	0.05
P/C box & slabs	0.10-0.15	0.14	0.08-0.40	0.30
Steel girders	0.08-0.20	0.14	0.05-0.20	0.10
Rigid frame, truss	0.10-0.25	0.17	0.12-0.30	0.26

Table 2 Dynamic Load from Simulations

	Mean	Standard deviation
Single truck	0.13	0.10
Two trucks	0.09	0.06

Table 3. Number of Trucks, Time Period and Probability

Time period T	Number of Trucks N	Probability 1/N	Inverse normal z
75 years	150,000,000	$7_{10^{-9}}$	5.67
50 years	100,000,000	$1_{10^{-8}}$	5.62
5 years	10,000,000	$1_{10^{-7}}$	5.19
1 year	2,000,000	$5_{10^{-7}}$	4.89
6 months	1,000,000	$1_{10^{-6}}$	4.76
2 months	500,000	$2.5_{10^{-6}}$	4.56
1 month	200,000	$5_{10^{-6}}$	4.42
2 weeks	100,000	$1_{10^{-5}}$	4.26
2 days	20,000	$5_{10^{-5}}$	3.89
1 day	10,000	$1_{10^{-4}}$	3.71

from 1 day to 75 years, are shown in Table 3. Horizontal line corresponding to different time periods are also plotted in Fig. 2 and 3.

The mean maximum moments and shears corresponding to various periods of time can be read directly from the graph (Fig. 2 and 3). For example, for 60 ft span and T = 75 years, the mean maximum moment is 1.82 of HS20 moment (3). This is a horizontal coordinate of intersection of the extrapolated distribution and $z = 5.67$ on the vertical scale. The mean maximum shears are plotted in Fig. 9. For comparison, the means are also plotted for an average truck.

The coefficients of variation for the maximum truck moments and shears can be calculated by transformation of the distribution functions in Fig. 2 and 3. Each function can be raised to a certain power, so that the calculated earlier mean maximum moment (or shear) becomes the mean value after the transformation. The slope of the transformed distribution determines the coefficient of variation. For 75 year period, the coefficients of variation is about 0.11 for 1 month it is about 0.18, and for 1 day it is over 0.20.

Maximum Lane Load (moment or shear) is caused by a single truck or two (or more) trucks following behind each other. For a multiple truck occurrence, the important parameters are the headway distance (from rear axle of one truck to front axle of the other truck) and degree of correlation between truck weights. The maximum lane load is determined by simulations. Several headway distances are considered (15 ft and more).

It is assumed that, on average, about every 10th truck is followed behind by another truck with the headway distance less than 50 ft; about every 50th truck is followed behind by a partially correlated truck; and about every 100th truck is followed behind by a fully correlated truck.

The two trucks are denoted by T_1 and T_2. Three cases of the coefficient of correlation, ρ, are considered.

$\rho = 0$, no correlation between T_1 and T_2; T_1 is the maximum year truck (10th truck) and T_2 is an average truck.

$\rho = 0.5$, partial correlation between T_1 and T_2; T_1 is the maximum 1.5 year truck and T_2 is the maximum daily truck.

$\rho = 1$, full correlation between T_1 and T_2; T_1 and T_2 are both the maximum 9 month trucks.

The results of calculations indicate that single truck governs for spans up to about 100-120 ft for the moment and 90 ft for shear. For longer spans, depending on headway distance, two fully correlated trucks govern.

The minimum headway distance (15 ft) is associated with non-moving vehicles or trucks moving at reduced speeds. This is important in consideration of dynamic loads. In further calculations it is assumed, conservatively, that the headway distance is 15 ft even for normal speeds.

The mean maximum single lane moments are shown by dashed lines in Fig. 8 and 9. For comparison, in Fig. 10, the mean maximum 75 year moments are plotted with HS20 moments and AASHTO factored moments (2.17 times HS20 moment).

The equivalent uniformly distributed loads (UDL) were calculated for the mean maximum 75 year moments and shears. The uniform load, u, as a function of loaded span, x, is plotted in Fig. 11.

Calculation the maximum moments and shears for two lanes 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 are calculated by simulations. For side-by-side trucks three values of the coefficient of correlations, ρ, are considered: 0, 0.5 and 1.

It has been observed that, about every 50-100th truck is on the bridge simultaneously with another truck (side-by-side). In further calculations it is assumed that every 50th truck occurs on the bridge side-by-side with another truck, which is conservative. For each such a simultaneous occurrence, it is assumed that every 5th time the trucks are partially correlated ($\rho = 0.5$) and every 10th time they are fully correlated with regard to weight ($\rho = 1$). It is also assumed that the transverse distance between two side-by-side trucks is 4 ft (wheel center-to-center).

Two lane loads are denoted by L_1 and L_2. Three cases are considered:

$\rho = 0$, no correlation between L_1 and L_2; L_1 is the maximum 1.5 year lane load and L_2 is an average lane load.

$\rho = 0.5$, partial correlation between L_1 and L_2; L_1 is the maximum 3 month lane load and L_2 is the maximum daily lane load.

$\rho = 1$, full correlation between L_1 and L_2; L_1 and L_2 are both the maximum 1.5 month lane loads.

The structural analysis was performed using an advanced finite element method. The model is based on a linear behavior of girders and slab. Calculations clearly indicate that two fully correlated side-by-side trucks govern. The ratio of the mean maximum 1.5 month lane moment to the mean maximum 7.5 year moment is equal to about 0.85 for all spans.

Girder distribution factors in AASHTO (1989) are linear functions of girder spacing (s/5.5 where s is girder spacing), as shown in Fig. 12. The actual calculated distribution factors are also plotted in Fig. 12.

DESIGN LIVE LOAD AND DYNAMIC LOAD

Criteria considered in the selection of design live load include the uniformity of safety level, simplicity of the code format and tradition (live load model should resemble a real truck). A uniform safety level is an important objective of the LRFD code. To safety this requirement, ratio of the mean maximum 75 year (L + I) to nominal value of (L + I) should be constant. Recommended value of nominal I is 0.25 (for spans larger than 20 ft). Therefore, the mean-to-nominal ratio of L should be constant.

The ratio calculated for the current HS20 load are shown in Fig. 8 and 9, for the moment and shear, respectively. The ratio of the maximum single lane load and the maximum two lane load (per lane) is 0.85. In AASHTO (3) there is no multiple lane reduction factor for two lanes. Therefore for two lane bridges, the ratios of mean-to-nominal (Fig. 8 and 9) can be reduced by 15 percent.

For simply supported spans, for both moments and shears, a perfect fit (constant mean-to-nominal ratio) is obtained by using a uniform load varying with span, u(x), where u is uniform load and x is the span, as shown in Fig. 11.

For continuous spans, the uniform load intensity depends on the loaded length, x, rather than span. The calculation of the moment and shears involves maximization of u(x) and the area under the influence line. For example, in case of influence line shown in Fig. 13, the mean moment, M, is,

$$M = \max\left[u(\Sigma x_i)\ \Sigma(A_i)\right] \qquad (1)$$

where the summations are calculated for all combinations of intervals i.

CONCLUSIONS

Models are derived for bridge live load and dynamic load. The calculations are based on the available data base including truck surveys, bridge tests, analysis and simulations. The maximum load parameters are determined for various periods of time. The calculations are performed for single lanes and two lane bridges.

A single lane live load is governed by a truck for spans up to 100-120 ft for moment and 90 ft for shear. For long spans, two (or more) trucks following behind each other produce the maximum effect.

For two lane bridges, a simultaneous occurrence of two side-by-side trucks governs, with perfectly correlated weights. The maximum 75 year moment and shear is modeled by two maximum 1.5 month trucks. The ratio of the mean maximum 1.5 month truck and the mean maximum 75 year truck is about 0.85.

Dynamic load is a function of road roughness, bridge dynamics and vehicle dynamics. Simulations indicate that dynamic load decreases with increasing truck weights. It is also lower for two trucks compared to a single truck.

Design live load should produce a uniform mean-to-nominal ratio. Current HS20 load (3) does not satisfy this requirement. Uniformly distributed load provides a perfect fit. A uniform value of dynamic load, 0.25, is recommended for all spans larger than 20 ft.

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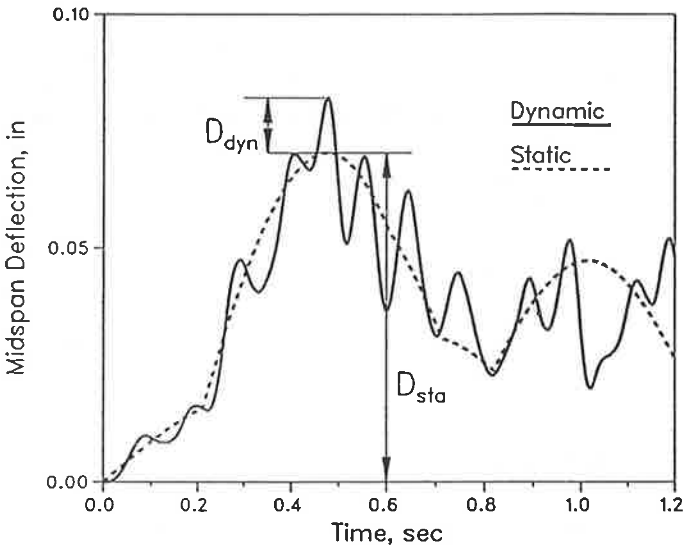


FIGURE 1 Static and Dynamic Deflection of a Bridge Girder.

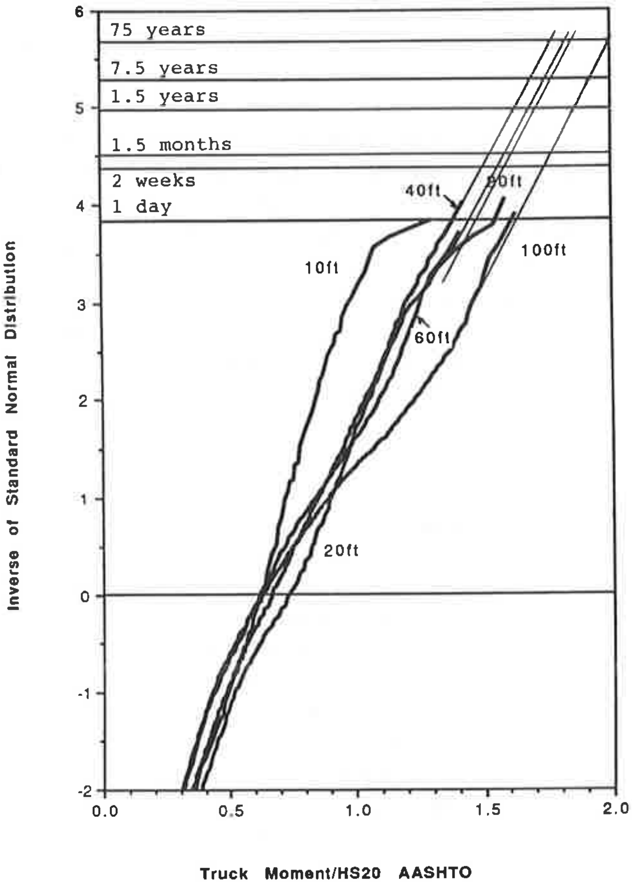


FIGURE 2 Cumulative Distribution Functions for Moments due to Surveyed Trucks.

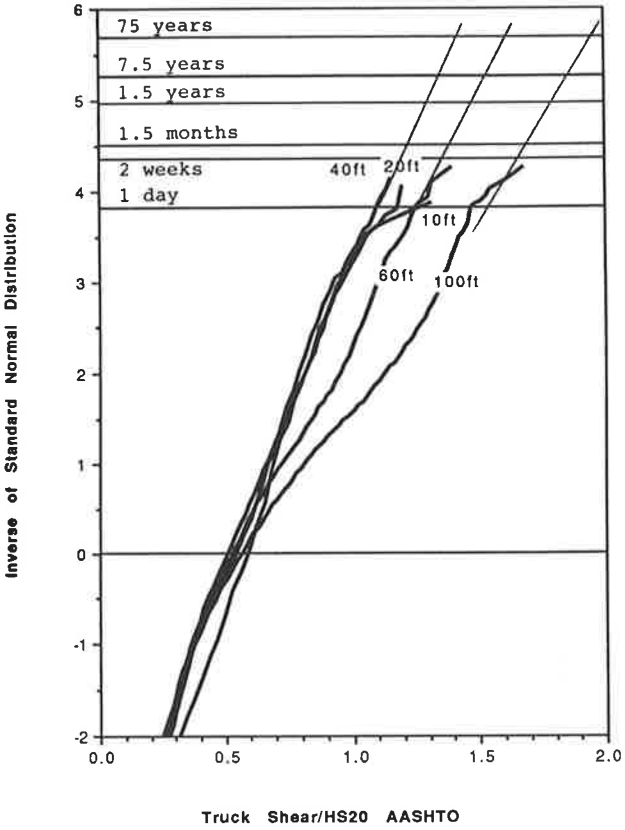


FIGURE 3 Cumulative Distribution Functions for Shears Due to Surveyed Trucks.

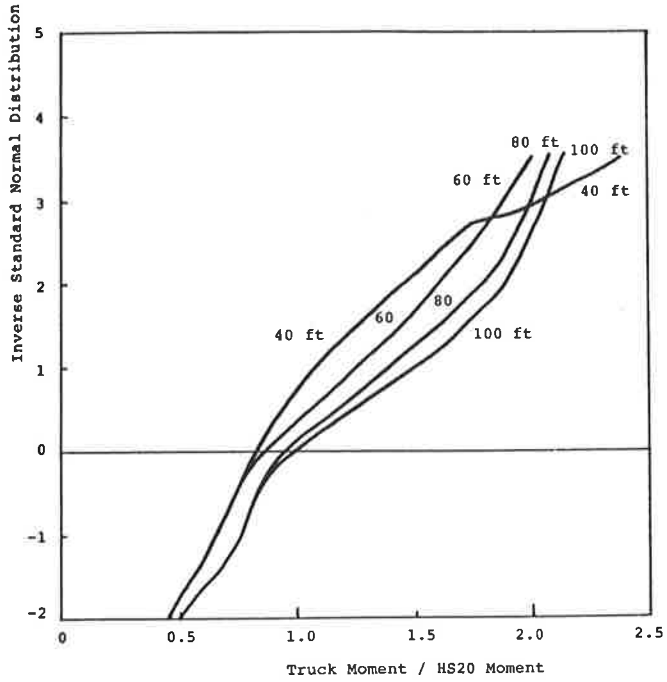
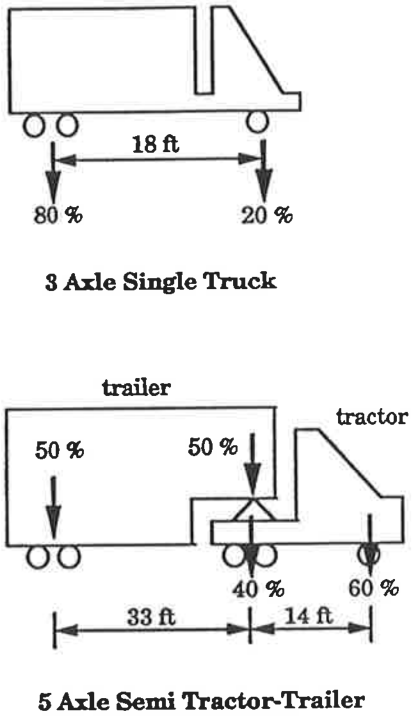


FIGURE 4 Cumulative Distribution Functions for Moment Due to Overloaded Trucks in Michigan (State Police Citation Files).



*percentage numbers are the fraction of tractor or trailer weight

FIGURE 5 Truck Configurations Used in Dynamic Simulations.

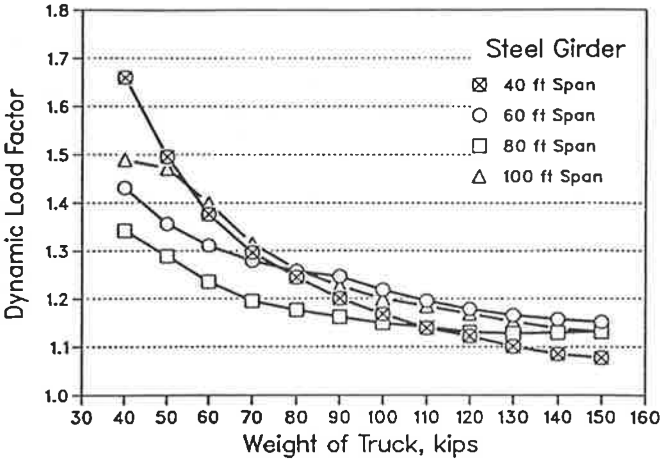


FIGURE 6 Dynamic Load vs. Truck Weight

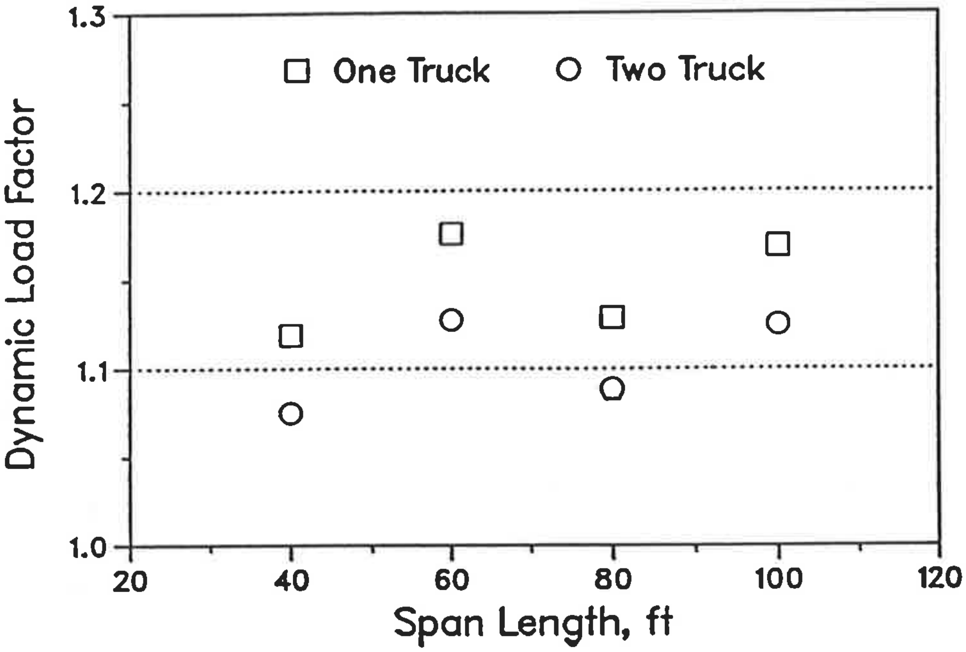


FIGURE 7 Dynamic Load for Single Trucks and Two Trucks.

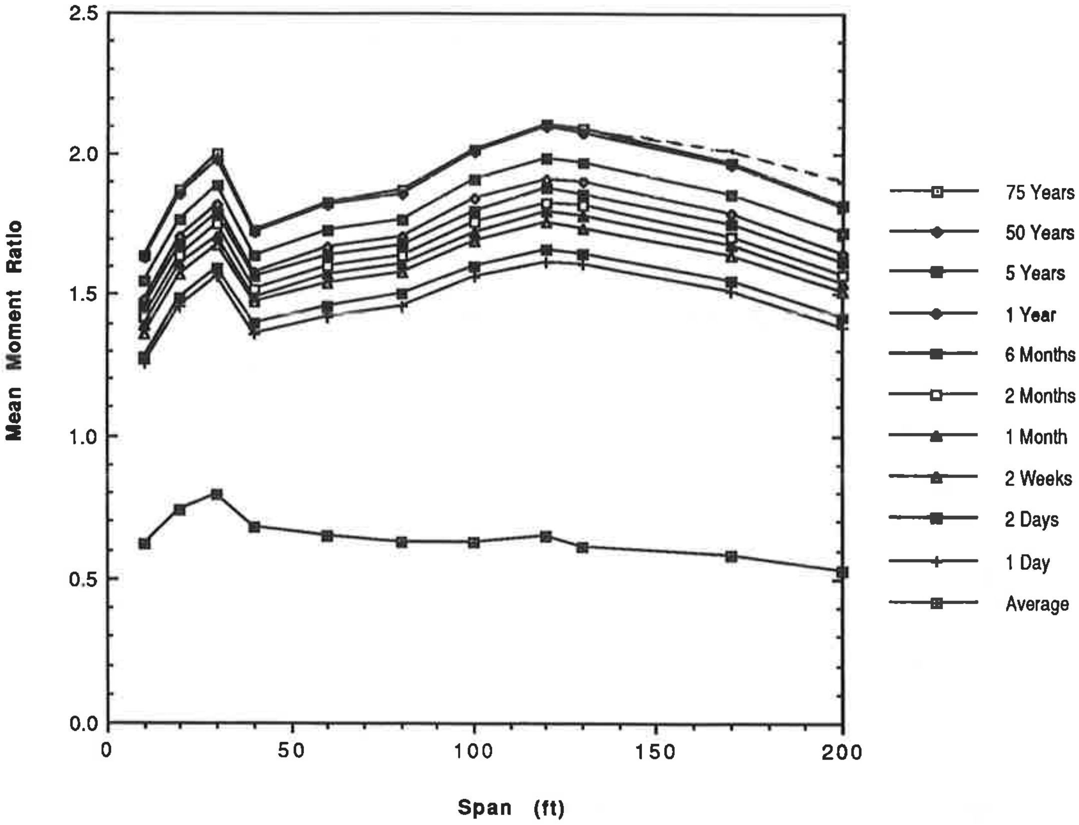


FIGURE 8 Mean Maximum Moments vs. Span Length.

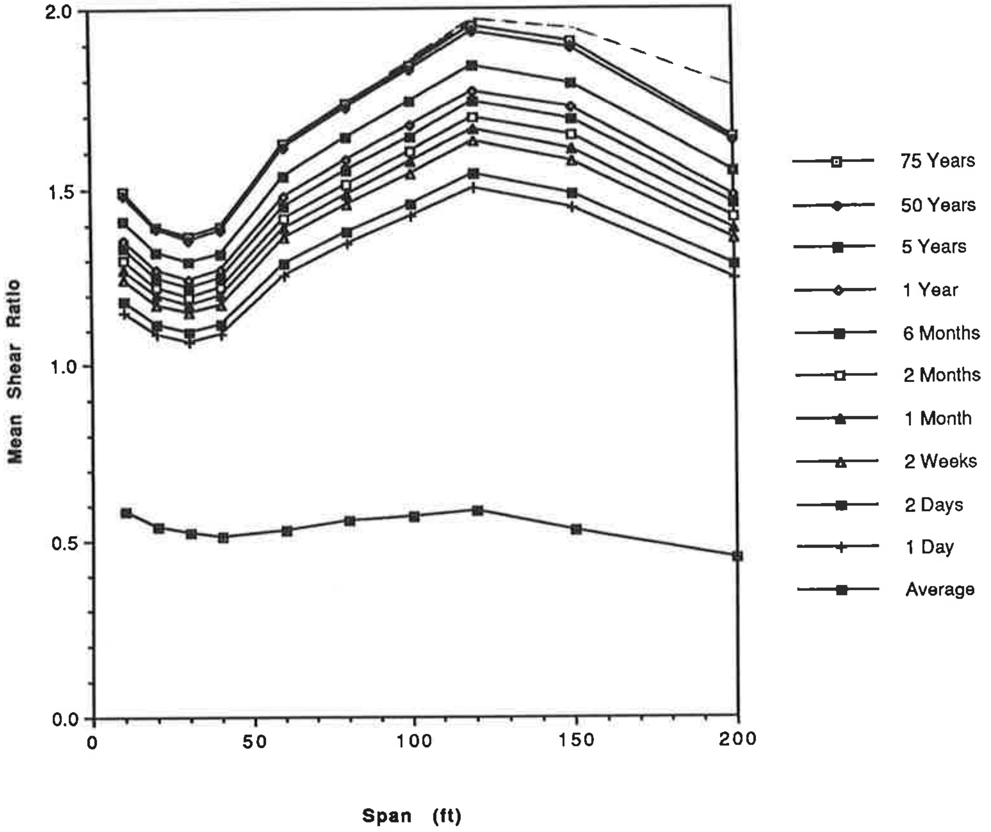


FIGURE 9 Mean Maximum Shears vs. Span Length.

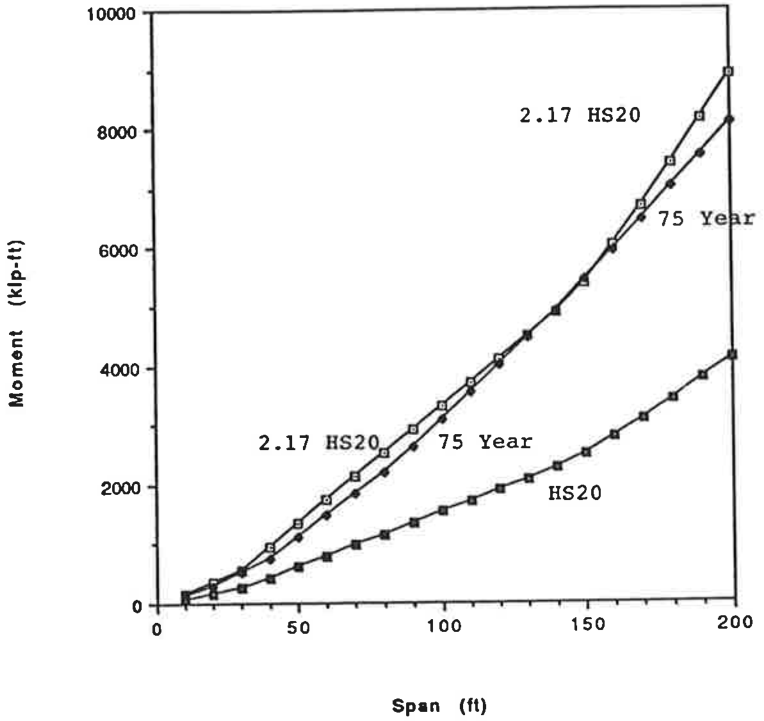


FIGURE 10 Mean Maximum 75 Year Moment, HS20 Moment and 2.17xHS20 Moment.

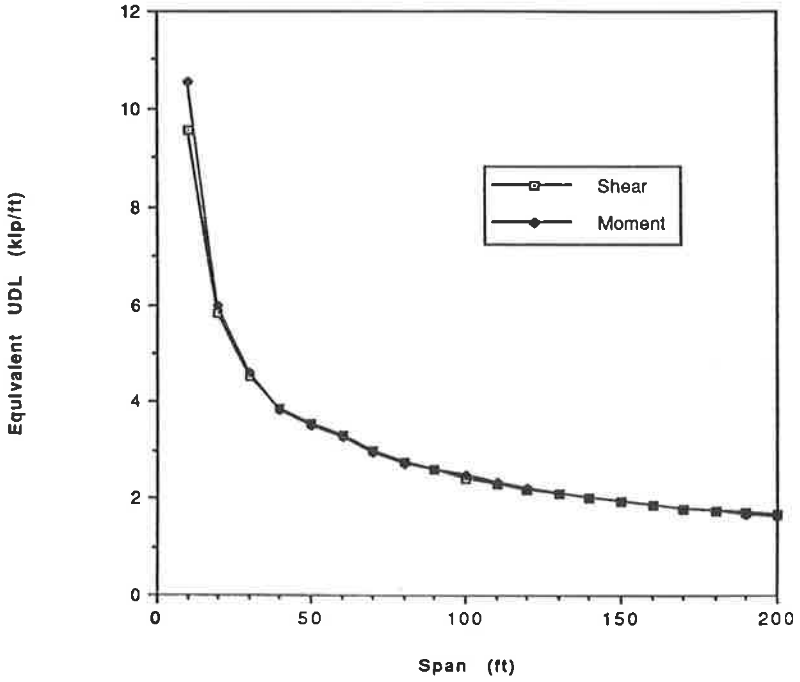


FIGURE 11 Equivalent Uniformly Distributed Load vs. Span Length.

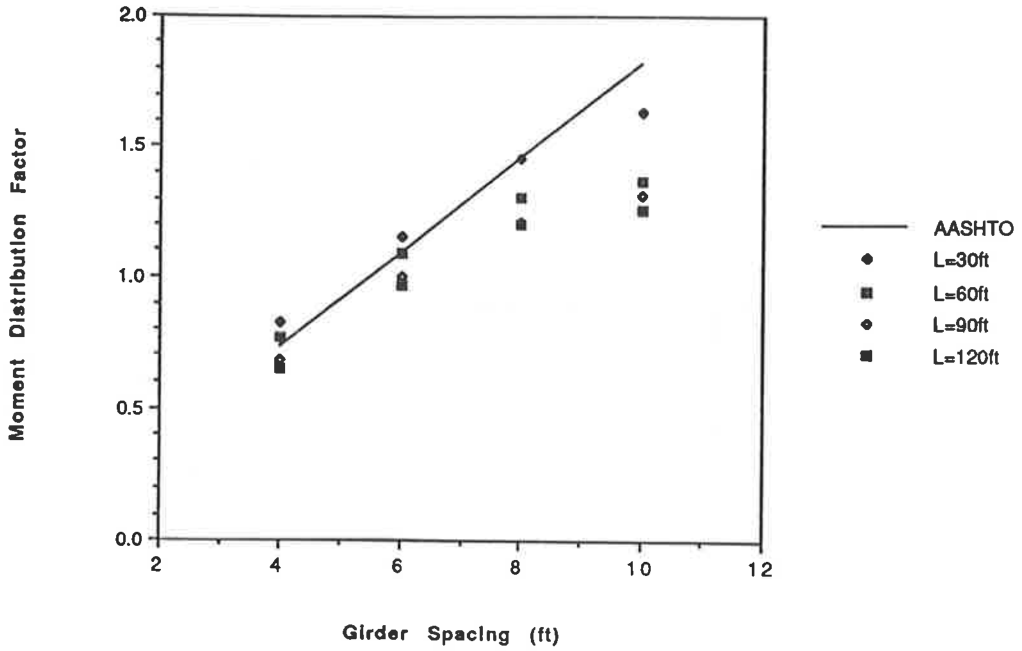


FIGURE 12 Girder Distribution Factors for AASHTO (3) and Calculated.

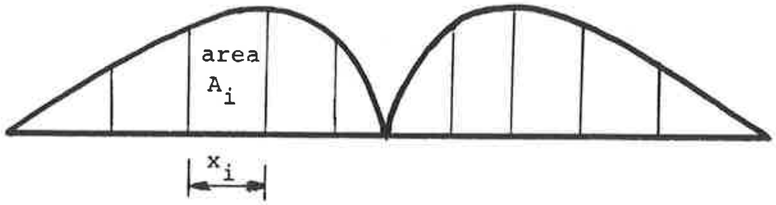


FIGURE 13 Example of an Influence Line.