EVALUATION AND POSTING OF BRIDGES IN ONTARIO

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The present system of posting substandard bridges in Ontario with a single load limit serves only as a vague warning to a driver that the bridge is somewhat deficient. Truck drivers generally disregard the posting sign, because they know they can carry heavier loads across without causing any apparent damage to the bridge. The quantitative definition of the posted value is based upon a design load reflecting vehicles in common use three decades ago, and herein lies the problem. Diverse modern traffic cannot be effectively represented by any single value posting which is generally too restrictive on short span bridges, especially for the long vehicles. Specified loads for the purpose of bridge design can be determined through statistically based load surveys to a significant degree of reliability. The procedure employs the concept of the 'Equivalent Base Length' to transform actual vehicles into uniformly distributed loads for mathematic manipulations leading to a single truck model which efficiently represents the wide variation in vehicle types. This report describes the development of live loads and a new triple posting system. Both have been adopted as the basis of capacity rating of existing bridges in the new Ontario Highway Bridge Design Code. The system employs the philosophy of ultimate limit states in evaluation of three levels of posting using an appropriate loading model for each level. Adjustments to the calculated load-carrying capacity are made to account for the operational overloads beyond legal limits, inherent to human nature, and the unusual distribution of loads on various axles in a partially loaded vehicle.

Permissible weights for commercial highway vehicles are regulated by the relevant provisions of the Highway Traffic Act in the Province of Ontario. In order to withstand these legal loads, a bridge must meet standards set in design specifications currently in use in the province. Where a bridge fails to meet these standards, certain restrictions are being applied. A restriction for maximum gross vehicle weight is presently displayed at the bridge by a sign that reads:

MAXIMUM WEIGHT X TONS

The quantitative definition of value X is based on design loads (1) that have not reflected specific Ontario conditions for the last three decades. Consequently, the value X bears little technical relationship to the load-carrying capacity of a bridge with respect to the modern commercial vehicles. The posted value has served only as an administrative tool and a vague warning for a truck driver that the bridge ahead is somewhat less than capable to carry legal highway loads.

Drivers have difficulty in properly interpreting the posting sign. Truckers consider the posting signs too restrictive and tend to believe from their experience that they can carry much heavier loads across without causing any apparent damage to the bridge. Some incorrectly think that the posted limit represents payload on the truck. The combination of these factors has rendered the posting signs useless because the truckers usually disregard them. The success of enforcement of a posted weight limit almost entirely depends upon the proper education and goodwill of a truck driver and his faith in the accuracy of the system.

As a first attempt to update the evaluation procedure to reflect modern highway traffic, a method was proposed by Csagoly (2). This method, still leading to a single velue posting, uses a design load based upon the 1971/72 vehicle survey conducted in the province, and the Ontario Bridge Formula which is the basis for the present vehicle weight regulations in Ontario (3). The background material and details of the design equation and various parameters involved are outlined by Csagoly and Dorton in their report on the Proposed Ontario Bridge Design Load (4).

This method incorporates modern highway loads; however, it produces a weight limit which is too liberal for short trucks which could seriously endanger the safety of the structure. It was later realized that the single value posting load had certain inherent problems irrespective of the design model to be used. A single value based upon a short truck model would be too restrictive for longer trucks and the single value based upon a long truck model would be too liberal for short trucks. Also,

on a short span bridge, the single value obtained by any method would be too restrictive for long vehicles because the procedures fail to recognize that only part of a long vehicle may be accommodated over a short bridge.

A new rating system based on multiple value posting was developed by the Ontario Ministry of Transportation and Communications and, in principle, has been adopted for the new Ontario Highway Bridge Design Code. This report describes the proposed new system and the procedure of evaluating the load-carrying capacity of a substandard bridge using this system.

Classification of Modern Highway Vehicles

To collect more recent data for commercial vehicles, a vehicle survey was conducted in 1975. The sample was statistically distributed across the province and the data for each vehicle included vehicle type and configuration, interaxle spacings, empty vehicle weight and the axle weights of loaded vehicles. Vehicle configurations observed during the survey are shown in Figure 1. Configurations seen most frequently were 1, 15, 19, 20, 24, 25, 26, 29 and 34.

Categorizing the vehicles by the total number of axles appeared to be a simple approach initially, but led to complications. When considering the range of permissible legal loads, a large number of vehicle categories resulted. A more viable classification is based upon the number of vehicle units in a vehicle combination. All commercial vehicles can be grouped into the following three categories.

Vehicle Category I

All single unit vehicles of configurations 1, 15 and 34 fall into this category. Five axle single unit vehicles, without trailer, although rare, are also included. The most common vehicles are of configuration 15 with a single steering axle in front and a dual tandem axle at the rear. The legal weight limit on such a vehicle is about 215 to 250 kN (48,320 to 56,180 lb.).

Vehicle Category II

All two unit vehicles consisting of a tractor unit and one trailer or semi-trailer are included in this category. Common configurations are 19, 20, 24 and 29 with five or six axles. Seven axle combinations of configurations 33 and 36 are also present but in very small numbers. Almost 75% of all vehicles in this category are of configuration 24 with a single steering axle in front and two dual tandems, one on the tractor and one on the trailer. The legal weight limit for most five axle vehicles is 380 to 430 kN (85,400 to 96,630 lb.).

Vehicle Category III

All vehicle trains consisting of a tractor unit and more than one trailer are included here. The most common types of configurations are 25 and 26. The legal weight limit for a seven axle vehicle train is about 530 to 580 kN (119,110 to 130,340 lb.) whereas eight axle trains may carry up to 600 kN (134,840 lb.).

The Rating System

The new system consists of three posting levels illustrated by the typical posting sign given in Figure 2. Levels 1, 2 and 3 control vehicle weights in Categories I, II and III, respectively. The sign may appear to provide too much information to read while travelling at high speed but once the system is operational, it is believed a truck driver will quickly learn to read the value applicable to his own vehicle.

Evaluation Methodology

Evaluation of a bridge with low complexity and well known behaviour is usually done by analysis. Where doubt exists regarding the actual behaviour, a full-scale load testing may be required to establish the proper mathematical model of the bridge structure for analysis. In some cases, a proof load testing may also be conducted to ascertain the accuracy of analytical findings and to verify assumptions regarding material properties and strength. However, bridge testing is beyond the scope of this report and details of only the analytical system are given here.

The three levels of posting are determined by analytical evaluation of the bridge structure using a different live load model for each level. Each model is representative of actual vehicles in the corresponding vehicle category and includes an operational overload allowance beyond the legal limits for all operations other than special permits.

Characteristic Evaluation Equation

Substandard bridges are generally posted for a short period of time before remedial measures of strengthening or replacement are taken. For such a short term evaluation, only ultimate limit states are considered.

The characteristic evaluation equation for the ultimate limit states can be written as:

$$(1-\mu)\,\phi\,R_n \geq \text{Effect of}\left[\sum_{i=1}^{4} \alpha_{D_i} \cdot D_i + F(\alpha_L L_L + \alpha_I L_I)\right] \quad (1)$$

where
- μ = degree of deterioration
- ϕ = performance factor
- R_n = nominal resistance of structural components
- α = load factor
- F = scale down factor
- D_1 = dead load of factory produced structural components, excluding wood components
- D_2 = dead load of cast-in-place structural concrete components, structural wood components, and all non-structural components other than a superimposed wearing surface
- D_3 = dead load of superimposed wearing surface
- D_4 = dead load of earth fill
- L_L = live load
- L_I = dynamic load allowance

The degree of deterioration is established by a thorough inspection and is governed by the net

Figure 1. Vehicle configurations observed during the 1975 survey.

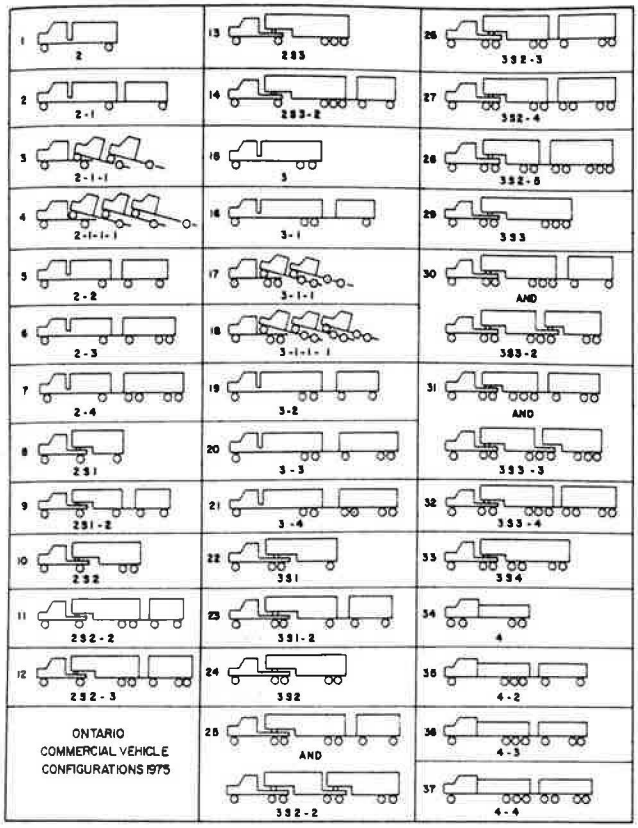


Figure 2. Posting sign.

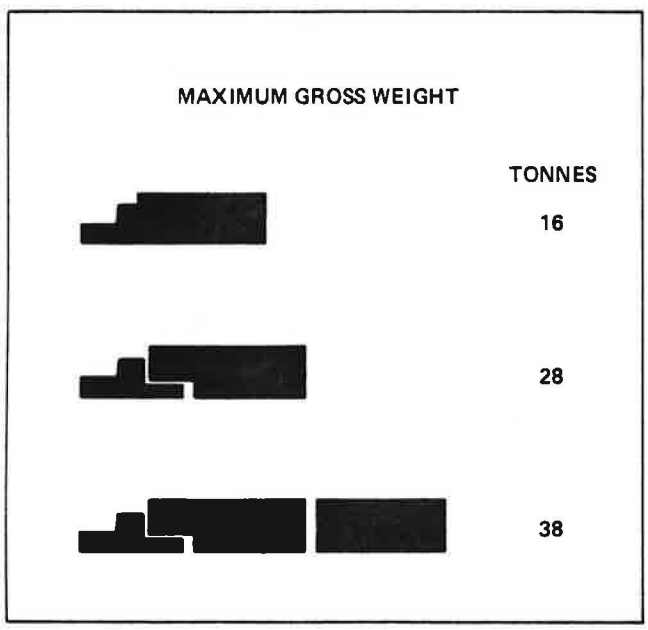


Figure 3. Equivalent base length concept.

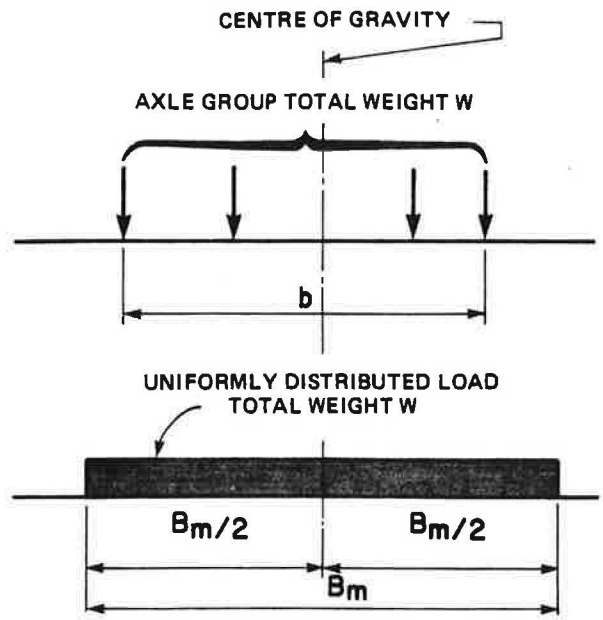
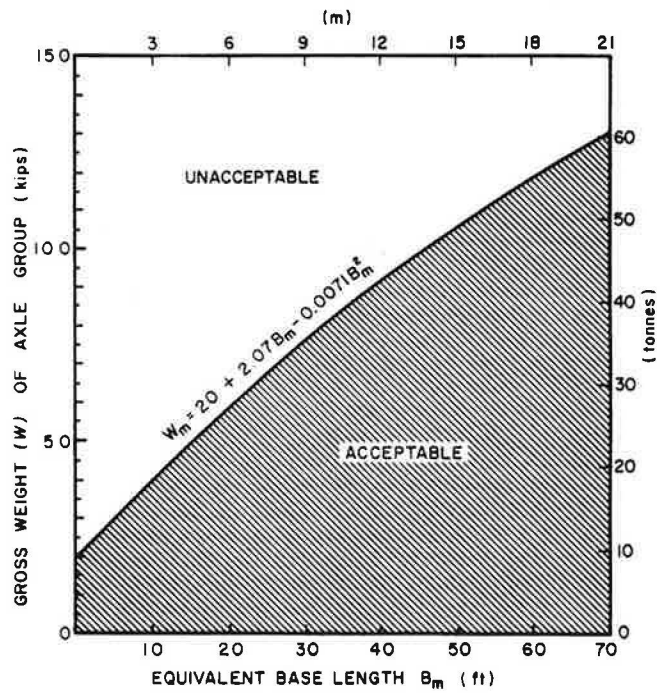


Figure 4. Acceptance test diagram.



cross-sectional area of the reliable material. For deteriorated compression members, strength will be affected not only by the reduced area directly, but also by any change in effective buckling capacity.

The variability factors ϕ and α have been derived for the design of new bridges (5). They may be subject to change for short-term bridge evaluation, particularly for posting purposes. The performance factor may be modified depending upon age, condition, type and past service of the structural component but any change must not exceed 0.10. The live load factor, α_L, may be reduced to a minimum value of 1.20 for short-term evaluation. Dead load factor, α_{D_3}, for the superimposed wearing surface may be reduced to $(1 + t)/t$ where t is the average measure of asphalt thickness in inches. The above modifications of load factors apply only where the load increases the maximum response.

Structural components which are critical to the strength or stability of the entire bridge and whose individual loss would cause a catastrophic failure may be assigned a reduction in the performance factor by 10%.

The scale down factor, F, defines the fraction of the representative vehicle model that can safely be carried across the bridge. This factor can be determined from the characteristic evaluation equation 1.

There is a possibility that the above modifications in ϕ and α may lead to an unsuitably low overall safety against failure. To guard against this possibility, a minimum overall safety factor of 1.25 must be maintained. Hence the scale down factor, F, should not be greater than the value given by the following equation:

$$F \leqslant \frac{\dfrac{(1-\mu)\,\phi\, R_n}{1.25} - \text{Effect of } (D_1 + D_2 + D_3 + D_4)}{\text{Effect of } (L_L + L_I)} \qquad (2)$$

Development of Representative Vehicle Models

Modern highway traffic consists of several variations in vehicle types ranging from short two axle trucks to long truck trains. There exists an infinite number of combinations of interaxle spacings and axle weights. The discontinuous nature of highway loads does not lend itself to a simple mathematical manipulation. However, the concept of 'Equivalent Base Length' permits a simple transformation of highway loads into a continuous mathematical function. Equivalent base length, B_m, illustrated in Figure 3, is defined as the length over which the total weight of a group of axles can be uniformly distributed to cause force effects in a bridge structure similar to those caused by the group of axles itself. This transformation makes it easier to determine the force effects caused by a vehicle or a part thereof.

In 1967 data were collected on the axle weights and interaxle spacings for 6,763 vehicles in Ontario. Analysis of these data, using the equivalent base length concept (6), led to the development of the Ontario Bridge Formula. This formula became the basis for heavy vehicle weight control in the Province of Ontario in 1970. The Ontario Bridge Formula is given as:

$$W_m = 88.96 + 30.21B_m - 0.34B_m^2 \qquad (3)$$

where W_m = permissible total weight on a group of axles in kilonewtons

B_m = equivalent base length for the group of axles in metres

$$\left[W_m = 20.0 + 2.07B_m - 0.0071B_m^2\right.$$

where W_m is in kips and B_m is in feet.]

The Ontario Bridge Formula is displayed as a curve in Figure 4. Such a diagram is commonly known as an 'Acceptance Test Diagram' and serves as an excellent tool to check a loaded vehicle for violation of legal limits and to compare the force effect of different vehicles on bridge structures. An example truck is displayed on the acceptance test diagram in Figure 5. The full truck or any of its subconfigurations is represented by a single point. If the point lies below the Bridge Formula curve, the subconfiguration is considered to be within the legal limits.

Maximum Observed Load Level

Through various load surveys in Ontario, it has been established that a certain relationship does exist between the legal and actual loads. Based on a commercial vehicle weight survey in 1971/72, in Ontario, a level of maximum observed load (MOL) was established. This level was found to be about 100 kN (22.5 kips) higher than the Ontario Bridge Formula and was further verified by the vehicle survey in 1975 (7).

Modified OBF and MOL Levels

The Highway Traffic Act for heavy vehicle weight control in Ontario was amended in 1978 (8). The new legal limits are based on a modified Ontario Bridge Formula given as:

$$W_m = 9.806\ (10.0 + 3.0B_m - 0.0325B_m^2)$$

The modified MOL level is given as:

$$W_{MOL} = 9.806\ (20.0 + 3.0B_m - 0.0325B_m^2)$$

The modified MOL level has been adopted as the level of specified live load models for the Ontario Bridge Design Code.

Representative Truck Models

During the early stages of writing the Ontario Bridge Code, truck models for the design and evaluation of bridges were developed independently. The reason for this is that evaluation trucks need represent only the corresponding vehicle category whereas the design truck model must represent the entire truck population. A few important observations were made from the 1975 vehicle survey:

1. For vehicles in Category I, the maximum single axle weight was less than 140 kN (31.47 kips) and violation of legal gross weights was within 90 kN (20.23 kips). The most common spacing for a dual tandem was about 1.22 m (4 ft.). Loads as high as 270 kN (60.70 kips) were observed on these axle units.
2. For vehicles in Category II and III, single axle weights as high as 184 kN (41.5 kips) were observed. Violations on axle units and axle groups reached up to 107 kN (24.05 kips). The largest single axle weight in the 1971 survey was 202 kN (45.5 kips).

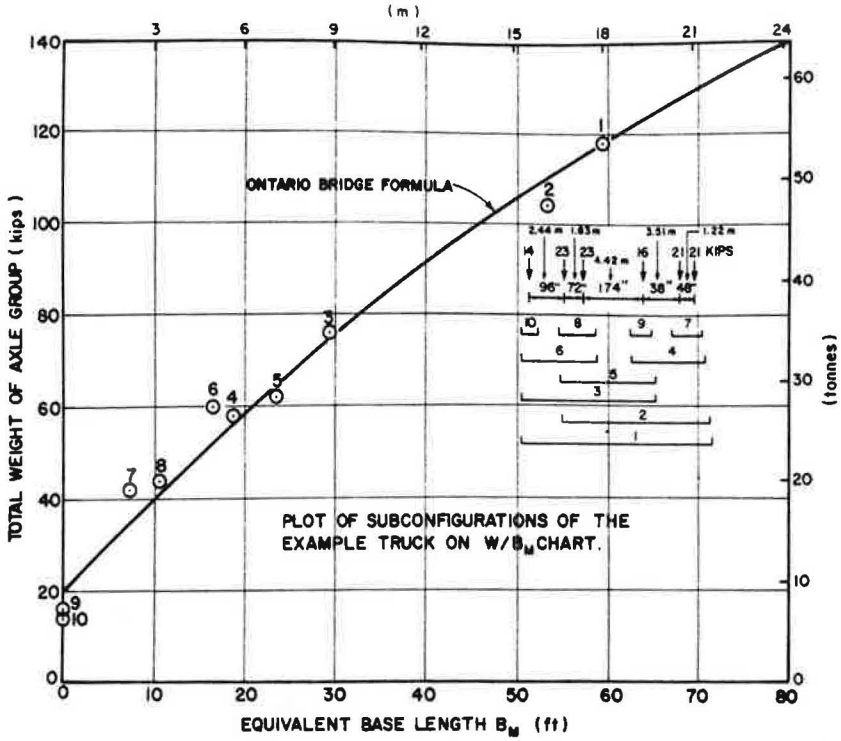


Figure 5. Equivalent base length B_m (ft.)

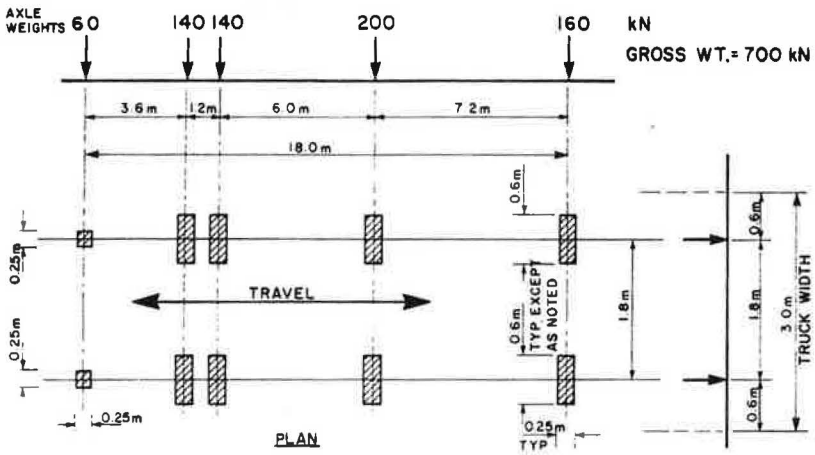


Figure 6. Ontario Highway Bridge Design Truck (OHBD Truck).

Figure 7. Comparison of OHBD Truck with the maximum observed load level.

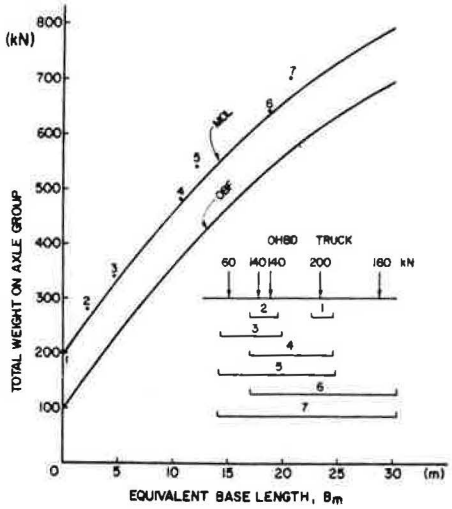
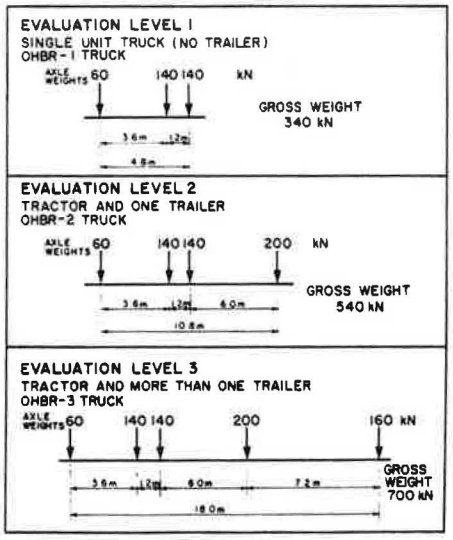


Figure 8. Trucks for rating of bridges.



The truck models which would be used frequently in future design and evaluation should be simple and spacings and axle weights should be easy to remember. The requirements for the design truck model and the Level 3 evaluation truck model are essentially similar. The model should have:

1. At least one single axle weight of 200 kN (44.96 kips).
2. A light front axle typical of most highway vehicles. The common front axle weights were found to be close to 53 kN (12 kips).
3. A dual tandem axle at about 1.22 m (4 ft.) spacing, carrying close to 270 kN (60.70 kips).
4. A total length of about 18.3 m (60 ft.) which is the commonly observed distance between the extreme axles in truck trains.

For the truck model for Level 1 evaluation, the heavy single axle of 200 kN (44.96 kips) was not required, but the heavy dual tandem axle unit had to be retained.

Finally, it was possible to develop a truck model which, in its entirety, can be adopted for design and Level 3 evaluation, and whose subconfigurations can be utilized for Level 1 and 2 evaluation. This model, designated as the Ontario Highway Bridge Design Truck (OHBD Truck), is shown in Figure 6. Its subconfigurations are compared to the MOL level in Figure 7. The three truck models for evaluation are shown in Figure 8 and designated as OHBR-1, OHBR-2 and OHBR-3 Truck. The fact that OHBR-1 Truck is a part of the OHBR-2 Truck, which in turn is a part of the OHBR-3 Truck, makes the computation for three-level evaluation reasonably simple. It may also be noted that the OHBR-3 Truck is identical to the OHBD Truck. Although not essential, this is convenient for the Code. Gross weights of the three models are 340, 540 and 700 kN (76.44, 121.40 and 157.37 kips), respectively.

Multiple Presence of Vehicles

The live load model previously described represents a population of single trucks. In the evaluation of bridge capacity, the total live load effect is determined by considering the simultaneous presence of a number of trucks on the bridge. These trucks may belong to one or several vehicle categories. It can be proven that the load limitation determined by the exclusive use of a particular truck model for each level is valid for any mixture of truck types.

Consider a situation where two trucks are placed on the bridge for evaluation of bridge capacity for the three levels. The bridge is analyzed by placing two OHBR-1 Trucks and a posting load of 150 kN (33.72 kips) is obtained for Level 1. Similarly, a posting load of 250 kN (56.20 kips) for Level 2 is obtained by using two OHBR-2 Trucks. The bridge will be able to safely carry either two trucks from Category I, each loaded to 150 kN (33.72 kips), or two trucks from Category II, each loaded to 250 kN (56.20 kips). The governing effect would be due to either the gross weight of the trucks, or the weight on the axles, particularly for short span bridges and in the event a secondary member is most critical.

Now let us examine the effect of placing one truck from Category I, loaded to 150 kN (33.72 kips), and another from Category II, loaded to 250 kN (56.20 kips). If axle weights govern the bridge capacity, the effect of a truck from Category I would be similar to the effect of a truck from Category II, and the mixed truck case will have the same effect as with two trucks from either category. If the gross vehicle weight is the governing item, the mixed truck case would be less severe than the case using two trucks from Category II. Thus, mixing trucks from various categories need not be considered for the evaluation.

Highway Classification

The number of trucks to be placed simultaneously on a bridge depends largely on the type of road and the traffic volume using the bridge. For the design and evaluation of bridges, all roads and highways in Ontario are categorized into the following three classes:

Class A - includes all freeways and arterial roads. These roads carry high volumes of commercial traffic.

Class B - includes all collector roads. These carry a medium volume of commercial traffic.

Class C - includes all local roads carrying a light volume of commercial traffic. Roads with no commercial traffic also are included in this class. Roads in this class are limited to two traffic lanes.

Multiple Truck Arrangement

For all simple span bridges with span lengths up to 100 m (330 ft.) and continuous bridges where the sum of two adjacent spans does not exceed 122 m (400 ft.), no more than two trucks need to be considered in a traffic lane. Based upon his probabilistic study of multiple presences (9), Agarwal suggested to use a maximum of 4, 3 and 2 trucks simultaneously on a bridge in highway Classes A, B, and C, respectively. For the negative moments near, and the reaction at the intermediate supports in a continuous structure, up to 5 trucks are suggested for Class A highway bridges. Some truck arrangements for the three classes are displayed in Figure 9.

Representation by Uniformly Distributed Load

The multiple truck arrangement described above, although looks physically simple, may lead to some difficulties in positioning trucks on longer spans. Furthermore, it is considered to be a less efficient way to represent a wide variety of traffic mix which may also include a large number of light and/or non-commercial vehicles. It was found that such a diverse traffic mix can be more effectively represented by a complementary, uniformly distributed load in each traffic lane together with a fraction of the basic truck model.

Figure 10 shows Lane Load models for the three levels of evaluation. To determine the critical force effects on a structural component, one or more traffic lanes may be loaded. Each lane is loaded by one OHBR Truck or the corresponding Lane Load, whichever gives the larger effect. Total force effect is then multiplied by a reduction factor given in Table 1, to account for reduced probability of having simultaneous loads in more than one traffic lane.

Figure 9. General load patterns under the proposed multiple presence of a number of the trucks.

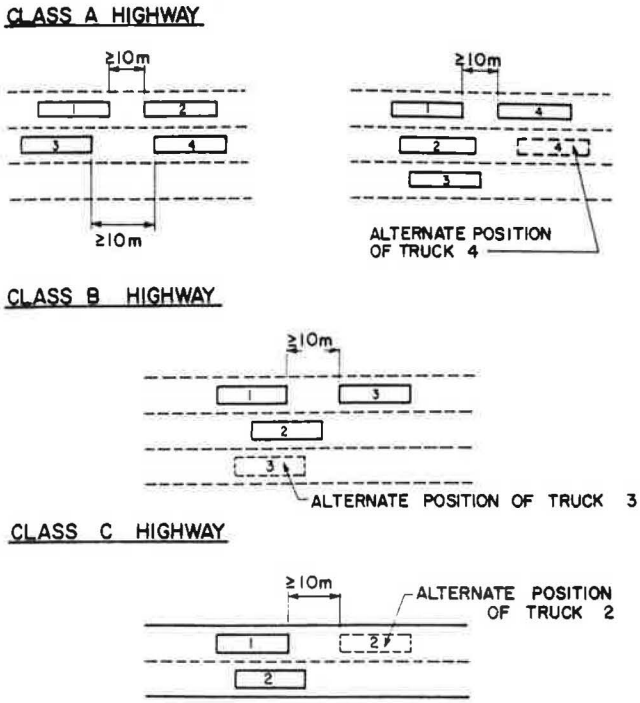


Figure 10. Lane loads.

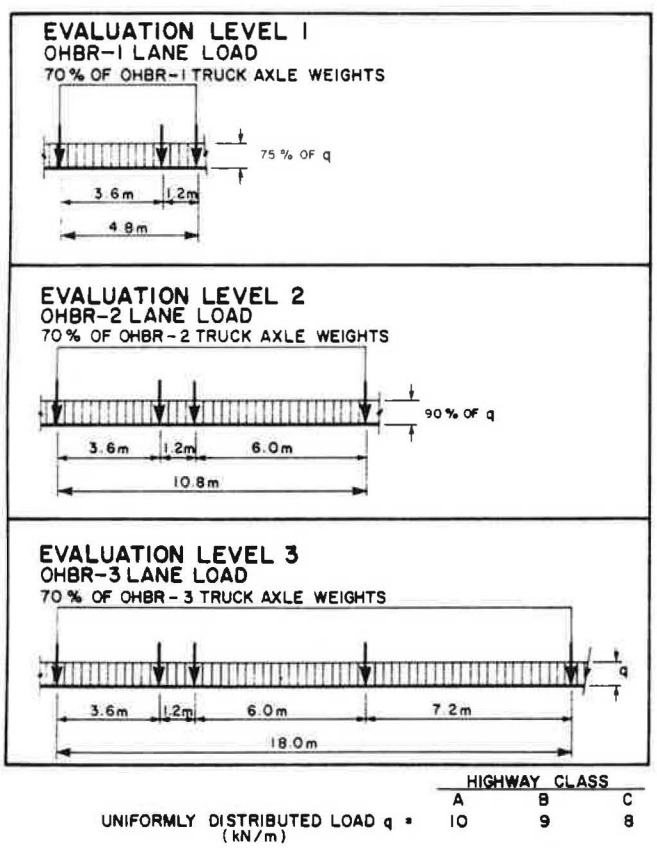
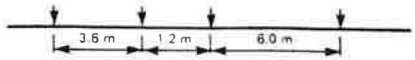


Figure 11. Partial loads on OHBR-2 Trucks.



Full Load	60	140	140	200	=	540 kN
Partial Loads	59	138	138	185	=	520
	58	136	136	170	=	500
	57	134	134	155	=	480
	56	132	132	140	=	460
	55	130	130	125	=	440
	54	128	128	110	=	420
	53	126	126	95	=	400
	52	124	124	80	=	380
	50	120	120	70	=	360
	48	116	116	60	=	340
	44	110	110	56	=	320
	40	104	104	52	=	300
	36	98	98	48	=	280
	32	92	92	44	=	260
	28	86	86	40	=	240
	24	78	78	40	=	220
	20	70	70	40	=	200
	20	60	60	40	=	180

Figure 12. Load shift factors for shear and moments.

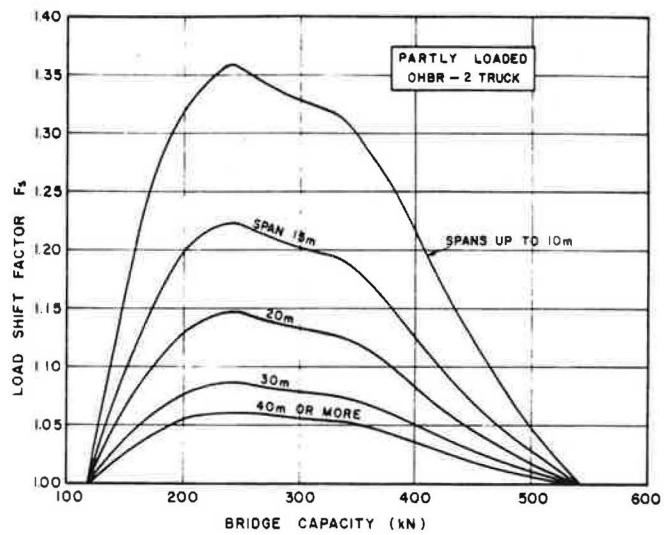


Figure 13. Posting load for first level.

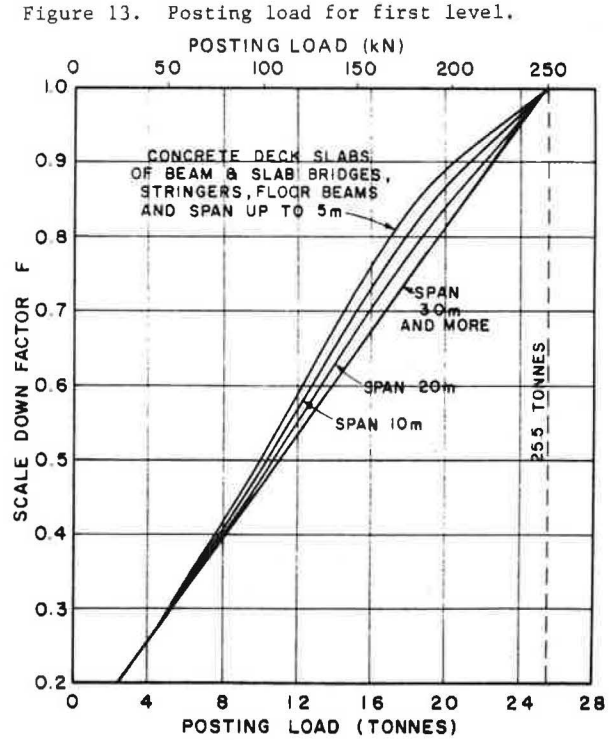


Table 1. Reduction factors for multi-lane loading.

Number of Loaded Lanes	Reduction Factor
1	1.00
2	0.95
3	0.85
4	0.75
5	0.67
6 or more	0.60

Partially Loaded Vehicles

An empty vehicle, or a vehicle loaded close to its legal limits in accordance with the Highway Traffic Act, would generally have an even distribution of load on various axles. The force effect per unit gross weight of the vehicle would be close to the force effect per unit gross weight of the truck models. Vehicles with partial loads may have an uneven distribution on various axles due to the unloading procedures. For instance, a truck train may travel with an empty second trailer but the first trailer may be fully loaded in the legal sense or even overloaded. Such a vehicle may cause much larger force effects per unit gross weight. Allowance, therefore, should be made in the bridge capacity rating for such odd distributions.

Load shift factor, F_s, defines the ratio of the force effect per unit gross weight of a partially loaded vehicle, and the force effect per unit gross weight of the truck model for the level of evaluation under consideration. The largest load shift factors are determined by using various unusual distributions of partial loads. Generally, force effects are found to be larger if the load is concentrated over the middle axles of a vehicle. Figure 11 shows an example of unloading an OHBR-2 Truck to obtain large load shift factors. For each loading level, the force effect per unit gross weight is determined for simple spans and compared to the force effect per unit gross weight due to a full OHBR-2 Truck. The results are shown in Figure 12. Load shift factors are found to be larger for shorter spans or secondary members and approach unity as the load level approaches empty vehicles or fully loaded vehicles.

Overload Allowance

From the commercial vehicle surveys in 1971/72 and 1975, it has been established that a considerable number of trucks do violate the legal limits. The degree of violation depends upon the clarity of vehicle weight regulations, its enforceability, the degree of enforcement and, to a great extent, on the penalty structure for overloads beyond legal limits. The truckers would like to carry maximum loads without endangering vehicle safety and receiving heavy penalties. Some may find it more economical to pay the fines for small overloads. In Ontario, the fines increase exponentially with the amount of overloads in order to discourage the truckers from carrying large overloads.

Using vehicle surveys, maximum overloads have been established for normal operation on routes where full Bridge Formula loads were permitted. The overload could be on the full vehicle or its subconfigurations. The maximum overload for Category I trucks was found to be about 90 kN (20.23 kips), while for other categories it could be as high as 107 kN (24.05 kips). For bridges which are not capable of carrying full legal loads, permissible weights would be less than those permitted by the Bridge Formula.

Unfortunately, no information is available regarding the degree of violation when only part of the full legal loads is permitted but, it is believed that these overloads will be somewhat smaller than the values given above. Prediction of such overloads is at present a matter of judgement. However, a minimum overload allowance of 50 kN (11.24 kips) for permissible load levels corresponding to empty vehicles seems to be justified. The overload allowances for the three levels of posting are given by the following equations:

First Level:

$$L_o = 35.0 + \frac{C}{6} \leq 90.0 \qquad (4)$$

Second Level:

$$L_o = 30.0 + \frac{C}{7} \leq 107.0 \qquad (5)$$

Third Level:

$$L_o = 30.0 + \frac{C}{9} \leq 107.0 \qquad (6)$$

where L_o = overload allowance in kN

C = bridge capacity rating in kN after adjustment for odd distribution of load for partially loaded vehicles

Posting Load Charts

The scale-down factor, F, defines the bridge capacity before any adjustment is made for partially loaded vehicles and overloads beyond permissible limits. Two steps of adjustments are made before arriving at the posting load. First, an adjustment is made for load shift in partially loaded vehicles to obtain the adjusted bridge capacity, C:

$$C = \frac{F}{F_s} \text{(Gross Weight of Truck Model)} \qquad (7)$$

Second, using equations 4 to 6, overload allowance, L_o, is determined. Posting load is then given by:

$$P = C - L_o \qquad (8)$$

Posting load charts have been developed which give the posting load, P, directly as a function of the scale-down factor, F. The above two adjustments are implicit in the charts. Figures 13, 14 and 15 give the three Posting Load charts for Levels 1, 2 and 3, respectively.

The following steps summarize the analytical evaluation procedure.

1. Select critical members and sections in the bridge and determine the force effect for various dead loads and live load placing an appropriate OHBR Truck or corresponding Lane Load in each of the traffic lanes.
2. Select appropriate variability factors.
3. Using equation 1, determine the scale-down factor, F, for each level of evaluation.
4. Check to assure that equation 2 is satisfied.

5. Read the posting load for three levels from the appropriate posting load chart for corresponding scale-down factor.

Figure 14. Posting load for second level.

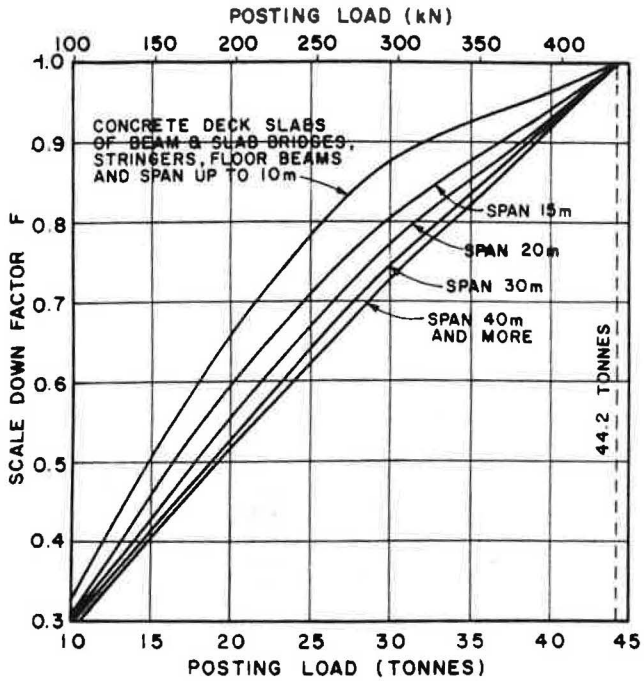
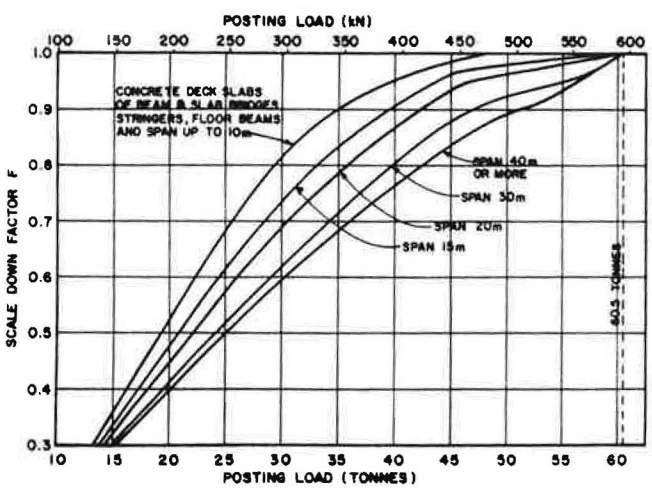


Figure 15. Posting load for third level.



Conclusions

1. It has been shown that a posting system that relates to a 20-ton AASHTO Truck weight is not compatible with modern commercial highway traffic.

2. Using statistically based load surveys and the principle of the Equivalent Base Length, vehicle models can be built for design and evaluation purposes to represent the total vehicle population.

3. The limit states design philosophy, which is the basis of the Ontario Highway Bridge Design Code, is readily adoptable for the evaluation and rating of existing bridges.

4. The three-level posting system appears to be reasonably accurate and operationally practical for controlling modern highway traffic.

5. The posting is to be considered as a temporary measure to assure the safety of the travelling public.

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