Traffic loads on bridges: rail traffic loads

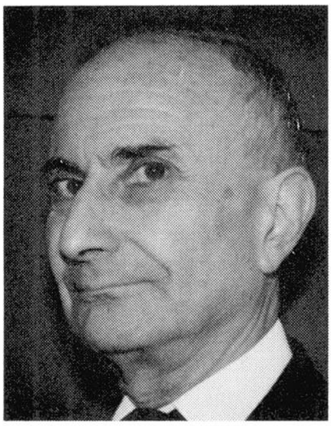
EC 1: Traffic Loads on Bridges – Rail Traffic Loads

EC 1: Charges dues au trafic sur les ponts-rails

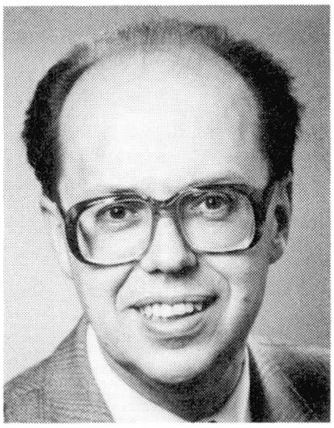
EC 1: Verkehrslasten auf Brücken – Bahnverkehrslasten

J.E. SPINDEL
Dr.
(formerly of British Railways Board)
London, UK

Marcel A. TSCHUMI
Head of Bridge Section
Swiss Federal Railways
Berne, Switzerland



Dr. Spindel, born 1925, graduated from Imperial College, University of London, 1945; held various appointments in bridge and works design with British Rail; was involved in the development of standard railway loading as a member and, later, chairman of the Bridge Sub-Committee of the International Union of Railways up to January, 1988.



Marcel A. Tschumi, born 1938, obtained his civil engineering diploma at the Swiss Federal Institute of Technology in Zurich in 1962. Since then he has been involved in the design of structures and bridges. Since February 1988 he is chairman of the Bridge Sub-Committee of the International Union of Railways (UIC).

SUMMARY
This section of volume 3 of Eurocode 1, provides the necessary information on the actions of railway traffic which bridges have to be designed to resist. The paper outlines the range of real traffic which has to be considered, and the actions associated with it. This is related to the simplified equivalent loads and load spectra to be used for design.

RESUME
Ce chapitre du volume 3 de l'Eurocode 1 donne des informations en ce qui concerne les actions dues au trafic ferroviaire, pour lesquelles les ponts doivent être dimensionnés. Le document donne un aperçu de l'étendue du trafic réel à prendre en considération et des actions qui en découlent. Celles-ci sont mises en relation avec les charges simplifiées équivalentes et les spectres de charges qui sont utilisés pour le dimensionnement.

ZUSAMMENFASSUNG
Dieses Kapitel von Band 3 des Eurocodes 1 liefert Informationen zu den Einwirkungen des Bahnverkehrs, mit welchen die Brücken rechnerisch nachgewiesen werden müssen. Dieser Beitrag gibt einen Überblick über die Vielfalt des wirklichen Verkehrs, der berücksichtigt werden muss, sowie die damit verbundenen Einwirkungen. Diese werden in Bezug gebracht zu den vereinfachten äquivalenten Lasten und Lastspektren, die für die Bemessung verwendet werden.

1. INTRODUCTION

The loading intended to represent rail traffic loads in Eurocode 1 bears little obvious resemblance to real trains. The various forces it imposes on bridges appear to be quite independent. It, therefore, seems wrong to consider most of them as part of one action.

The purpose of this paper is to outline the facts on which rail traffic loads are based with a view to explaining these matters. The first part considers what a given train does to a given bridge. The second part considers the general case of traffic on a population of bridges.

2. THE ACTION OF A GIVEN TRAIN ON A GIVEN BRIDGE

2.1 Vertical Forces

2.1.1 Static Load

A train is a mass, supported at discrete points (the axles), which is subject to various accelerations. The action of these on the part of this mass which is on a bridge causes the actions of the train on the bridge. This mass, therefore, links all of them either directly or indirectly.

The primary acceleration is that of gravity. This always acts, is constant, and causes the static load.

2.1.2 Dynamic increment

This, directly associated with the movement of the train, is due to the deformation and vibration of the bridge crossed by the train at speed. It can be considered as the total of three components:
- a dynamic amplification of the static deflection of the structure (forced vibration)
- a damped free vibration at the natural frequency of the structure
- random vibrations due to the movement of the unsprung mass of the train caused by track and wheel irregularities.

For a simply supported beam, the first two of these can, as a close approximation, be derived by replacing the train, with its complex system of sprung and unsprung masses on an elastically supported track, by the forces it exerts under gravity. The result is shown in Fig. 1 as the ratio of "dynamic" to static deflection at mid-span for a single force crossing the beam.

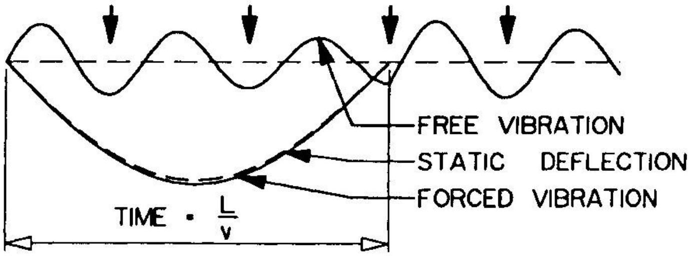


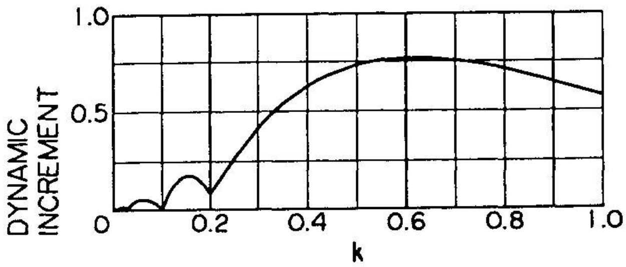
Fig. 1

Mid-span deflection of a simply supported beam under the passage of a single force (k=0.182)

It will be noted that the free vibration is such as to produce zero velocity when the force comes on the beam. (The velocity is proportional to the slope of the lines). It also shows that the maxima do not coincide with the maximum of the amplified static deflection. Whether this coincidence occurs or not depends on a parameter k, as does the amplitude of the free vibration. ($k = v/2Ln_o$, where v is the speed in m/sec, L the span in m and n_o the natural frequency of the unloaded bridge). As shown in Fig. 2, the total dynamic effect does not increase steadily with speed at low values of k.

Fig. 2

Dynamic increment for a single force as a function of k



The lines on Fig. 1 are influence lines from which the effect of a sequence of forces can be determined. It follows from this that a series of forces at the centres shown by arrows will cause the greatest dynamic effect on the bridge, while forces at half that spacing will produce practically none, as would any reasonable approximation to a uniformly distributed load.

Real cases lie between these limits. This, together with the effect in Fig. 2, accounts for the wide scatter in dynamic effects for the same value of k. A limited statistical analysis of a large number of test results for steel and concrete bridges produced standard deviations of the order of 70% and 55% of the mean for steel and concrete bridges respectively.

However, for a given train crossing a given bridge at a given speed the dynamic effect is determinate. This was confirmed by model tests and on a bridge under normal traffic. All fast passenger trains caused the same dynamic effect which was near the maximum. Even the apparently random effect of a track irregularity was reproduced.

2.2 Horizontal Forces

2.2.1 Lateral Forces

The easiest of these is the so-called centrifugal force. Given the mass of the train and the radius of the curve, it is as determinate as the speed of a train running to a given timetable. It is simply the mass multiplied by v^2/R, where v is the speed in m/sec and R the radius of the curve in m.

If the speed which the train can reach is at least the greatest allowed through the curve, the greatest horizontal force it can cause is the vertical force multiplied by $(c+d)/s$, where c and d are cant and cant deficiency allowed and s is the distance between centre-lines of rails, all in consistent units. On most railways this ratio has a value of about 0.2.

Another lateral force is that due to the lateral oscillation of vehicles. A value of 100 kN was deduced for this force on the bridge from measurements of rail seat forces. Research on this subject is in progress. As a very rough approximation, this force is also a measure of the dynamic effects due to centrifugal forces. It is, therefore, considered as combined with them though centrifugal forces tend to suppress lateral oscillations of vehicles.

2.2.2 Longitudinal Forces

Traction and braking, always mentioned together, differ so much that they require separate consideration and deserve different treatment.

Both act along the axis of the bridge, in opposite directions, and are limited by the adhesion (friction) between wheel and rail. Given clean wheels and rails, this can reach 42% (of the applied vertical force).

Traction is the force needed to accelerate a train from rest or after a speed restriction, and to keep it moving at speed and up gradients. Modern locomotives have devices to control wheel slip, thus ensuring that maximum adhesion is attained.

Traction acts continously, often at its maximum, and is proportional to the vertical load on the driving axles.

Since the heaviest trains need the greatest traction, design rules assume that traction is due to two heavy locomotives. This means that the force on the bridge remains constant once the loaded length exceeds about 29m.

Braking forces depend on adhesion, passenger comfort and, critically, on the type of brake used.

Comfort limits service braking to a deceleration of about 0.1g. Disc brakes, used mainly on modern passenger coaches, can, at most, increase this to about 0.13g. Brakes with cast iron brake shoes, used mainly on freight trains and on locomotives, will produce the same order of deceleration up to ½ second, or so, before the train stops. In that ½ second the deceleration will rise to the maximum limited by adhesion, 0.42g. It is this peak value which makes braking forces the most contentious issue in railway loading.

Braking deceleration acts on the mass of the whole train. When it reaches its peak the train has nearly stopped. At that time the only dynamic effect is the transfer of load from the rear bogies of the vehicles to the front ones. This was found to entail an increase in bogie load of some 30%.

Given the short duration of the peak braking force and that it is only likely to occur after emergency braking, there is an argument for treating it as an accidental load. It certainly justifies special treatment in the design of abutments and foundations.

Longitudinal forces tend to move the bridge as a whole in the direction in which they act. This movement is limited by the stiffness of the abutments and piers to which fixed bearings are attached. Unless the track across the bridge is isolated by expansion switches, some of this movement will be resisted by the track beyond the bridge.

This restraint can transfer some 30% to 60% of the longitudinal force to the track. The increase in force in the rails which can be tolerated, however, is limited by considerations of the stability of the track.

The proportion of load transferred depends on the relative stiffness of bridge and track.

The stiffness of the bridge can be taken as linear, but it includes the stiffness of the foundations under long and short term loading. Estimates of such stiffness are notoriously inaccurate. The stiffness of the track varies with its type and condition. It is non-linear because, after elastic movement of 1 or 2 mm, there is progressive slip between rail and sleeper and sleeper and ballast.

The difficulties in all this calculation are not so much those of computation but the accuracy, or lack thereof, of the basic data.

3. THE ACTION OF RAIL TRAFFIC ON BRIDGES

3.1 Railway traffic

The derivation of actions outlined in section 2 above can be applied only to bridges which carry only one kind of train at one speed. Examples are metro systems (without service or ballast trains) and railways built for one traffic, say from a mine to a port.

Most bridges are built to carry a mixture of traffic which is likely to change during their life of some 100 years.

The trains they will, or may, have to carry can be grouped as passenger and freight trains. All the latter are locomotive hauled. Table 1 shows their speeds, axle loads and average weights per metre, all as ranges of values commonly encountered or planned.

Type of train	Speeds km/h	Axle loads kN	Average weight kN/m
Passenger trains:			
. suburban multiple units	100 - 160	130 - 196	20 - 30
. locomotive hauled trains	140 - 225	150 - 215	15 - 25
. high speed trains	250 - 350	170 - 195	19 - 20
Freight trains:			
. heavy abnormal load	50 - 80	200 - 225	100 - 150
. heavy freight	80 - 100	225 - 250	45 - 80
. trains for track maintenance	50 - 100	200 - 225	30 - 70
. fast, light freight	100 - 160	180 - 225	30 - 80

Table 1 Trains

In relation to the above table it should be noted that:
- the average weight of locomotives ranges from 50 to 70 kN/m
- the length of the vehicles classed as heavy abnormal loads ranges from 15 to 60m; they mainly affect the support moments of continuously supported bridges and simply supported medium span bridges,

Where what trains run depends on any physical restrictions on a line (curves, gradients, weak existing bridges) and on commercial and operating requirements. All these are known and planned at any given time, but may, and probably will, change in the course of time. At present, for example, heavy abnormal loads are not allowed on a number of lines, including most suburban and high speed passenger lines.

High speed passenger lines, however, do also carry all kinds of freight on one railway, fast light freight only on another, and very high speed passenger traffic only on a third. This is the result of policy - not any physical limitations.

This is confirmed by the fact that all lines carry trains with machines and materials for track maintenance.

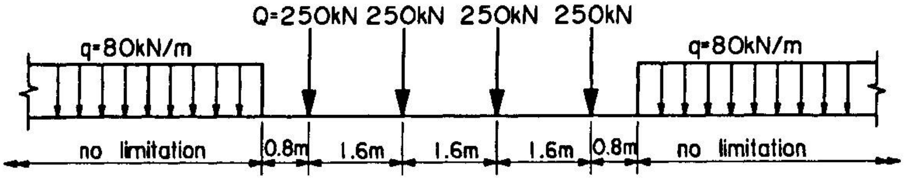
It is, therefore, reasonable to build new bridges so that they are capable of carrying any of the present and anticipated traffic, or at least that which is not highly likely to remain subject to restrictions.

3.2 Static load due to railway traffic

It is not difficult to produce a loading which will cover the greatest static actions of all known and planned trains on simply supported bridges, particularly if heavy abnormal loads are treated as a separate case. This is what the UIC loading shown in Fig. 3 does.

Fig. 3

UIC loading 71



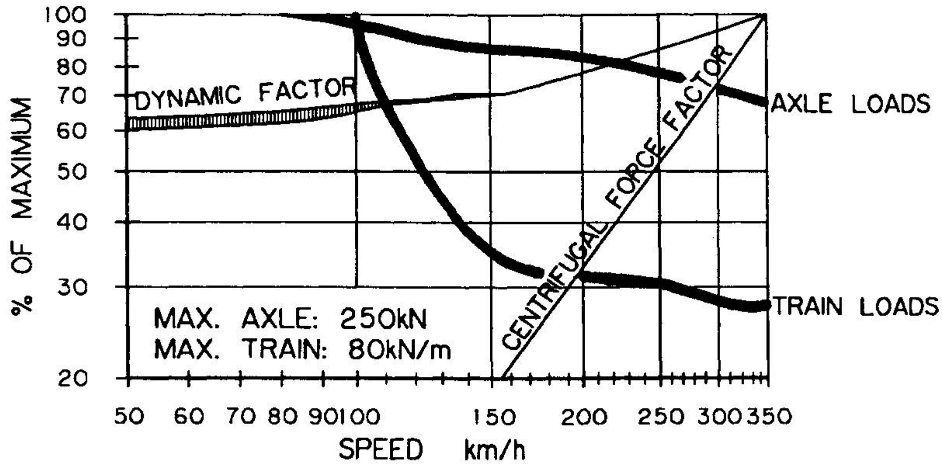
It was, of course, based on a much more detailed and extensive investigation than that outlined above.

3.3 Dynamic effects and centrifugal forces due to railway traffic

When it comes to dynamic effects and centrifugal forces, however, account must be taken of the greatest speeds of the various trains as well as their weight. It is a characteristic of railway, and road, traffic that heavy vehicles are slow and fast vehicles light. This is apparent from Table 1 and is shown, in broad outline, on Fig. 4 for "normal " trains.

Fig. 4

Changes in loads, dynamic effects and centrifugal forces with speed



The two lines from left to right show how axle and average train loads drop from their maximum values as speed increases. Values for bending moments on various spans will lie between these lines.

The curve from right to left shows how the dynamic factor, by which the static load has to be multiplied to arrive at the total vertical action, drops as the speed decreases from a maximum of 350 km/h.

Since the figure is plotted on a logarithmic scale, the required product is the sum of the ordinates of this line and those from one of the lines from left to right. For axle loads this product remains roughly constant. For train loads it drops considerably at very high speeds.

To arrive at a reasonable allowance for dynamic effects the calculations outlined in 2.1.2 above were repeated for a selection of trains and vehicles over a range of speeds to obtain an upper limit for the dynamic effects due to "all" trains as a function of the parameter k. By using this function with upper and lower bounds for the natural frequency of bridges of a given span, the total action of various trains on a given simply supported span was obtained. The ratio of the envelope of these total actions to those due to the static loading shown in Fig. 3 produced the apparently simplistic formulae for dynamic factors as a function of span, L, only, such as

$$\Phi = \frac{1.44}{\sqrt{L}-0,2} + 0.82$$

Similar considerations apply to formulating rules for centrifugal forces. The straight line from right to left in Fig. 4 relates to the v^2 term by which the mass of the train has to be multiplied. It will be noted that this line drops more steeply with decreasing speed than the mass of the train or axle rises.

The line has been drawn on the assumption that the radius of curvature is such as to allow a speed of 350 km/h. If it were such as to limit the speed to say 150 km/h, a parallel line would have to be drawn through the point where the 150 km/h ordinate intersects the 100% line. Again, the v^2 term decreases more steeply than the mass term rises.

It follows from this that, at least at speeds above 120 km/h, it is the fastest train which causes the greatest horizontal force.

It does not follow, however, that this force, combined with the reduced vertical load of the lighter train, produces the greatest load on the bridge as a whole or on one of its elements. It is, therefore, necessary to check that a slower, or even stationary, train does not produce a worse effect.

Again, an extensive and detailed investigation on the lines described above produced the rules given in the draft for EC1.

4. FATIGUE EFFECTS CAUSED BY RAIL TRAFFIC

4.1 General considerations

Fatigue failure is the result of the accumulation of the fatigue damage caused by large numbers of individual stress ranges of varying magnitude applied to an element of a structure.

Consequently rail traffic needs to be defined in terms of all the stress changes it causes in a structure and not just as its greatest effect.

This means consideration of axle spacing as well as load. The stress ranges which the sequence of axles produces are critically sensitive to the type and length of influence line for the part of the structure. Influence lines for bending moment and shear, for example, produce very different results.

In planning these calculations it must be remembered that a summation is involved.

This has the consequence that random variations in loads do not significantly affect the sum. Mathematically, it can be shown that the only effect of a random variation of a load about a mean value, assuming the variation to be log normally distributed, is an increase in the Palmgren-Miner sum by a factor of $[\exp(\frac{1}{2}m^2s^2)]$ where m is the slope of the S/N line and s the standard deviation of the ln of the load. For a coefficient of variation of 10% and a slope of 5, the increase is 12% in the sum, which corresponds to a reduction of 2.3% in permissible stress.

Another consequence is that any number of suitably selected trains can cause identical fatigue damage - a point of some importance when considering traffic rather than individual trains.

4.2 Load spectra for design

The stress changes for a given train can be collected and expressed as a load spectrum. Such spectra can be combined to give a spectrum for a traffic.

Traffic can vary in composition - various mixtures of passenger and freight trains - and in volume expressed as gross tonnes per annum, t/an., usually in millions.

Traffic may be all one train, for example on a suburban line, or a mixture of practically every kind of train. For the purpose of fatigue calculations occasional heavy trains can be neglected. For a given type of influence line complex real traffic can be, and is, represented by a carefully selected mixture of a few "typical" trains even if they do not look very realistic.

Volume of traffic may be as low as $0.5 \cdot 10^6$ t/an. for a branch line to a factory or quarry, and rise to $20 \cdot 10^6$ or $30 \cdot 10^6$ t/an. on a busy main line or, surprisingly, for a light railway. The most that has been claimed is $63 \cdot 10^6$ t/an.

In these circumstances design rules have to be flexible to allow type and volume of traffic to be varied to suit traffic on a given line. Making this choice does imply a prediction of traffic for the 50 or 100 year life of the bridge. Overestimating costs money in building bridges; an unforeseen great increase in traffic can probably pay for the earlier replacement of bridges.

The load spectra produced on the basis of the considerations outlined above can then be used for fatigue calculations as required, for example, in chapter 9 of EC3.

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