TRAFFIC LOADING OF LONG SPAN BRIDGES

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To estimate the traffic loading on long span bridges two independent statistical techniques were developed. One was purely analytical, the other used a computer to generate random "traffic" and calculate the maximum load on the bridge. The two methods gave remarkably similar results. Further research produced not only maximum loads, but also maximum moments and shears. From this work the following results emerge:

a) With a knowledge of the average mix of traffic, a design loading can be estimated with a good degree of confidence using the techniques developed.

b) The loading can be accurately represented by a uniform load and a concentrated load in the traditional manner.

c) Unlike the AASHO loading, one set of uniform and concentrated loads can be used to represent both maximum moment and maximum shear.

d) As expected, the uniform load per foot reduces as the loaded length is increased.

e) Unlike AASHO and previous assumptions, it is found that the concentrated load increases as the loaded length increases.

f) When several lanes are loaded simultaneously they do not, as suggested by AASHTO, all carry the same load. A simple distribution formula has been found.

These results have significant implications for the designers of long span bridges; and typical results have been produced for various types of traffic.

It has been recognized by several authorities (e.g. references 2, 4, 6, 7) that the traffic loading per unit length on a bridge diminishes as the loaded length increases. When faced with the need to accurately estimate the load on a bridge (8), however, the authors could find no satisfactory theory available and were obliged to develop their own methods. Having developed the techniques, they have now been applied to the general bridge as reported herein.

Two completely different methods were derived. One was an analytical solution of probability equations and has been described in reference 9. The other uses the random scatter capability of the computer to simulate traffic coming onto the bridge and has been described in reference 5. These two methods served as an excellent check on each other.

From this work, summarized in reference 5, four main conclusions emerged:

1. The maximum loading occurs with traffic stationary. Video-samplings of traffic from the tower of a suspension bridge confirmed this finding by Asplund (2). When traffic starts to move the vehicles separate such that the loading intensity is reduced, even if an allowance is added for impact.(Fig. 0)

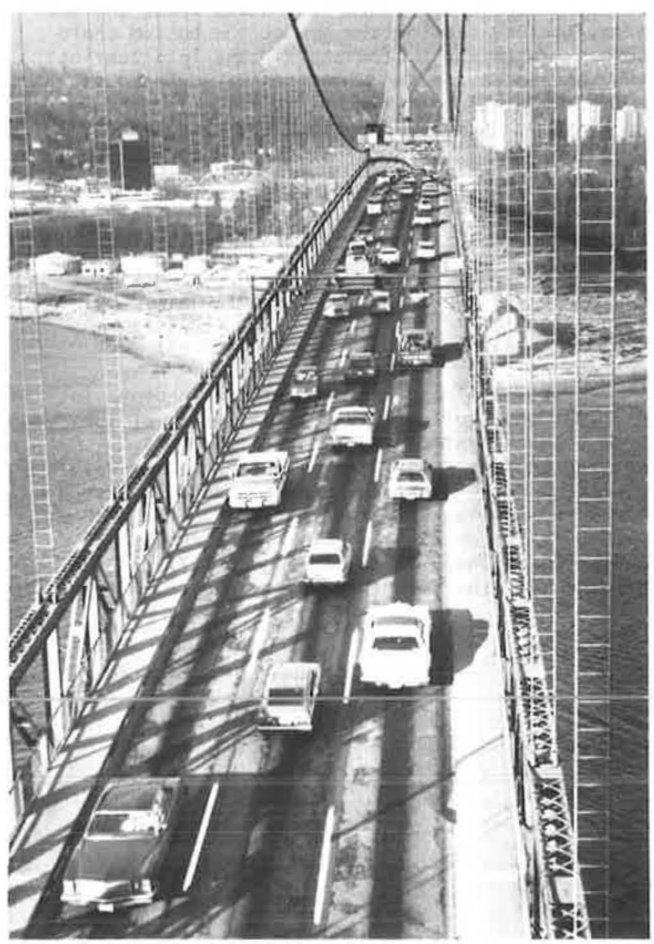


Fig. 0. Dense traffic travelling on a long span bridge. Moving traffic clearly spaces out to produce a less severe loading case than that caused by stationary "bumper-to-bumper" vehicles.

2. The loading can be represented as a uniform load and a concentrated load in the traditional manner, as shown in Fig. 1. This will predict maximum shears and moments on a span with reasonable accuracy, irrespective of the end conditions of the span. Multiple span loadings have not been studied in depth.

3. Unlike AASHTO loading a single pair of loads, the concentrated load, P, and uniform load, U, will produce both maximum shears and maximum moments. Reference to Fig. 1 will show that the maximum moment, M, shear, S, and total weight, W, can be produced by the expressions

$$M = \frac{PL}{4} + \frac{UL^2}{8} \qquad 1$$

$$S = P + \frac{UL}{2} \qquad 2$$

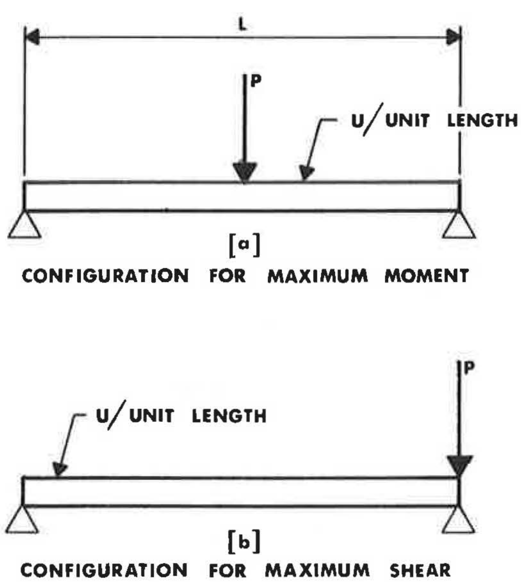
$$W = P + UL \qquad 3$$

Equations 1, 2 cannot be solved simultaneously, but it is found empirically (see ref. 5) that P, U derived from the solution of equations 2, 3 provide good approximations to the solution of equation 1.

4. Unlike traditional loading, the concentrated load (P in figure 1) increases as the loaded length increases. The uniform load decreases as expected.

This paper offers loading for four widely differing types of traffic, comments on their accuracy, compares them with established loading codes and discusses cross-lane distribution.

FIGURE - 1
UNIFORM AND CONCENTRATED LOADS FOR SIMPLE SPANS



SIMULATION PROGRAM

The computer program which is used to calculate weights, shears and moments for spans up to about 2000 m (6400 ft.) operates by simulating random traffic crossing over the bridge.

It allows random stoppages of traffic in one or more lanes, on or off the bridge. It then scans the stopped traffic, searching for the maximum load, moment or shear on any length of 15, 30, 61, 122, 244, 488, 975 and 1951 m (50, 100, 200, 400, 800, 1600, 3200 and 6400 ft.). These are referred to as the loaded lengths. The maximum values for each length found during a simulated 3 month period are retained in the memory.

Having found the maxima in one lane, it then searches for the maxima in the other lanes. The traffic in these lanes may be stopped or moving.

The maximum values for each time period of 3 months are printed out, and the mean and standard deviation of these maxima are calculated. A Gumbel extreme value distribution is then used to predict the maximum loading, shear or moment for any required return period, using the formula:

$$Y_R = \bar{Y}_T + K\sigma_T$$

where Y_R is the maximum value expected with a return period R, R is expressed in units of 3 month time periods, $\bar{Y}_T$ is the mean of maximum values observed over T time periods, σ_T is the standard deviation of maximum values in T time periods, and K is a constant depending on R and T.

Although the loading can thus be predicted for any return period, certain rare loading conditions can produce a large standard deviation which will produce unrealistically conservative results if a long return period is used (i.e. K is large). A return period of 5 years has therefore been taken by the authors.

Input to the program falls into four main categories:

Fixed or Arbitrary Data

This includes the length of bridge and approaches on which a stoppage may affect traffic on the bridge, the number of lanes, and the number of 3 month time periods for which the bridge is run.

Bridge Dependent Data

The number and type of stoppages (accidents or breakdowns) and the number of affected lanes for each stoppage can be varied. Stoppages occur randomly in time and position, but a bias can be built in to have more stoppages in some places than others, or at certain times. The length of time to clear a stoppage is random, but the limits are controllable and are different for accidents and breakdowns. The volume of traffic and its average speed are variable by hour of day, as are the number of cars, buses and trucks. The overall percentage of each type of vehicle in each lane is variable.

Driver Dependent Data

For stationary traffic the distance between vehicles is taken as constant, for moving traffic this distance is increased linearly depending on the speed. The speed of "trickle" past an accident is taken as a fraction of the average speed and can be different in each direction.

Vehicle Dependent Data

Cars and buses are each assumed to be of constant length and weight. Trucks are allowed to vary independently in both weight and length. Although the program will handle many mixtures of truck types, insufficient data are available about the traffic, mainly because most authorities study only heavy trucks, not empty or lightly laden ones.

CALCULATED LOADS

Although there is no doubt that more data are needed to ensure accuracy of the results, the authors have nevertheless studied four loading cases which can be considered as a guide.

Case 1 – is based on a two-day observation of traffic on the Second Narrows Bridge in Vancouver, B.C., and is considered fairly typical highway loading. The daily volume on 6 lanes has been taken as 85,900 cars, 351 buses and 6,510 trucks for a total of 92,761 vehicles, of which 7.4% are "heavy vehicles", i.e. buses and trucks over 53 kN (12,000 lb.). The maximum truck weight has been taken as 534 kN (120,000 lb.). The return period is 5 years, with 2000 stoppages per year.

Case 2 – is as for Case 1, but with the proportion of heavy vehicles increased by a factor of four to 29.6%.

Case 3 – again has the same data except that the proportion of heavy vehicles has gone up to 100%. This hypothetical condition represents an "upper limit" of bridge loading for this mix of heavy vehicles.

Case 4 – has very light traffic taken from a seven-day count on Lions' Gate Bridge in Vancouver where a weight restriction is in force. The proportion of heavy vehicles is 2.4% and the heaviest vehicle is 178 kN (40,000 lb.).

PARAMETERS P, U

When the concentrated load, P and the uniform load, U, are calculated for the 4 load cases, the smoothed curves of Figure 2 can be derived. The interesting point, mentioned earlier, is that the concentrated load, P, increases as the loaded length increases. Values of P, U are tabulated in Table 1.

The degree of accuracy obtained by using P, U for simply supported weights, shears and moments for the case with 7.4% heavy vehicles can be seen in Fig. 3, which shows that the average weight is least accurate although, presumably, least important. The shear is within 2% from 61 m (200 ft.) to 975 m (3200 ft.) and the moment is over-estimated by 6% or less, except at 61 m (200 ft.) where the error is safe by 9%.

FIGURE - 2

PARAMETERS P,u FOR DIFFERENT PERCENTAGES OF HEAVY VEHICLES (H.V.)

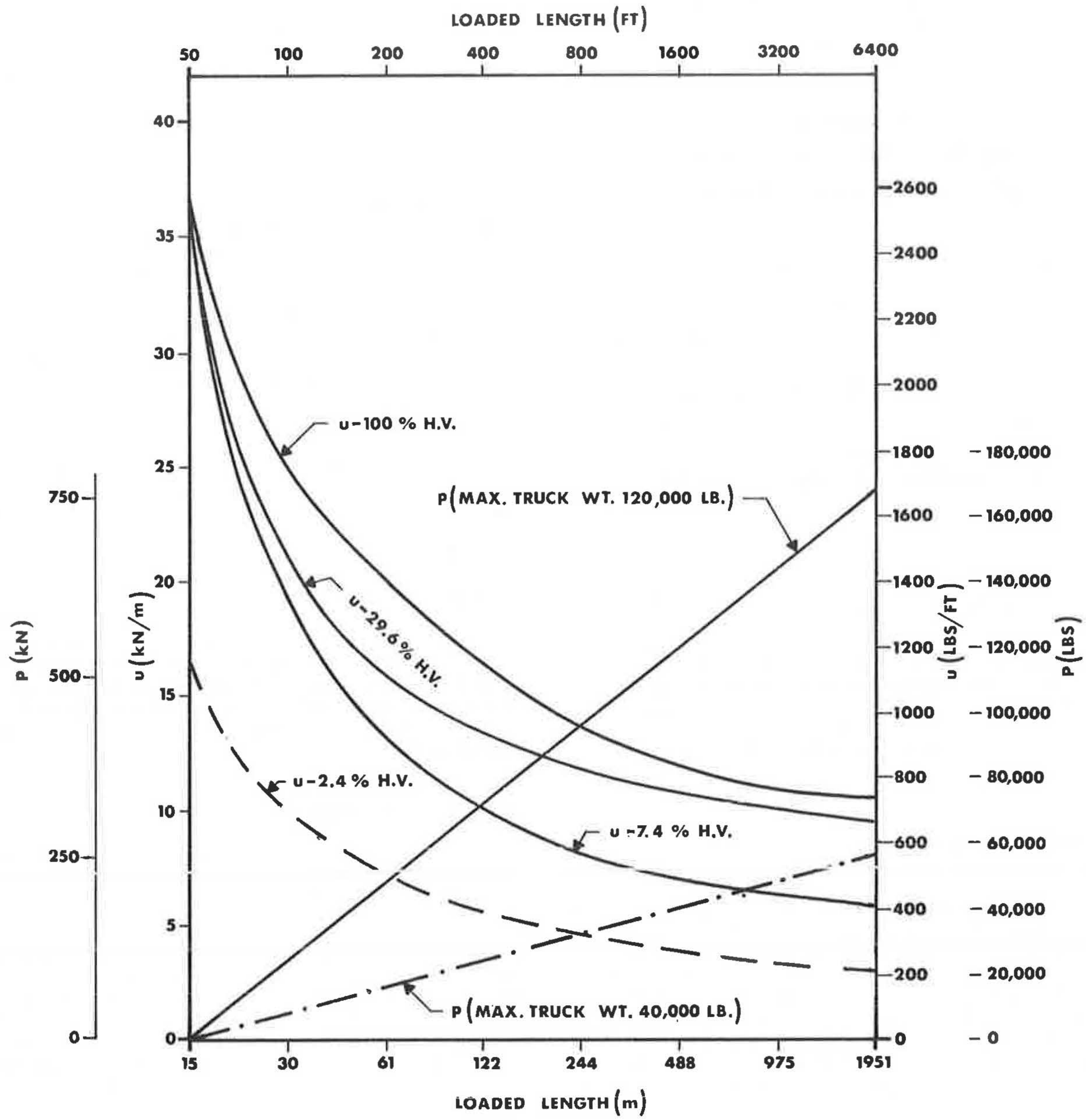
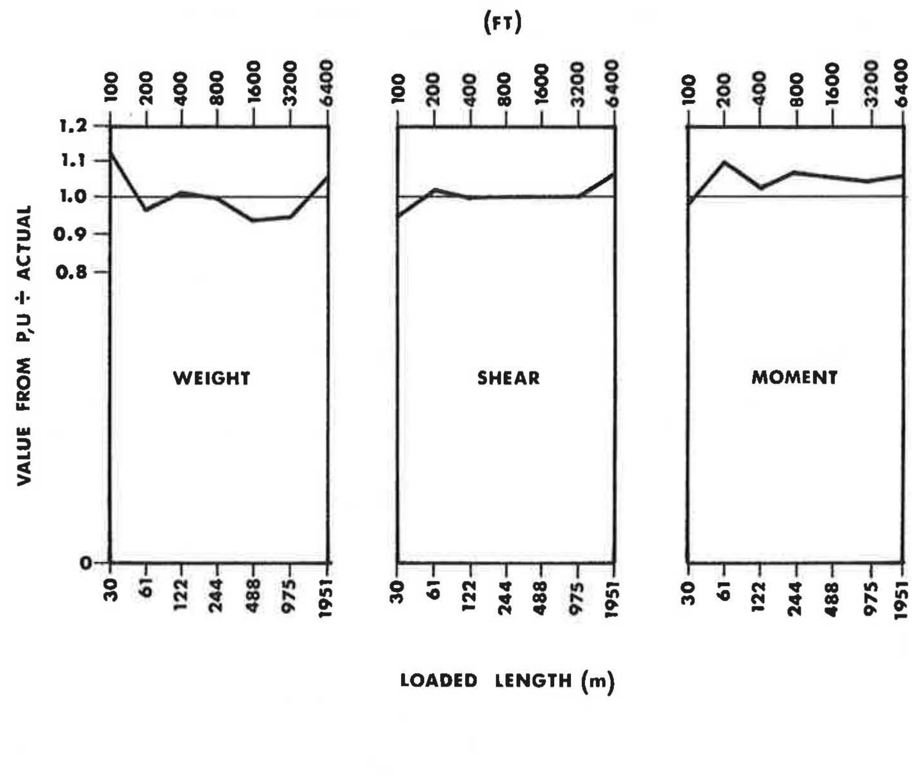


TABLE I. Proposed uniform and concentrated loads for design of long span bridges

Loaded Length		Concentrated Load (P) with 7.4% 29.6% 100% H.V.[a]		Uniform Load (U) kN/m (lbs./ft.) 7.4% H.V.		29.6% H.V.		100% H.V.		Concentrated Load (P) with 2.4% H.V.		Uniform Load (U) 2.4% H.V.	
m.	(ft.)	kN.	(lbs.)							kN	(lbs.)	kN/m	(lbs/ft.)
(1)		(2)		(3)		(4)		(5)		(6)		(7)	
15.25	(50)	0		38	(2600)	38	(2600)	38	(2600)	0		16.8	(1150)
30.5	(100)	107	(24,000)	20.4	(1400)	21.9	(1500)	25.5	(1750)	35.6	(8,000)	10	(690)
61	(200)	214	(48,000)	13.7	(940)	16	(1100)	20.8	(1425)	71.2	(16,000)	7.6	(520)
122	(400)	320	(72,000)	10.4	(710)	13.9	(950)	17.1	(1170)	107	(24,000)	6	(410)
244	(800)	427	(96,000)	8.3	(570)	12.1	(830)	14	(960)	142	(32,000)	4.8	(330)
488	(1600)	534	(120,000)	7.1	(485)	10.8	(740)	12.3	(840)	178	(40,000)	3.9	(270)
975	(3200)	640	(144,000)	6.4	(440)	10.2	(700)	11.2	(770)	213.5	(48,000)	3.4	(235)
1950	(6400)	747	(168,000)	5.8	(400)	9.9	(680)	10.5	(720)	249	(56,000)	3	(210)

Note: [a]% H.V. denotes percentage of heavy vehicles over 53 kN (12,000 lbs.) in the traffic.

FIGURE-3
ACCURACY OF PARAMETERS

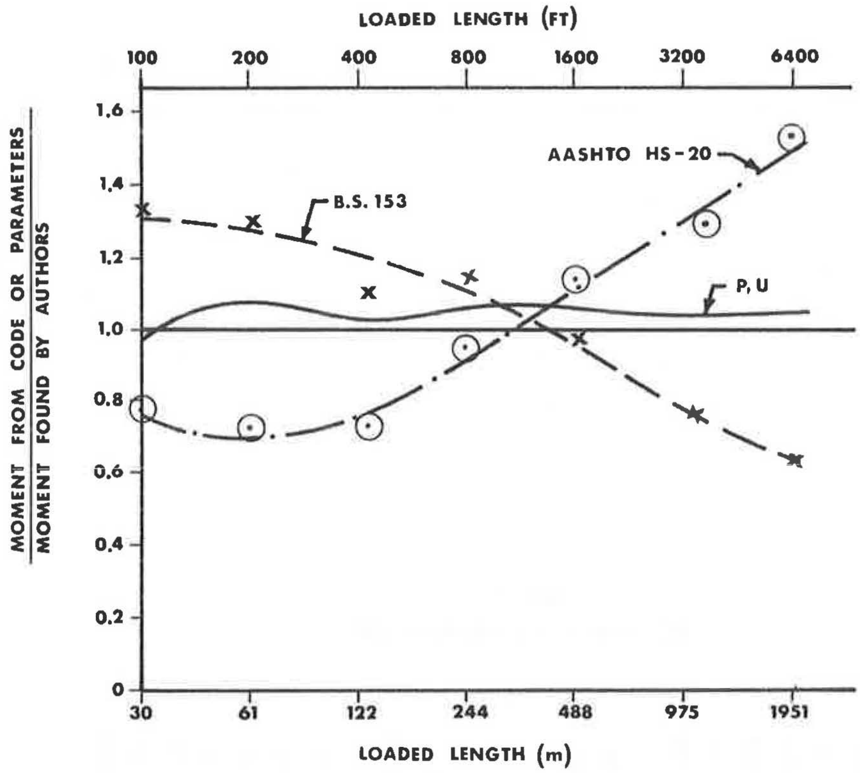


Thus the parameters P, U given in Fig. 2 produce simply supported shears and moments with good accuracy. Justification for their use on non-simple spans can be found in reference 5.

COMPARISON WITH AASHTO AND BS153

A comparison is made in Fig. 4 between the simply supported moments found in the authors' example, and those which would be derived from AASHTO (1) HS-20 loading, which is a common North American loading for bridges up to 122 m (400 ft.) span (and sometimes extrapolated beyond that limit), and British Standard B.S. 153 (3) which gives loadings for spans up to 900 m (2952 ft.). Shears follow a pattern very similar to moments and are therefore not shown separately. It can be seen that between 244 and 488 m (800 and 1600 ft.) all three methods give approximately the same answer, whereas for lower loaded lengths AASHTO underestimates and B.S. 153 overestimates, and above 488 m (1600 ft.) the opposite is true, the errors sometimes exceeding 30%.

FIGURE-4
COMPARISON OF MOMENTS (7.4% H.V.)



COMPARISON OF TRUCK INTENSITIES

Second Narrows Bridge traffic was chosen for this study as it was thought to be fairly typical. The other theoretical truck intensities were studied, however, in order to determine some upper and lower bounds, should Second Narrows Bridge not be typical.

Fig. 5 compares maximum shears for traffic with 2.4%, 29.6% and 100% heavy vehicles (H.V.) with those for traffic with 7.4% heavy vehicles. It can be seen that at short loaded lengths the three greater loadings tend to converge. This is because they all have the same maximum vehicle weight of 534 kN (120,000 lb.), and at short lengths a single vehicle can govern. The lower curve (2.4% H.V.) has a lesser value at short lengths as its maximum vehicle is only 178 kN (40,000 lb.). At first sight it may appear that the loading at short lengths for 2.4% H.V. should thus be a third of that for the other curves. Such is not exactly the case because the 178 kN (40,000 lb.) truck is shorter than the 534 kN (120,000 lb.) truck, thus resulting in a load intensity somewhat greater than a third.

At longer loaded lengths there is more divergence, but it is interesting that within the range considered even traffic with 100% heavy vehicles produces loading not more than 70% greater than the 7.4% case. When it is considered that at these large lengths the total live load is small relative to the dead load, it can be argued that taking 7.4% H.V. or 29.6% H.V. or somewhere in between will not cause undue errors in stress.

A few cases were considered with a small number of very heavy trucks in the traffic stream, which might represent overloaded logging trucks at 890 kN (200,000 lb.) each. The effect was very small, except at short loaded lengths.

CROSS LANE DISTRIBUTION

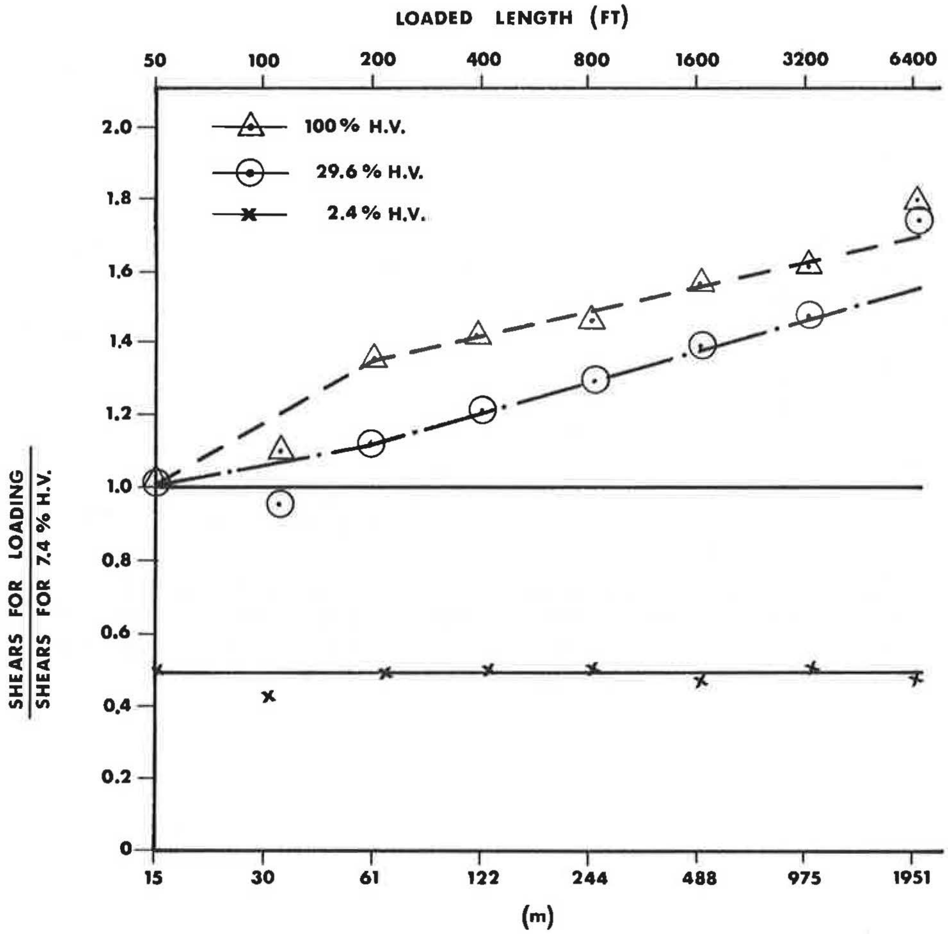
A common question to arise in bridge loading is: if the loading on one lane is known, what is the loading on the other lanes? There are several ways in which this can be tackled. One method is to assume that the total loading on two lanes of length L is the same as the loading on one lane of length 2L. In this case the known single lane curves can be used, although the two obvious deficiencies in this line of attack are (a) knowing the loads on two lanes does not indicate how it is distributed between the lanes, and (b) it assumes that all lanes carry identical traffic, which they certainly do not.

AASHTO directs that when several lanes are loaded, the load on every lane shall be reduced to 90% of single lane loading when 3 lanes are loaded, and to 75% of single lane loading when 4 or more lanes are loaded. It can be argued, however, that this is both illogical and erroneous. If a single lane can have a certain load on it, then the addition of two more lanes would tend to increase the load in the curb lane as trucks gravitate towards it. Loads in the second and third lanes may well be reduced, however.

B.S. 153 takes some recognition of this phenomenon by requiring the first two lanes of the bridge to be fully loaded and the remaining lanes to be loaded with one third of the single lane loading.

The fact is that neither standard method is correct because the cross-lane distribution depends on the loaded length. A single ratio independent of loaded length will never be better than approximate. This can be seen by reference to Fig. 6. Making the assumption that all lanes carry identical traffic, two lanes at 30 m (100 ft.) long might carry the same as one lane at 61 m (200 ft.) which is

FIGURE-5
COMPARISON OF MAXIMUM SHEARS FOR DIFFERENT PERCENTAGES OF HEAVY VEHICLES



17 kN/m (1180 lb/ft.) of lane, or 34 kN/m (2360 lb/ft.) of bridge. Since one lane could be carrying the maximum load for 30 m (100 ft.) which is 24 kN/m (1640 lb/ft.), the second lane would be carrying 34 - 24 = 10 kN/m (720 lb/ft.) and the ratio of second lane to first lane would be 10 ÷ 24 = 0.42. At a longer loaded length, however, say 488 m (1600 ft.), two lanes would carry the same as 975 m (3200 ft.) of single lane, which is 7.1 kN/m (485 lb/ft.) per lane, or 14.2 kN/m (970 lb/ft.) of bridge. A single lane of 488 m (1600 ft.) could carry 8.2 kN/m (560 lb/ft) leaving the second lane to carry 14.2 - 8.2 = 6.0 kN/m (410 lb/ft.) for a ratio of 6.0 ÷ 8.2 = .73.

Thus the ratio of second lane to first lane can vary depending on the length of bridge considered. The authors' method does not make the simplified assumptions of the previous paragraph, but actually calculates the maximum loads for every length on 1, 2, 3 and 6 lanes, and gives, for each, the amount of load on each lane.

Fig. 7 gives the ratios of second lane to first lane, third lane to first lane and the average of lanes 4, 5 and 6 to the first lane, for total weights in the case of 7.4% heavy vehicles. As expected, the ratios vary considerably, but in the interests of simplicity one could approximate the situation by using lane loading ratios of 0.7 for the second lane, and 0.4 for the remainder. These ratios are compared with those of the other codes in Fig. 8.

When selecting a "general" cross-lane distribution it is important to bear in mind the purpose for which it will be used. Fig. 9 shows four bridge cross sections. Section (a) shows a typical through truss arrangement. The important consideration here is the maximum load which can occur on one truss. A similar case to this would be a suspension bridge where the load on one cable is governing. Section (b) shows two plate girders. Again, the important effect is the maximum load on one girder. Section (c) shows all the lanes carried on a single box girder and section (d) shows a single central support (perhaps cable-stays) and a torsion box. In the last two cases the bending in the box (or the load on the central support) is governed by the total weight on all the lanes, and the torsion in the box is governed by only the lanes on one side of centre-line being loaded.

Thus the main considerations are the total load, the maximum torque, and the maximum load on one support of a double support system. This last depends on the spacing of the supports.

Table 2 compares these three effects using the AASHTO and B.S. 153 distributions with the distribution suggested by the authors. The maximum load on one side is calculated assuming the supports at the outside edges of the outside lanes and no median.

FIGURE - 6
AVERAGE LOAD PER UNIT LENGTH

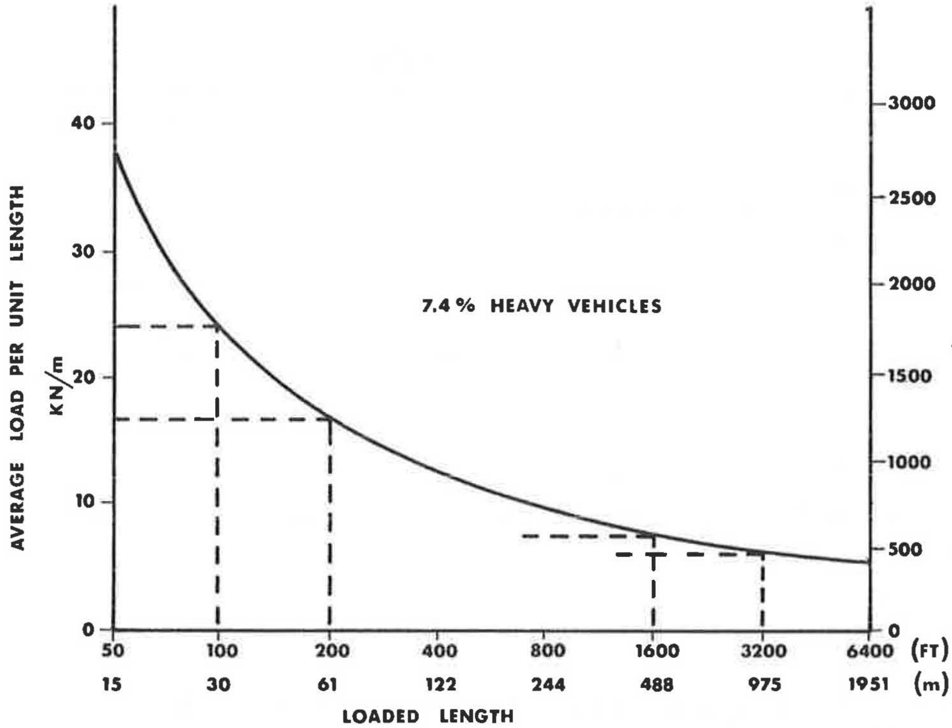


FIGURE - 7
RATIO OF LANE LOADS

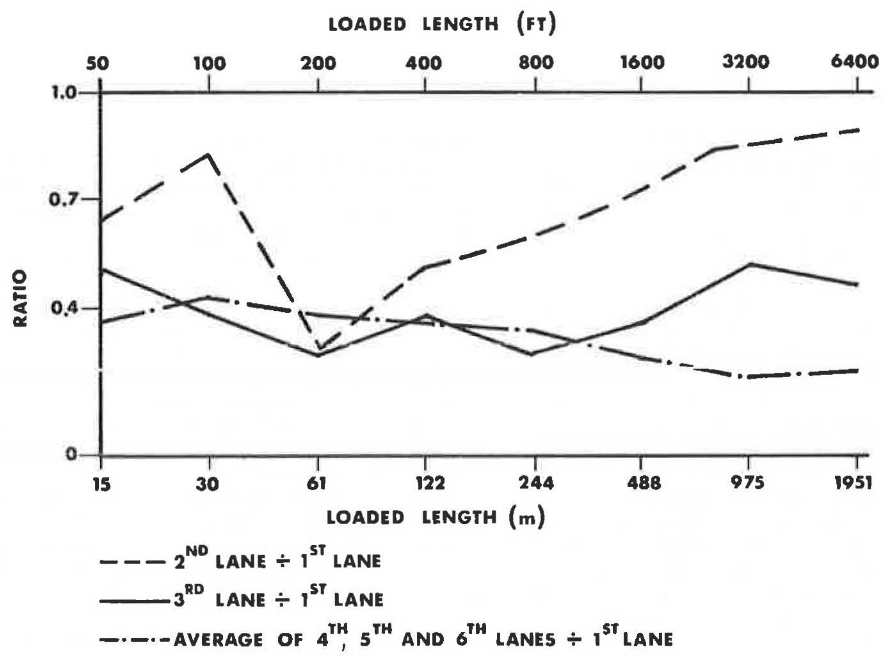


FIGURE - 8

CROSS LANE DISTRIBUTIONS

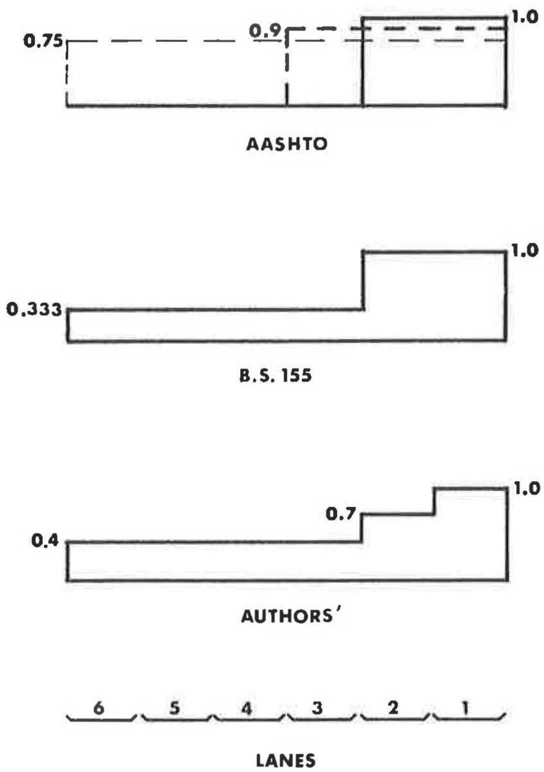
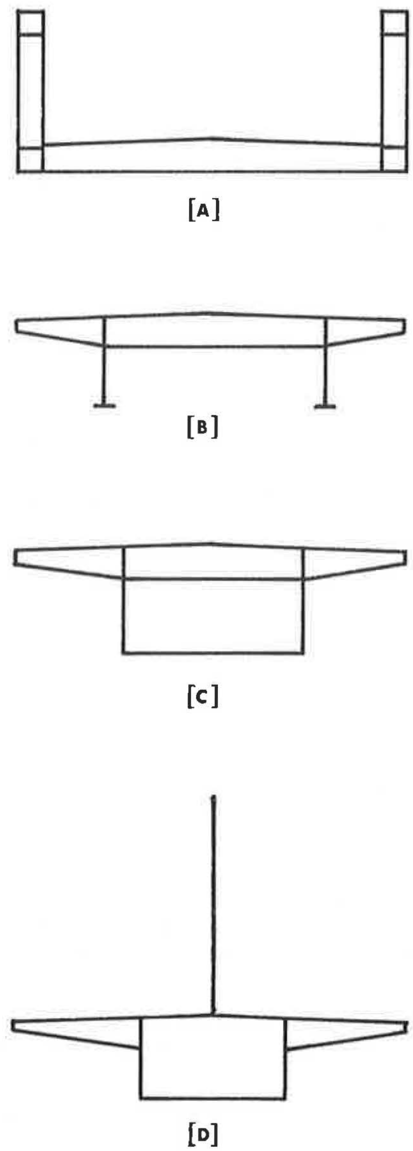


FIGURE - 9

TYPICAL BRIDGE CROSS-SECTIONS



This is a compromise rather than a typical situation, but serves as an illustration. The load in the heaviest laden lane is taken as unity.

It can be seen that there is in practice very little difference in the three methods except that AASHTO tends to overestimate the total load on the bridge by 20 to 36%. This would have been of little concern before the introduction of large box girders and single plane cable stays. Indeed this overestimate has probably discouraged the use of single supports in North America, since there has been no economy to be gained by using them. Whereas in Europe, where the cross-lane distribution is more realistic, they have flourished.

MISCELLANEOUS

Three further opinions can be expressed:

Position in Lane

Most codes state that traffic must be placed in the worst place within a lane. This makes good sense for a short bridge governed by a small number of vehicles, but the authors query its validity for a large bridge carrying many vehicles randomly spaced. They have therefore assumed all traffic at the centre of the lane.

Impact

Impact need not be added to stationary traffic loading. For the moving lanes the authors have also ignored impact on the grounds that (a) impact is random and as some traffic bounces up and some down, the mean effect must be near zero, and (b) moving traffic is the least important anyway, both because of its light weight and its small effect on the major bridge components (see figs. 8 and 9).

Suspension Bridges

Much of this loading will apply to suspension bridges (for which it was originally derived). Because the concentrated load, P, increases with loaded length, it would appear that it can dominate unreasonably. For example, with the entire bridge loaded, P can produce massive shears at the ends of spans, which would seem excessive. It is probable that the best way to handle this is to take the loaded length which produces the worst condition for uniform load only, and then add in the concentrated load, i.e. do not allow U to be applied in the negative region of the influence curve in order to boost P by having a greater loaded length.

TABLE 2. Comparison of cross-lane distributions.

Effect	Number of Lanes	Distribution				
		Authors'	AASHTO	AASHTO % difference[a]	B.S. 153	B.S. 153 % difference[a]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2	1.7	2.0	+18	2.0	+18
Total	3	2.1	2.7	+29	2.33	+11
Load	4	2.5	3.0	+20	2.67	+7
	6	3.3	4.5	+36	3.33	+1
	2	0.5	0.5	–	0.5	–
Torque[b]	3	1.0	1.0	–	1.0	–
	4	1.85	2.0	+8	2.0	+8
	6	3.75	4.05	+8	4.17	+11
Maximum	2	.93	1.0	+8	1.0	+8
Load on	3	1.25	1.35	+8	1.39	+11
Support	4	1.51	1.5	-1	1.67	+11
	6	1.98	2.25	+14	2.11	+7

Note: [a]compared to the authors' distribution (column 3).
[b]assuming a lane width of unity.

SUMMARY

The main conclusions to be drawn from this study can be summarized as follows:

1. The facility is now available to calculate the loading on a long span bridge with a fair degree of accuracy. More data are needed about the traffic.
2. The loading can be represented as a uniform load and a concentrated load. The uniform load diminishes as the loaded length increases. The concentrated load increases with loaded length. The same loads produce the maximum shear and the maximum moment, unlike those in AASHTO.
3. Maximum loading conditions will occur with the traffic stationary, therefore no allowance need be added for impact.
4. Guide-line loadings can be derived from fig. 2 or Table 1. Increasing the number of heavy vehicles in the traffic has only a moderate effect on the load.
5. Neither AASHTO HS20 loading nor B.S. 153 are particularly accurate, nor consistent with each other, but they coincide with the authors' loading over a limited length range.
6. No single cross-lane distribution is accurate, but there is little practical difference between the authors' recommended distribution and those of B.S. 153 and AASHTO, except that the latter overestimates the load on a central support system, such as a box girder or cable stays.

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The conclusions presented in this paper represent the authors' opinions, and are not necessarily endorsed by any of the above parties.

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