

FATIGUE-BASED METHODOLOGY FOR MANAGING IMPACT OF HEAVY-PERMIT TRUCKS ON STEEL HIGHWAY BRIDGES

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ABSTRACT: Currently, in many areas of North America, special permits are issued to extra heavy vehicles without a detailed evaluation of individual components, considering only the ultimate capacity of the bridge inventory as a whole. Based on this, a large number of special permits have been issued to extra heavy vehicles. In this perspective, the ultimate and cumulative effect of such overloads on steel bridge components is studied. It is found that steel bridge members have adequate ultimate capacity to accommodate such overloads; however, they may suffer fatigue damage due to the cumulative effect of these overloads. Accordingly, a fatigue-based methodology is developed to assess the reduction in service life of bridges due to heavy-permit trucks. It is found that a reasonably large number of special permits can be issued at small reductions in fatigue life, but because stress ranges in excess of the constant-amplitude fatigue limit significantly alter the shape of the *S-N* curve, it is essential to appreciate that the concept of infinite fatigue life cannot be relied upon anymore.

INTRODUCTION

For practical, technical, and/or economic reasons, the limitations on legal vehicle weight must sometimes be exceeded for heavy inseparable loads. Currently, in Ontario, Canada, as in many other areas of North America, special permits issued to these vehicles are granted based on compliance to wheel-loads/axle-spacing charts (Agarwal 1981) or other methodology considering the ultimate capacity of the bridge inventory as a whole. Based on this, a large number of special permits have been issued to extra heavy vehicles, and therefore concerns have been raised that the cumulative effect of such overloads have never been assessed.

In this perspective, the ultimate and cumulative effect of heavy-vehicle configurations, typical of permit trucks in North America, on steel bridge members is studied. A number of existing bridges are analyzed to find the bridge members largely affected by such overloads. Finally, a methodology is developed for the issuance of permit to heavy trucks, which acknowledges and manages the cumulative impact of such extra heavy loads on the inventory of existing steel bridges.

HEAVY-PERMIT TRUCK MODELS

Five vehicle models representative of various types of heavy-permit trucks in North America are considered. General properties of the truck models are presented in Table 1 and spacing of the axles and their weights are tabulated in Table 2. The specifics of these five different vehicle models have been provided by the Ministry of Transportation of Ontario (MTO), based on their permit-issuing experience. They have been chosen in anticipation that their observed aggregate impact on steel bridges will match that due to a broad spectrum of permit truck types and configurations. As a comparison, the truck model developed for the Ontario Highway Bridge Design Code (OHBDC) (Ontario 1983a, b) is also considered since the model has been developed to be representative of maximum normal truck traffic conditions in Ontario (Dav-enport and Harman 1977).

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Note. Associate Editor: Dennis R. Mertz. Discussion open until April 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on June 25, 1993. This paper is part of the *Journal of Structural Engineering*, Vol. 121, No. 11, November, 1995. ©ASCE, ISSN 0733-9445/95/0011-1651-1659/\$2.00 + \$.25 per page. Paper No. 6451.

PRELIMINARY SENSITIVITY ANALYSES

To determine which spans are most likely to be detrimentally affected by heavy-permit trucks, their global effect on bridges of various spans is studied using simple influence-line concepts. A single-span simply supported and a two-span continuous beam are selected to represent, respectively, single-span and continuous-span bridges. A computer program was written to obtain the effect of truck models for spans ranging from 1 m up to 125 m. The upper limit corresponds to the 1983 edition of OHBDC stated range of applicability, and that of codes in many other areas of North America. Although 1 m is not a realistic bridge span, the results obtained for such small spans can be useful in examining the local effect of heavy-permit trucks on short bridge members such as stringers or cross beams in steel truss bridges, as well as on some types of expansion joints.

The ratio of live loads (i.e. the ratio of live load due to heavy-permit trucks to the design live load) and the ratio of total load effects (i.e. the ratio of total load due to heavy-permit trucks and dead load to that due to design live load and dead load) are considered in comparing the effects of heavy-permit trucks with those of design live loads. The ratio of live load effects is most meaningful when addressing potential fatigue problems, on the other hand, the ratio of total load effects reflects the reduction in the original safety factor.

For simply supported bridges, influence line analysis results showed that the most detrimentally affected spans range between 11 and 25 m for truck models 1 to 4 and 1–10 m for truck model 5. Based on these results, spans ranging between 15 and 20 m would be ideal for studies with truck models 1 to 4. Nonetheless, since the detrimental effect of truck 5 is mostly due to its unusually large axle loads, it is anticipated that local problems will also occur in various bridge members regardless of span length for this truck model.

For two-span continuous bridges, influence line analysis results comparable with those of simply supported bridges were obtained. Therefore, the study of continuous bridges in the 10–25 m span ranges seems appropriate.

EXISTING STEEL BRIDGES SELECTED FOR EVALUATION

One truss and three slab-on-girder steel bridges of different types and layouts, and of spans within the aforementioned range of interest, were selected as representative of bridges in North America. However, they were modified as necessary in order to investigate the effects of a broader range of parameters. Furthermore, some bridges were found to be either overdesigned or underdesigned for the current live-load re-

TABLE 1. General Properties of Model Trucks

Truck number (1)	Definition (2)	Number of axles (3)	Axle width (m) (4)	Length (m) (5)	Weight (kN) (6)	Speed limit (km/h) (7)	Travel restrictions (8)
1	Mobile crane	6	2.5	10.08	660	25	Only the truck is on the bridge
2	Mobile crane	7	2.5	16.96	810	25	
3	Float	9	2.0	33.09	1,176	25	
4	Float	10	1.8	51.02	1,314	10	Only the truck is on the bridge and travels down the centerline
5	Scraper	2	1.8	10.97	586	10	Only the truck is on the bridge and travels in the traffic lane
6	OHBD truck	7	1.8	18.00	700	None	None

TABLE 2. Weight Distribution and Axle Spacing of Model Trucks

Axle number (1)	Truck 1		Truck 2		Truck 3		Truck 4		Truck 5		OHBD-Truck	
	Axle weight (kN) (2)	Axle spacing (m) (3)	Axle weight (kN) (4)	Axle spacing (m) (5)	Axle weight (kN) (6)	Axle spacing (m) (7)	Axle weight (kN) (8)	Axle spacing (m) (9)	Axle weight (kN) (10)	Axle spacing (m) (11)	Axle weight (kN) (12)	Axle spacing (m) (13)
1	112	—	104	—	60	—	68	—	264	—	60	—
2	112	2.87	104	2.54	128	4.37	146	2.87	322	10.97	140	3.60
3	100	1.70	122	2.21	128	1.42	146	1.82	—	—	140	1.20
4	100	2.11	122	1.78	158	4.22	118	6.04	—	—	200	6.00
5	118	1.70	122	1.78	158	1.37	146	3.04	—	—	160	7.20
6	118	1.70	118	7.37	138	15.16	146	1.82	—	—	—	—
7	—	—	118	1.27	138	1.37	136	28.96	—	—	—	—
8	—	—	—	—	134	3.81	136	1.52	—	—	—	—
9	—	—	—	—	134	1.37	136	3.43	—	—	—	—
10	—	—	—	—	—	—	136	1.52	—	—	—	—

requirements of the OHBDC, without any consistent patterns. These were therefore redesigned to be in compliance with these requirements, and without excess capacity. The original character and properties of all bridges were preserved when modified or redesigned. The names of the bridges, their geometric properties and list of modifications are presented in Table 3.

ANALYSIS OF SELECTED BRIDGES

The semicontinuum method is selected as the preferred analysis technique for modeling the slab-on-girder bridges (Jeager and Bakht 1989); in many cases the accuracy of the

results was also verified by the grillage analogy method. Comparative studies were conducted, for a two-lane, three-lane, and 15° skewed simply supported bridge, as well as for a two-span continuous bridge. In all cases the results obtained from both methods are in good agreement. It is noteworthy that the curb's contribution to the exterior girder stiffness is considered here in all analyses. All the bridge analyses for the design truck are also conducted using the semicontinuum program to confirm the results obtained from the code procedure.

The exterior and interior girder bending moments at critical positions (e.g. at the end of cover plates on girder flanges in

TABLE 3. Properties of Modified Bridges

Bridge name (1)	Design year (2)	Span		Type (5)	Width (m) (6)	Number of design lanes (7)	Design lane width (m) (8)	Curb width (m) (9)	Number of girders (10)	Girder spacing (m) (11)	Material Strength (MPa)		List of modifications (14)
		Number (3)	L (m) (4)								Steel (12)	Concrete (13)	
MCB-I ^a	1958	1	22	Slab-on-girder ^e	8.5	2	3.75	0.45	4	2.0	230	20	Curb width reduced to 0.45 m; number of lanes reduced to two
MCB-II ^a	1958	1	22	Slab-on-girder ^e	12.5	3	3.83	0.45	6	2.0	230	20	Curb width reduced to 0.45 m
SRB-I ^b	1970	1	24	Slab-on-girder, ^c 15° skew	12.4	3	3.53	0.90	6	2.0	350	27	None
SRB-II ^b	1970	1	24	Slab-on-girder, ^c 45° skew	12.4	3	3.53	0.90	6	2.0	350	27	Skew angle is increased to 45°
SSRB ^c	1960	2	9	Slab-on-girder ^e	10.5	2	4.25	1.00	5	2.3	230	20	Number of spans reduced to two, skewness is removed
GB ^d	1945	1	28	Through truss	7.70	2	3.65	—	5	1.8	230	20	None

^aMud Creek Bridge.

^bSaugeen River Bridge.

^cSouth Saugeen River Bridge.

^dGrigg Bridge.

^eAll slab-on-girder bridges are composite.

some of the bridges for the fatigue limit state or at points of maximum moment for the ultimate limit state) are obtained for each truck using semicontinuum analysis method as well as for the design live load using the OHBDC recommended simplified analysis method. These bending moments are then used to compare and assess the significance of each load condition and identify the cases for which detrimental effects are anticipated. For the slab-on-girder steel bridges studied, it is found that the shear strength of the girders typically exceeds the design shear force by at least 50%, thus making shear distress improbable even when the bridges are loaded by heavy-permit trucks. Furthermore, because most connections are sized to transmit shear, this finding can be broadly extended to the details. Finally, the adequacy of the reinforced-concrete bridge deck in resisting local overloads by arching action is well documented and is therefore not questioned here (Batchelor et al. 1978; Batchelor and Hewitt 1978; Perdikaris et al. 1989). Therefore, only bending moments are considered in investigating the potential negative impacts of heavy-permit trucks on steel slab-on-girder bridges relative to the effect of OHBDC design loads. Understandably, a more in-depth survey for all members of the truss bridge was warranted and performed.

The absolute expression of the maximum exterior (M_e), interior (M_i) girder moments, and maximum moment range over any girder (M_r), are calculated for each of the five heavy-permit truck models, as well as for the OHBD truck as obtained from computer analyses and from the code's simplified method of analysis. Hereafter, the girder moments obtained from computer analysis and code's simplified method of analysis for the OHBD truck will, respectively, be denoted by subscripts OHBDT and OHBDC. It is noteworthy that in all analyses, the M_r -values are for trucks traveling in the middle of their design lanes, because M_r is only significant in the perspective of fatigue. Moreover, the fatigue results for OHBD truck are multiplied by a load factor of 0.8 (in compliance with the code requirements).

ANALYSES RESULTS

The effect of heavy-permit trucks on the ultimate limit state of the bridges' exterior girders is shown in Fig. 1 in a bar-chart form. There, the bars measure the effect of the factored loads applied to the structure, i.e. $\alpha_D \cdot M_D + \alpha_L \cdot DMF \cdot M_L$, where subscripts D and L refer to dead and live loads and α s are load factors. In the figure, α_D is 1.2 and α_L is assigned a value of 1.15 instead of the customary 1.4 value used for design, as permitted by the 1983 edition of the OHBDC when there is better supervision on vehicle's axle weights and spac-

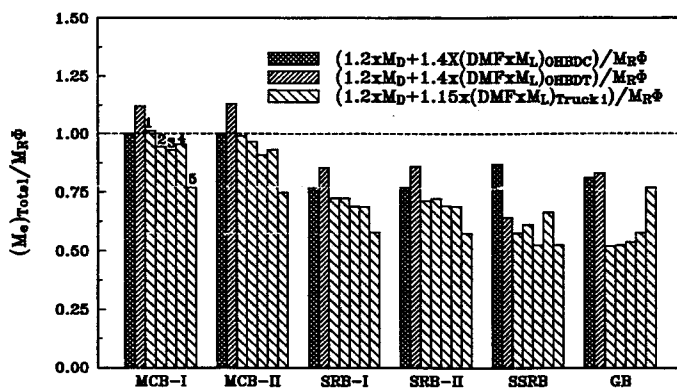


FIG. 1. Ratio of Total Applied Moment to Factored Resistance of Bridges for Five Permit Trucks ($i = 1, 2, 3, 4, 5$) and Design Live Load Obtained from Computer Analyses (OHBDT) and for Design Live Load Obtained Using Code's Simplified Method of Analysis (OHBDC)

ing (controlled vehicle, such as heavy-permit trucks). The dashed line indicates the level of supplied ultimate strength (ϕM_R) of the bridges. Given the constraints of design, the supplied capacity is often in "overstrength" when compared to the demands. Thus, Fig. 1 also allows for a direct comparison between the permit truck loading levels and that of the original design.

To verify whether the serviceability limit state has been violated, the ratio $\{(DMF \cdot M_r)_{\text{Permit Truck}} / (0.8 \cdot DMF \cdot M_r)_{\text{OHBDC}}\}$ is calculated, where DMF is the dynamic magnification factor. In Fig. 2, the effect of heavy-permit trucks on the fatigue limit state of the bridges, as expressed by the aforementioned ratio is illustrated. Values above 1 (dashed line) indicate a violation of the fatigue limit state.

For the slab-on-girder bridges studied, none of the permit trucks considered produced detrimental effects on the interior girders. For bridges having more than one design lane, two design trucks can be placed closely together with their adjacent wheels loading an interior girder to produce moments much larger than those resulting from a single heavy permit truck. Therefore, the absence of detrimental effects due to heavy-permit trucks on the interior girders of slab-on-girder steel bridges should not be surprising.

For the exterior girders, the absolute static live-load bending moments produced by the permit trucks are often more than both those obtained from the design truck or predicted by the code's simplified design method procedure. However, because the dynamic magnification and live load factors for controlled vehicles are lower than those for the design truck, the total factored load from the heavy-permit trucks is less than the ultimate strength capacity as seen in Fig. 1. It is also found that the most critical effects of permit trucks occur on bridges having a combination of small curb width and large overhang and that potential problems attributable to the permit trucks will progressively be attenuated as they are moved further away from the bridges' edge.

However, as seen in Fig. 2, all slab-on-girder simply supported bridges studied were found to be detrimentally affected by heavy-permit trucks with respect to fatigue limit state. For continuous bridges, the conservative assumptions built into the OHBDC simplified design method (i.e. the negative and positive moment regions of the continuous bridge being modeled as two separate equivalent simply supported bridges) result in a design apparently adequate to reduce, but not eliminate, the detrimental fatigue effect of permit trucks.

For truss bridges, permit trucks with extra heavy axle loads will produce bending moments, in the exterior stringers, in excess of those obtained from the design truck or predicted by the code's simplified procedure. The stringers of such bridges are found to have a sufficient ultimate capacity to accom-

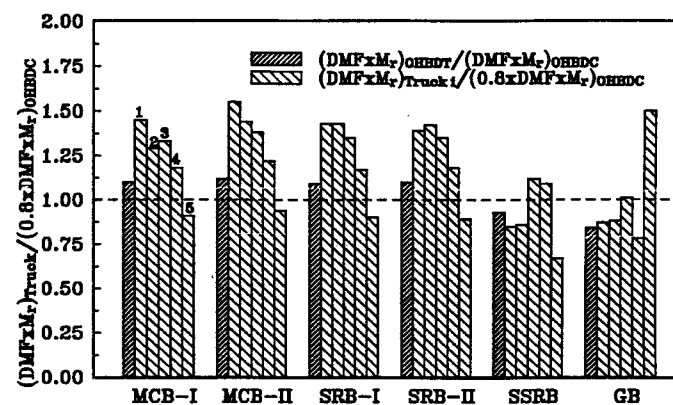


FIG. 2. Ratio of Moments due to Five Heavy-Permit Trucks ($i = 1, 2, 3, 4, 5$) to Design Live Load Moment Obtained using Code's Simplified Method of Analysis (OHBDC)

modate this higher demand. However, for such permit trucks, fatigue distress is strongly expected to occur in the exterior stringers of truss bridges if they are designed to be identical to the interior stringers (which they usually are).

Because special-permit issuance policies are currently being developed by many departments of transportation throughout North America, a special attention must be paid to the problems created by the cumulative effect of permit trucks on steel bridges. A methodology to address this issue is presented following.

ASSUMPTIONS IN DEVELOPMENT OF METHODOLOGY

The stress ranges in steel bridge members produced by normal truck traffic do not have a constant amplitude like those used to generate conventional $S-N$ curves, i.e. curves of the stress range amplitude (S) versus number of cycles to failure (N) curves. The traffic load on bridges is of random nature. In past surveys, Agarwal and Wolkowicz (1976), gathered statistical data of the weight and axle configuration of the truck population in Ontario, which incidentally resembles that found in many other areas of North America. From these data, probability density spectra of the flexural stress ranges in structural members generated by normal truck traffic were constructed by passing those truck samples over moment-influence lines corresponding to spans ranging from 10 to 100 m. These spectra were normalized by the stress range from the OHBD fatigue truck. The mean spectrum obtained by averaging all these normalized spectra is illustrated in Fig. 3. The histogram constitutes a variable-amplitude stress-range spectrum (VASRS) due to normal truck traffic for which various constant-amplitude stress ranges are assigned a corresponding frequency of occurrence.

Fisher and Mertz (1983) tested full-size specimens with various fatigue detail categories. In their test, they used a stress-range history defined by the VASRS shown in Fig. 4, which represents the heavy portion of the normal truck traffic. They demonstrated that if any of the stress ranges from a VASRS exceeds the constant-amplitude fatigue limit (CAFL) of the $S-N$ curve even by a small amount or by a small frequency, then the fatigue life is not infinite anymore. As a consequence, the CAFL, below which fatigue life is assumed to be infinite, is not valid anymore and the $S-N$ curve must be extended below the CAFL. Tests on American Association State Highway Transportation Officials (AASHTO) (American 1991) detail Categories E and E', such as cover plate details and thick web attachments, demonstrated that this extension should be of the same 1:3 slope of the finite-life portion of the $S-N$ curve, but similar tests on type C details,

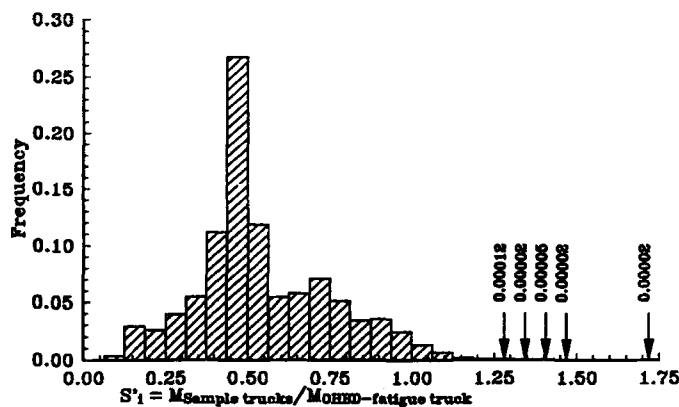


FIG. 3. Average Flexural Stress Range Spectrum of Ontario's Normal Truck Traffic

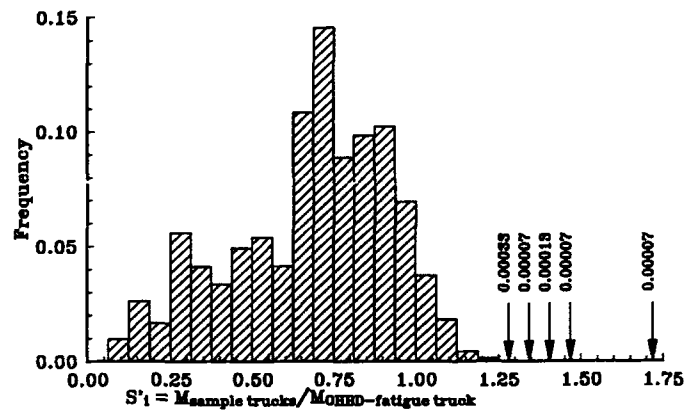


FIG. 4. Average Flexural Stress Range Spectrum of Heavy Portion of Ontario's Truck Traffic

such as vertical stiffeners suggested that a less severe slope could be more appropriate (Fisher et al. 1993).

Therefore, in this study, to develop a fatigue-based methodology, the stress-range spectrum generated by Agarwal and Wolkowicz (1976) and a straight-line extension of the $S-N$ curve below the CAFL, are used. $S-N$ curves with bilinear segments of different slopes have also been considered and found to have little influence on the results. This more comprehensive treatment is presented elsewhere (Bruneau and Dicleli 1994).

ESTIMATION OF FATIGUE LIFE

Miner (1945) assumed that the fatigue damage to the life of a component is a linear function of the cycle ratio. Past experiments have demonstrated this to be an adequate model that is not affected by the sequence of application of stresses (Shilling et al. 1978; Albrecht and Friedland 1979). The VASRS is composed of m various stress range S_i of constant amplitude, each assigned a corresponding frequency of occurrence f_i . These frequencies can be normalized by dividing each of them by their sum to obtain

$$\sum_{i=1}^m f_i = 1 \quad (1)$$

Every stress range is then considered separately, and the number of cycles N_i of each stress range that could be carried safely is calculated using (2)

$$N_i = N_L (S_L / S_i)^3 \quad (2)$$

where S_L and N_L = respectively, allowable stress range and number of cycles corresponding to the CAFL and vary for various detail categories.

The number of application n_i of each stress cycle during the fatigue lifetime can be obtained by multiplying its frequency by the total number of applied cycles N_c

$$n_i = N_c f_i \quad (3)$$

Substituting (3) in Miner's cumulative damage equation (Miner 1945), the safe fatigue life, in cycles, of a detail can be calculated as

$$N_c = 1 / \left(\sum_{i=1}^m \frac{f_i}{N_i} \right) \quad (4)$$

Assuming that each truck passage causes n_s stress cycle, the safe fatigue life, N_{ys} , in years is calculated by the following equation:

$$N_{ys} = \frac{N_c}{ADTT \times n_s \times 365.25} \quad (5)$$

where $ADTT$ = average daily truck traffic volume; and 365.25 = number of days in a year.

To obtain the mean fatigue life, the ratio of mean to allowable stress ranges in the $S-N$ curve can be used. It was proven that, for all detail categories, this ratio does not vary greatly and averages to 1.243 (Moses et al. 1987). Because of the power of 3 in the $S-N$ curve, the corresponding ratio of mean to safe lives is equal to 1.243 cubed, or 1.92. Consequently, the mean life N_{ym} in years can be obtained by multiplying the above equation by 1.92.

Obviously, at the component level, the distribution of forces depends on the geometric and structural properties of the bridge as well as the axle width of the truck (Bakht and Jeager 1985). Therefore, for a more accurate estimation of the fatigue life, a stress-range spectrum reflecting the stresses in the components of interest should be employed in the calculations. However, a spectrum reflecting the overall stress range at a bridge cross section is generally accepted and can be used to estimate the fatigue life of major structural components such as steel girders, in which number of cycles per truck passage can be taken as 1.

PERCENT REDUCTION IN FATIGUE LIFE DUE TO HEAVY-PERMIT TRUCKS

Some obvious difficulties arise when trying to determine what constitutes a tolerable reduction in fatigue life due to heavy-permit trucks in an absolute number of years. This clearly depends on the actual fatigue life under normal traffic. It is proposed here that only a relative loss of service life on the entire bridge inventory can be managed. Therefore, percent reduction in fatigue life is chosen as a meaningful dimensionless variable.

Frequency of passage, f_{hpt} , of the heavy-permit truck, which is expressed as a percentage of the current truck traffic, and the magnitude of stress range, S_{hpt} , of the heavy-permit truck are the only live-load parameters affecting the reduction in fatigue life. The same procedure, described for the calculation of fatigue life under normal traffic, can be used to obtain the reduced fatigue life N_R if the frequency and stress range of the heavy-permit truck are included in the VASRS. Doing so, as a first step, the frequencies of the VASRS must be renormalized by including the frequency of the heavy-permit truck

$$f'_i = \frac{f_i}{1 + f_{hpt}}; \quad f'_{hpt} = \frac{f_{hpt}}{1 + f_{hpt}} \quad (6, 7)$$

Then, (1) is presented in a different form using (6) and (7)

$$f'_{hpt} + \sum_{i=1}^m f'_i = \frac{1}{1 + f_{hpt}} \left(f_{hpt} + \sum_{i=1}^m f_i \right) = 1 \quad (8)$$

Next, the reduced fatigue life is calculated using (3) and (8) in conjunction with Miner's cumulative damage equation (Miner 1945)

$$N_R = (1 + f_{hpt}) / \left(\frac{f_{hpt}}{N_{hpt}} + \sum_{i=1}^m \frac{f_i}{N_i} \right) \quad (9)$$

where N_{hpt} = number of cycles of stress range S_{hpt} that could be carried safely if applied alone and can be obtained from (2). The normalized frequency of the heavy-permit truck is multiplied by the reduced fatigue life in cycles to obtain

$$n_{hpt} = \frac{f_{hpt}}{1 + f_{hpt}} N_R \quad (10)$$

where n_{hpt} = total number of passages of a heavy-permit truck during the fatigue lifetime. Then, the number of heavy-permit truck passages per month, n_{pm} , corresponding to a specified frequency is obtained from the following equation:

$$n_{pm} = \frac{n_{hpt} ADTT 30.44}{N_R} \quad (11)$$

The constant 30.44 in (11) is the average number of days in a month. The frequency of the heavy-permit truck can also be expressed as a function of the allowable number of passages of these trucks per month if (10) is substituted into (11)

$$f_{hpt} = \frac{n_{pm}}{30.44 ADTT - n_{pm}} \quad (12)$$

The reduced fatigue life in cycles, N_R , includes also the cycles applied by heavy-permit truck. To obtain the maximum number of cycles N_{CR} that can be applied by the normal truck traffic (spectrum without the heavy-permit truck) during the reduced fatigue lifetime, the number of cycles of heavy-permit truck, n_{hpt} , should be subtracted from the reduced life

$$N_{CR} = N_R - n_{hpt} \quad (13)$$

The difference between N_C and N_{CR} gives the reduction in fatigue life in cycles. Finally, the percentage of reduction, PR , in fatigue life due to heavy-permit truck is calculated as

$$PR = \frac{N_C - (N_R - n_{hpt})}{N_C} 100 \quad (14)$$

EFFECT OF SPECTRUM AND DETAIL TYPE ON PERCENT REDUCTION IN FATIGUE LIFE

In Fig. 5, percent reduction in fatigue life of a bridge girder with Category D fatigue detail is plotted for spectra obtained for spans up to 100 m length as well as for the average of these spectra. This plot is presented as a function of stress level with respect to CAFL (i.e. the ratio of heavy-permit trucks stress range to the CAFL stress range). These spectra represent the effect of heavy portion of the truck population. $ADTT$ of 1,000 and 100 heavy-permit trucks per month are used in the calculations. As observed from Fig. 5, the difference in percent reduction in fatigue life for various spectra increases as the magnitude of the stress range increases, yet the difference is within acceptable limits to enable the use of a mean spectrum as plotted by a thick solid line in the figure. Hereafter, the average spectrum will be used in all the calculations.

Percent reduction in fatigue life for various detail cate-

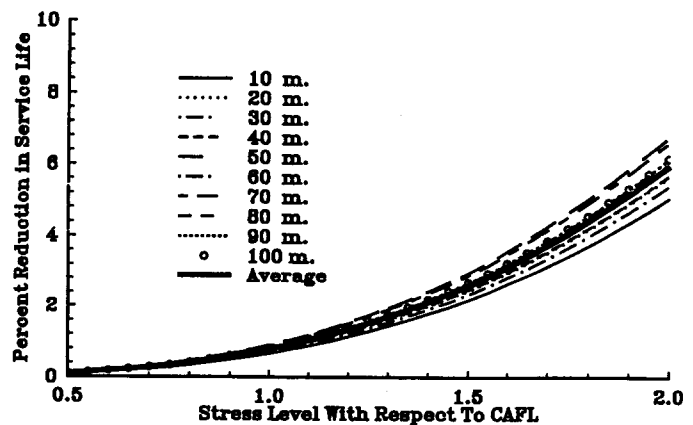


FIG. 5. Effect of Spectrum Type on Reduction in Fatigue Life for Detail d, 100 Permit Trucks per Month, and Average Daily Truck Traffic of 1,000

gories, as a function of the stress range due to heavy-permit trucks is illustrated in Fig. 6. The average spectrum that represents the effect of heavy portion of the Ontario's truck traffic is employed in the calculations. *ADTT* of 1,000, 100 heavy-permit trucks per month and a slope of 1:5 below the CAFL (to consider the possibility of bilinear *S-N* curves) are used in the calculations. As observed from the figure, percentage of reduction in fatigue life does not depend on the detail type.

DEVELOPMENT OF METHODOLOGY

A flexible methodology was developed to assess the reduction in service life of the bridges due to heavy-permit trucks. This methodology considers the alternative regulations of heavy-truck permits and the change in the volume of the normal traffic as well as the weight of the permit vehicles. The objective is to obtain the allowable number of passages of a heavy-permit truck per month, for a specified percentage of reduction in fatigue life and the significance of this percentage in real terms. Considering these constraints, an equation is formulated to be used for issuing permits to heavy trucks. In this equation, three parameters (the tolerable percentage of reduction in fatigue life, *ADTT*, and the type and weight of the heavy-permit trucks) are chosen as variable, while the type of spectrum is kept constant. However, if the spectrum type changes in the future, it will be possible to modify the equation for the new spectrum.

To obtain the aforementioned equation, first, (9) is substituted into (14) and simplified to obtain

$$f_{hpt} = N_{hpt} \left[\frac{100}{N_c(100 - PR)} - \sum_{i=1}^m \frac{f_i}{N_i} \right] \quad (15)$$

Then, (4) is substituted into (15) and simplified to obtain

$$f_{hpt} = \frac{N_{hpt} PR}{N_c(100 - PR)} \quad (16)$$

Then, from (12) and (16) the allowable number of a certain type of heavy-permit truck per month is obtained as

$$n_{pm} = \frac{N_{hpt} PR ADTT 30.44}{N_c(100 - PR) + N_{hpt} PR} \quad (17)$$

Eq. (17) is a general expression that can be used to estimate the allowable number of permits issued to a certain type of heavy-permit truck per month for a specified percentage of reduction in fatigue life. However, this equation can further be simplified for practical applications that do not require a detailed consideration of all the variables.

As mentioned earlier, the five vehicle models considered

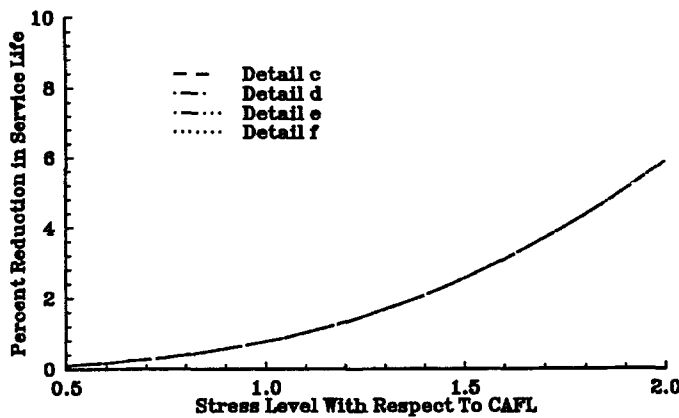


FIG. 6. Effect of Detail Type on Reduction in Fatigue Life for 100 Permit Trucks per Month and Average Daily Truck Traffic of 1,000

in this study are representative of the types of heavy-permit trucks in North America. Each truck is currently assigned a specific weight when it is fully loaded. These weights may increase with time as the trucking industry is developing very fast and therefore trucks capable of carrying heavier loads are manufactured. On the other hand, not all the trucks are always loaded to their full capacity. Consequently, the weight of these trucks is subject to change. Besides this, the stress ranges in structural components due to these trucks varies significantly with the span length of the bridge. Therefore, the weight of these trucks as well as the span length of the bridge should be variable in the equation to be derived.

For added flexibility, in the subsequent application of the methodology the following tools are developed using all the heavy-permit truck models as arbitrarily normalized to have a gross weight of 1,000 kN. However, the known proportional distribution of this 1,000 kN weight among the axles of each permit truck model is respected in all cases. Then, the previously defined live load ratios, *LLR*, are scaled with respect to 1,000 kN weight and also divided by 0.8 to account for fatigue live load. The resulting envelope curves are illustrated in Figs. 7 and 8, respectively, for simply supported and continuous bridges. It is noteworthy that in the case of continuous bridges, the largest of *LLR* for negative and positive moment ranges are considered. For a truck model of a different given weight, *W*, its *LLR* as per the figures need only be multiplied by 0.001*W*.

Heavy-permit trucks usually travel with a slower speed than the normal trucks, consequently, the dynamic load allowance, *DLA*, for these trucks is smaller than those of normal trucks. To take into consideration this effect, the *LLR* obtained from Figs. 7 or 8 should be multiplied by the dynamic load allow-

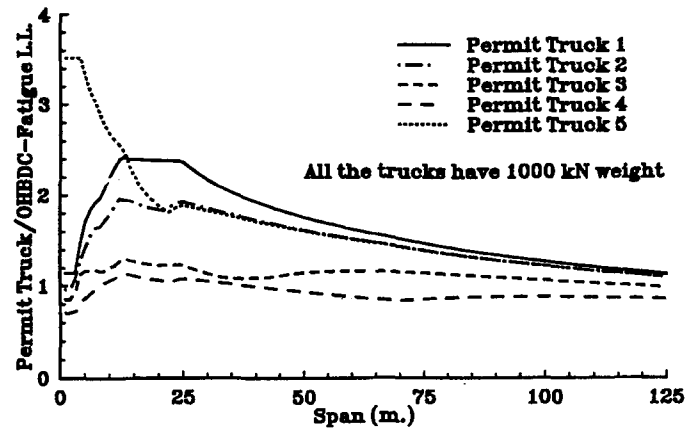


FIG. 7. Live-Load Ratios for Simply Supported Bridges

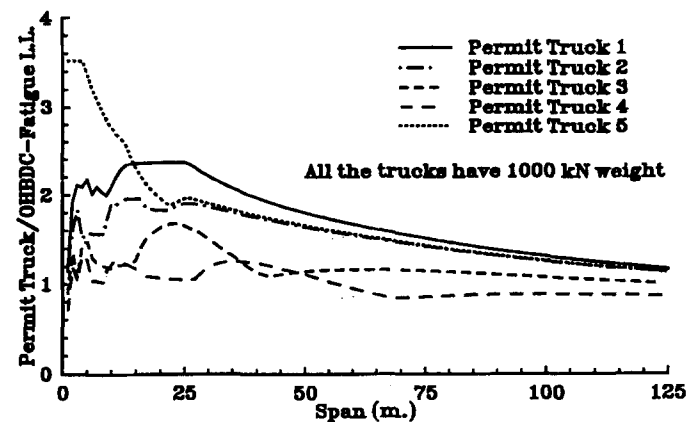


FIG. 8. Live-Load Ratios for Continuous-Span Bridges

ance ratio, $DLAR$, which is a function of speed, V and DLA . The function is expressed as follows:

$$DLAR = \begin{cases} \frac{1 + 0.3DLA}{1 + DLA} & \text{if } V \leq 10 \text{ km/h} \\ \frac{1 + 0.5DLA}{1 + DLA} & \text{if } 10 < V \leq 25 \text{ km/h} \\ 1 & \text{if } V > 25 \text{ km/h} \end{cases} \quad (18a-c)$$

The procedure in the 1983 edition of *Ontario Highway Bridge Design Code* (OHBDC) (1983a,b) or the 1991 edition of AASHTO code can be used to obtain the DLA . DLA is a function of the first national frequency of the bridge superstructure and varies between 0.2 and 0.4, therefore, for practical purposes an average value of 0.3 could be considered.

Heavy-permit trucks may have axles wider than the standard 1.8 m axle width of the design truck. It is known that the distribution of flexural moment among the girders in slab-on-girder bridges is a function of the axle width (Bakht and Jeager 1985). This should also be considered in the methodology. For this purpose, a methodology similar to that developed by Bakht and Jeager (1984) for calculating the allowable increase in vehicle weight as a function of axle width is used as a tool to obtain the following expression, which accounts for the percent decrease in fatigue stress as the axle width increases:

$$SRC = 1 - 0.07(AW - 1.8) \quad (19)$$

where SRC = stress-reduction coefficient; and AW = axle width in meters. Eq. (19) was developed for vehicles with two lines of wheels, and would produce conservative values should the width between the outermost wheels be used for vehicles having more than two lines of wheels. If the axle width of the heavy-permit truck is larger than 1.8 m, the LLR should be multiplied by the SRC to obtain a close approximation of the heavy-permit truck's stress in the girders of the slab-on-girder bridges. However, because SRC -values are generally close to 1.0, this added refinement can be optional.

The structural components of steel bridges are designed for fatigue on the basis that the computed stress range at each location and detail of interest is nearly equal to the corresponding allowable stress, which is the CAFL stress. Consequently, the fatigue live-load stress is approximately equal to S_L . Using this information, the heavy-permit truck's stress is depicted by the following equation:

$$S_{hpt} = S_L LLR DLAR SRC \frac{W}{1,000} \quad (20)$$

Eq. (20) is substituted in (2) to obtain N_{hpt} as

$$N_{hpt} = N_L \left(\frac{1,000}{LLR DLAR SRC W} \right)^3 \quad (21)$$

Then, (21) is substituted into (17) and simplified to obtain

$$n_{pm} = \frac{30.44 \times 10^9 N_L ADTT PR}{N_L(100 - PR)(LLR DLAR SRC W)^3 + N_L PR (1,000)^3} \quad (22)$$

As demonstrated in Fig. 6, the percentage of reduction in fatigue life is independent of the detail type. It was also illustrated that slight variations in spectrum shape, within limits, do not have a significant effect on the percentage of reduction in fatigue life. Therefore, the values of N_C and N_L obtained for any detail type and the average spectrum, can be substituted in (22). The values of N_L and N_C for detail category A are 2,000,000 and 9,223,786, respectively. Sub-

stituting these values in (22) and simplifying, n_{pm} is obtained as

$$n_{pm} = \frac{6 \times 10^{10} ADTT PR}{9.2(100 - PR)(LLR DLAR SRC W)^3 + 2 \times 10^9 PR} \quad (23)$$

Eq. (23) can be used in conjunction with Figs. 7 and 8 to calculate the allowable number of heavy-permit trucks per month for a specified truck type and weight, span length as well as the percent reduction in fatigue life. It is noteworthy that for a specified heavy-permit truck frequency and a constant ratio of heavy-permit truck stress range to that due to normal truck traffic, the percent reduction in fatigue life is constant and does not depend on the amplitude of the CAFL. Therefore, for a specified percent reduction in fatigue life, Eq. (23) yields the same number of permit trucks per month regardless of whether the bridge is over- or underdesigned.

However, bridges that are underdesigned may not have been loaded by the heavy trucks found in normal traffic but would be certain to suffer the extreme effects of extra heavy trucks for which permits are issued. Therefore, Eq. (23) should be used only in a general screening process for heavy-permit trucks because its application for individual bridges is limited.

Eq. (23) can easily be extended to calculate the aggregate fatigue damage for various types of permit trucks. Consider m types of heavy trucks to be permitted. Accordingly, there will be n_1 number of truck 1, n_2 number of truck 2 and n_i number of truck i . For a specified percentage of reduction in fatigue life, the allowable number of each truck, $(n_{pm})_i$, that can be permitted alone is calculated using (23). If truck 1 is permitted only n_i times, then only a fraction, $n_i/(n_{pm})_1$, of the allowable reduction in life is consumed. Similar to Miner's rule, the specified period of fatigue life is consumed when

$$\sum_{i=1}^m \frac{n_i}{(n_{pm})_i} = 1 \quad (24)$$

Eq. (24) can be used to permit various number of heavy trucks which have different effects.

Example

A transportation agency decides, as a policy, that bridges be able to provide a minimum service life of 50 years as calculated by current traffic volume. Consider a simply supported slab-on-girder steel bridge of 20 m span with a worst-case fatigue detail Category C. The bridge has been in service for 19 years. Within a given month, there is a request for a mobile crane (permit truck type 1) to cross the bridge 30 times. There is another request for a float (permit truck type 4) of 1,600 kN weight to cross the bridge 40 times. The problem is to find how many more permit trucks can be allowed to cross the bridge for the current month ($ADTT = 1,200$).

Using (5) and the VASRS for normal truck traffic, the mean fatigue life for detail category C is obtained as 75 years. Assuming that the stress ranges from the same VASRS has been acting on the bridge, the consumed fatigue life is equal to its age, i.e. 19 years. The allowable percent reduction in service life is then calculated as

$$PR = \frac{75 - 19 - 50}{75} \times 100 = 8\% \quad (25)$$

For the mobile crane, LLR is 2.40, $DLAR$ is 0.88, SRC is 0.951, and W is 790 kN. Substituting these variables in (23), the allowable number of mobile cranes, $(n_{pm})_1$, is calculated as 169. For the float, LLR is 1.09, $DLAR$ is 0.885, SRC is 1.000, and $W = 1,600$ kN. Substituting these variables in (23), the allowable number of floats, $(n_{pm})_2$, is calculated as

184. Then, the allowable number of trucks per month and the number of intended passages of these trucks are substituted in (24) to obtain the consumed portion of the allowable reduction in fatigue life as

$$(30/169) + (40/184) = 0.40 \quad (26)$$

Only 40% of the allowable reduction in fatigue life will be consumed. Therefore, more permit trucks can be allowed to cross the bridge for the current month. If no other permit trucks cross the bridge, the remaining 60% can be carried over the next month.

SAMPLE PERMIT POLICY

It is possible, using (23) to formulate a number of different policies governing the emission of special permits for extra heavy trucks. A simple and effective permit policy example follows upon which more elaborate strategies can be modeled as needed.

The number of permissible heavy-permit trucks on a given bridge is a function of the assumed service life of the bridge. As in many other codes, OHBDC requires a minimum service life of 50 years. Conservatively assuming that this service life to be the fatigue life for all bridges, a 1 year or 2% reduction in a 50-year fatigue life seems reasonable considering the practical and economical consequences of permitting heavy trucks.

ADTT, weight and axle width of the trucks, as well as the *DLA* are the factors affecting the number of trucks that can be permitted. Conservative values are assigned to these variables to establish a policy to permit heavy trucks. A lower-bound value of *ADTT* which is 1,000 for class A highways is assumed. The original weights of the five heavy-permit truck models are taken as a basis, and the trucks which cause the most detrimental effect for a specified span length are considered only. Furthermore, axle width and the *DLA* are conservatively assumed to be the same as those of the normal trucks.

The foregoing assumed values are substituted in (23) to obtain the allowable number of heavy trucks per month for various span ranges. For slab-on-girder steel bridges, 15, 30, 45, and 60 heavy trucks per month may be permitted for spans shorter than 35 m, 35–50 m, 50–75 m, and longer than 75 m, respectively.

Truck model 5 has the most detrimental effect on stringers up to 10 m in steel truss bridges. Since this truck has only two axles and the distance between the axles is about 11 m (longer than usual length of stringers), two cycles per passage is considered appropriate. Accordingly, for steel truss bridges, 8, 12, and 33 heavy trucks per month may be permitted for stringer spans less than 7 m, 7–10 m and more than 10 m, respectively.

Considering that each detail category has a specific fatigue life, different percent reduction values for various detail categories could also be assigned to obtain an alternative permit policy. Ultimately, an effective permit policy will be the one that helps establish a rational schedule of permit fees to recoup the progressive loss of serviceability attributable to heavy-permit trucks.

CONCLUSIONS

The more rigid control of weight, weight distribution, lateral position on bridges, and driving speeds of extra heavy trucks has made possible the development of special permit-issuance policies based on rational simplified concepts. Rigorous analysis verifies that the full three-dimensional distribution of effects produced by permit trucks allowed by such policies does not violate the ultimate limit state of steel bridges.

However, the stress ranges produced by such permit trucks on key structural components are found to often largely exceed those considered for the normal truck traffic during design, and fatigue-related failures could ensue.

The issuance of special permits to extra heavy trucks undeniably reduces the service life of existing steel-bridge infrastructure. To manage this problem, a fatigue-based methodology has been developed and is proposed to assess the percentage reduction in the fatigue life of steel bridges caused by heavy-permit trucks for various fatigue detail categories. As part of this methodology, an analytical expression was provided to calculate the allowable number of heavy-permit trucks per month as a function of a specified percentage of reduction in fatigue life, weight, axle width, axle configuration as well as the speed of the permit truck, and average daily truck traffic. It was found that a reasonably large number of special permits can be issued at small reductions in fatigue life, but because stress ranges in excess of the CAFL significantly alter the shape of the *S-N* curve, it is essential to appreciate that the concept of infinite fatigue life cannot be relied upon anymore. The proposed methodology also takes into account that some portion of the existing normal truck traffic also produces stresses in excess of the CAFL, even though not as excessively as permit trucks.

ACKNOWLEDGMENTS

The findings of this research through a grant from the Ontario Ministry of Transportation is gratefully acknowledged. Special thanks are extended to A. C. Agarwal, B. Bakht, and T. Tharmabala for their valuable comments. The findings and conclusions of this paper are, however, those of the writers alone.

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