Local load effects on road bridges

M. PRAT and B. JACOB

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1 - INTRODUCTION

The purpose of this paper is to present an overview of a large number of experimental results concerning the local traffic loads, static and dynamic, transmitted to road bridges via the tyres of heavy goods vehicles in normal operating circumstances. A few extreme cases, due to accidental situations, are also considered.

These thoughts and analysis results concern the origin, kinematics, and distribution of loads on the decks of bridges, and have been produced with a regulatory aim, for the generation of EUROCODE 1 (Part 3) on road traffic loads ([1],[2]); the objective is to define load models applicable to the design of structures.

2 - LOCAL LOADS INDUCED BY HEAVY GOODS VEHICLES

The action of a heavy vehicle on a bridge includes a quasi-static component, determined by its mass and invariant during a trip, and a variable dynamic component, caused mainly by the vibrations of the vehicle induced by the irregularities of the pavement. These oscillations of the sprung masses (cab, body, etc.) and of the unsprung masses (axles, wheels, etc.) increase the loads transmitted to as much as twice the static load.

2.1 - Static load

The static loads of the vehicles, measured when stopped, are subject to regulations. Below the legal limits, they present no risk to structures of which the design is calculated using correctly measured characteristic values with allowance for factors of safety. These static loads result in pressures on the soil that are distributed over small areas - the contact surfaces of the tyres.

2.2 - Dynamic load

The dynamic loads (in what follows, this term will be used only to refer to the dynamic portion of traffic loads) are superimposed on the static loads and may cause the authorized loads to be exceeded. They are stated either in the form of additive forces, dynamic loads added to the static loads, or in the form of a total equivalent load obtained from the static loads by multiplication by a impact factor ("IF").

On bridges, the increases for dynamic effects are related to 4 factors that may, in consequence, induce unauthorized loads:

- the quality of pavement evenness;
- the condition of the suspensions of the vehicles;
- tyre/road interaction;
- the dynamic responses of the bridges to excitation by traffic.

Wearing course surface defects, combined with the speed of the vehicle, initiate vibratory phenomena that go through a number of "two -way" filters (suspension, shock absorbers, etc...) and set in motion, selectively, from bottom to top, at specific frequencies, all of the sprung masses, whereas the unsprung masses act more directly and rather rigidly on the pavement (elastic impacts).

For a loaded truck wheel the ratio of the sprung masses to the unsprung masses is in the vicinity of 7.

Table 1 gives a few ranges containing the usual frequencies and the amplitude of the corresponding impact factors. It should be noted that the dynamic loads are not proportional to the static loads and depend on many parameters. Thus, observations show that the highest IFs are measured on vehicles with lightly loaded axles [3]. However, in this case the equivalent total loads remain below the values obtained for the most heavily loaded vehicles, which have weaker vibrations.

TABLE 1	Sprung masses	Unsprung masses	Axle peak
Frequency of resonance (Hz)	[1 to 6]	[6 to 20]	[12 to 15]
Impact IF	[1.1 to 1.4]	[1.1 to 1.7]	

3 - TYRE/ROAD/BRIDGE INTERACTION

Differences of relative level in the pavement profile are in most cases the origin of dynamic loads. But the braking forces of the vehicle also induce vibrations and dynamic loads. Finally, an instantaneous deformation of the deck of a bridge also engenders vertical movements of the vehicle.

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

3.1 - Quality of pavement evenness

When an axle moves, it engenders degradations of pavement evenness, which will in turn initiate and amplify further excitations of vehicles; these will add more damage that will contribute to damage of the structures and to the user's discomfort and unsafety.

It is therefore essential to attentively monitor the evolution of the longitudinal profile of a pavement and to be able to measure it in order to decide on the justification of a maintenance action.

3.1.1 - Analyseur de Profil en Long (APL) [4]

In France, the LCPC has developed a system called APL intended for investigation of the evenness of pavements and the rapid qualification of highway routes. Variations of level of the road surface are translated into a function combining elementary analog signals that may be continuous (waves) or discrete (joints). Computer processing of the profile function breaks the signals down into wavelength bands L. On the basis of these "full-scale" wavelengths and an energy-per-band criterion, an evaluation scale makes it possible to characterize the effect of variations of level for various applications, mainly those that are relevant to the local loads of axles and vehicles on bridges. We distinguish 3 types of application: the "macrotexture" type (2mm<L< 2cm), the "short distance evenness" type (2cm<L< 50cm), and the "long distance evenness" type (50cm<L< 50m).

TABLE 2 - Mean maximum difference of level (mm)

Quality of pavement evenness	Macro-texture type	Short distance evenness type	Long distance evenness type
Good evenness	1	2	10
Medium evenness	2	6	20
Poor evenness	5	15	50

3.1.2 - Application of measurements

Various inspections and ratings of pavements are based on the APL measurements. All of the results, used for many simulations, are centralized and stored in the SETRA's Road Data Base. In addition to some special studies relating quality of evenness, comfort, and/or safety, the APL is used both in the completion inspections of new structures and in management follow-up of existing assets. It is also used to measure the discontinuities of the profile and to determine, for a given section, an Evenness Discontinuity Index [4] that is very useful in characterizing concrete pavements and the wearing courses of bridges.

3.2 - Effect of a discontinuity of road profile

The passage of a tyre over an obstacle induces a vertical force that may be treated as an elastic impact. The force is greatest on the edge of the obstacle. The response time of the axle is greater than the duration of the shock (frequency 10Hz) and it is the tyre that, by being crushed, and therefore undergoing an increase of contact area, and a temperature rise, transmits, over the length of the obstacle, all of the dynamic load. In the case of bridges, the dynamic load caused by the impact depends on the length of the span. The peak increases occur when this length is close to 5 metres and the impact factor can then reach 2.3 for obstacle heights of 3 cm and speeds less than 100 km/h. This factor falls to the vicinity of 1.7 for a span of 10 metres. Beyond 20 metres, the bridge absorbs part of the impact and acts in a sense as a shock absorber. We do not find this phenomenon with pavements.

The table below gives experimental impact factor values on pavements versus the shape of a few obstacles.

TABLE 3 - Effect of vehicle rebound

Obstacle	Height h (cm)	Time of passage (s)	Stiffness of tyre	Place of maximum action	IF
Manhole cover	1	<0.01	0.6	On obstacle	1.6
Bump	1	<0.01	-	20 cm behind the obstacle	1.4
Hollow	2	<0.01	Reduces the load	Behind the obstacle	1.5

When the differences of level are longer (potholes or humpbacks), the time of passage becomes greater than the excitation time, the sprung and unsprung masses start vibrating gradually, and this movement substantially attenuates the effect of the impact.

For the reasons reported above, smaller values may be used for bridges.

3.3 - Braking

The longitudinal and transverse forces that can be mobilized on bridges by trucks are generally related to braking and to centrifugal forces and depend on coefficients of friction that involve the qualities of adherence of both the tyre and the road [5]. The table below gives a few values of coefficients.

TABLE 4 - Coefficient of friction

Vehicle	Longitudinal	Transverse	Rainy weather
Truck	0.5	0.4	0.4
Private car	1	0.4	0.4
Formula 1	2.5		

The braking distance is proportional to the square of the speed divided by the coefficient of friction. It is therefore beneficial to have a high coefficient of friction. But if this coefficient becomes too large, the accelerations that can be mobilized during braking may cause skids or wheel hop that are harmful in several ways: safety, load transfer onto a limited number of axles, etc. Improvements of surface characteristics must therefore be accompanied by improvement of the roadholding of vehicles during braking: anti-locking devices for example. In any case, the shorter the stopping distance the greater the dynamic load on the bridge.

3.4 - Distribution of load

The loads applied to the decks of bridges are distributed, at the level of the pavement, over contact surfaces of which the contour (shape) depends on the type of tyre used. But in reality the load is diffused into the mass of the bridge and acts structurally at the level of the midplane. The active zone of load distribution is thus larger than the contact surface.

Studies performed in particular in the United States [6] have shown that the pressures due to high loads decrease with depth inside the slab, spreading with a 1/1 ratio of linear plan dimensions to depth.

But it is important to report that the pressure under the tyre is not always uniformly distributed. In accidental situations like sudden braking, a skid, wheel hop, or the onset of aquaplaning, pressure concentrations appear under some favoured zones of the tyre, and these transmit the load to midplane of the structure in a harder manner.

The loads may then be distributed over a third of the contact surface and be diffused into the concrete along an oblique close to the vertical.

3.5 - Dynamic response of bridges

Bridges have the particularity of deforming elastically and vibrating under the dynamic action of heavy vehicles. Calculations [7] have shown that the flexibility of bridges, whether old masonry bridges or lightweight metallic structures, does not exceed certain limits.

A static load of 220 kN induces, for short spans, a sag of between 0.3 and 30 mm, depending on the bridge. The mean is in the vicinity of 1.3 mm. Neglecting the dynamic aspect, a bridge with a maximum difference of level can therefore be compared, from the point of view of the effect, to a pavement of the poor long distance evenness type. The bridge in efect amplifies long-wavelength evenness defects.

An important characteristic of the dynamic behaviour of a bridge is its frequency [8]. Many standards in fact prefer to relate the dynamic load to the frequency of the bridge rather than to other parameters such as the mean of the spans or the ratio of live loads to permanent loads ([9],[10]). Generally the frequencies of bridges are greater than 1 Hz and rarely exceed 15 Hz, with a mean of 4 Hz.

Two types of coupling can therefore exist: axle/bridge for frequencies greater than 6 Hz and, in most cases, sprung masses/bridge for low frequencies.

4 - CHARACTERISTICS OF TYRES

The tyre transmits the propulsive force and the load of vehicles to the structure. It acts both as a spring and as a shock absorber. It transmits and filters the action on the pavement according to its own characteristics, coupled to those of the vehicle, the pavement, and the bridge.

To better understand the loads on bridges, it is therefore important to have a thorough knowledge, via the mechanical and geometrical characteristics of the tyres, of the extreme dynamic behaviours of vehicles. But these extreme behaviours, which depend on the technical capacities of the tyres, can be known. In effect, standards require manufacturers to mark, on the sidewalls of tyres, a number of coded letters and figures having to do with (see figure 1):

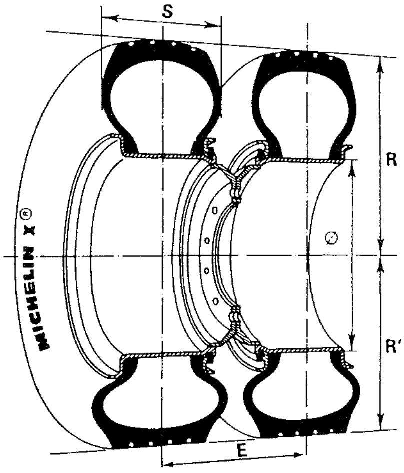


Figure 1

- the maximum width S of the tyre,
- the maximum height H of the tyre (H/S close to 0.8),
- the structure of the tyre (radial, diagonal, mixed carcase (this last rare)),
- the inside diameter Φ of the rim,
- the type (single, wide, paired tyres),
- the maximum load capacity,
- the maximum speed V or speed symbol from which the pressure can be deduced.

More detailed analysis of this information is therefore very useful for the definition and prediction of local loads on bridges.

4.1 - Authorized load

A few maximum loads per axle and per wheel in conformity with European standards are given in tables 5 and 5A.

TABLE 5 - Tyres with radial carcase for trucks

Φ Rim dia. (inch)	Max. load /axle, single wheel (kN)	Max. load /axle, twin wheels (kN)	Tyre pressure (bars)	V max in kph	Use
20	85	150	9.25	70	Urban area
20	110	198	6.75	65	Special
24	80	146	7.5	105	Road

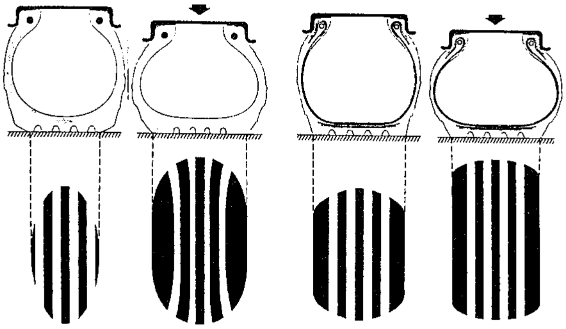
TABLE 5A - Tyres with radial carcase for industrial vehicles

Φ Rim dia. (inch)	Max. load /wheel, driving axle (kN)	Max. load /wheel, trailer (kN)	Tyre pressure (bars)	V max in kph	Use
15	55	50	10	10	Trailer road
24	177		10	5	Road
25	369		7	5	Road /track

The maximum loads per wheel or per axle may be reached or even exceeded. The speeds permitted by the tyres are sometimes high, often far higher than the legal speed limit. One should therefore expect to find large static loads on roads because of the behaviour of road carriers. The rolling conditions may also induce dynamic loads leading to the technical limits of use of the tyres, which gradually deteriorate and so also damage the pavement. The study of tyre wear accordingly provides information about the extreme conditions of use and shows that there exists a high probability of occurence even of loads regarded as exceptional.

4.2 - Contact surface

Two main tyre architectures are used: diagonal carcases are used for aircraft and farm tractors and radial carcases for almost all road vehicles. We shall speak here only of radial tyres, the particularity of which is that they can be deformed by crushing only longitudinally.



Diagonal tyre Radial tyre

Figure 2

The load is applied to the wearing surface only on a limited area, always changing, and the mean pressure "p" on the ground is equal to the inflation pressure "p_g" plus the structural reaction of the tyre, which remains small. The footprint of the heavy load is substantially a rectangle of which the transverse dimension "b" is constant.

If we assume $p=p_g$, we can deduce, as a function of the possible crushing "$f=R-R_f$" of the tyres, the longitudinal dimensions $a=2[f(2R-f)]^{1/2}$ of the corresponding contact surfaces (R is the radius of the tyre with no load and R_f the radius of the tyre under the maximum load).

Table 6 - Tyres with radial carcase for industrial vehicles

Φ of rim (inch)	D=2R tyre with no load (mm)	Radius R' of tyre under load (mm)	S mm	H/S mm	b mm	a max mm	Use
19.5	1098	494	477	.65	470	480	Road
20	1348	611	412		412	570	Road /track
24	1257	570	338	.65	338	527	Road /track
15	934	420	278		278	420	Trailer
25	1744	795	671		671	716	Self-propelled crane

We find that the impact surfaces on roads are rather square and that in any case, under load, the transverse dimensions are less than or equal to the longitudinal dimensions. Concerning the dimensions of impact, another point deserves to be reported. Road carriers have, for some time, stated their preference for the wide single wheels of semi-trailers over the old twin wheels, which are still used for construction site trucks and some driving axles. The advantages of the wide single wheel are undeniable from the standpoint of:

- safety (lowering of centre of gravity of vehicles, effect of improved suspension, better load distribution, gains in load volume, elimination of risks of blowout because of the frequent pressure differential between the twin wheels),
- savings of sets of tyres (reduction of the unsprung masses),
- consumption (lower rolling resistance, tyres with more flexible sidewalls),
- damage to pavements, less aggressive skidding, etc.

The contact area of wide tyres on the extrados of the skeleton of a bridge is calculated from a transverse dimension equal on average to 400 mm and a longitudinal dimension that is a little larger than the transverse dimension in a dynamic situation.

To correctly represent the coupling between the phenomena, the formula below gives the axle load Q in function of the pressure p for a given speed and a contact area a little larger than 400x400mm2.

$$Q=22(p+0.7) < 140\text{kN}$$

This type of wide tyre is already fitted on most heavy industrial vehicles and will tend to be used generally. The bridge designer cannot ignore this reality and must take the corresponding type of contact surface into account in his calculations, punching included.

4.3 - Pressure in tyre

The pressure in the tyre, a function of the load and of the speed, is the decisive factor in the potential dynamic load. This pressure is not constant because, when the vehicle rolls, the temperature rise caused by the various friction causes a normal increase of the pressure, then stabilizes if the tyre is initially correctly inflated. If the tyre is underinflated, the temperature rise is greater and the damage to the tyre may become irreversible (formation of an unstable mixture) because then the equilibrium pressure "no longer supports the tyre".

The rigidity of the tyre is related to the pressure. In the stopped condition, the tyre behaves like a linear structure: deflection proportional to load. But this rigidity evolves with the speed in the course of rolling. In terms of deflection, curiously, experience shows that the rigidity decreases with increasing speed, whereas the pressure increases. But this is primarily a problem of the modelling of the tyre. The boundary conditions of the body representing the tyre must also be incorporated in a global model of the energy at large deformations type. The phenomena involved are very complex and can not be reduced to a simple linear elastic model.

4.4 - Internal tyre impact factor

We have just seen that the pressure in a tyre depends on the speed. The characteristics of tyres are stated by the manufacturers in relation with the conditions of use, the dimensions, and the type of tyre. For example, a truck tyre that can roll at 100 kph can be loaded in the stopped condition with 2.5 times the reference load at 100 kph.

The same technical data sheets also show that the pressure capacity can vary under identical conditions in a ratio of 1 to 1.4 as the speed decreases from 120 kph to zero. Physically, the pressure must therefore remain less than 1.4 times the nominal pressure. This coefficient acts on the rigidity of the tyre, itself a factor in the dynamic load.

We obtain here, in another way, a new estimate of the impact factors. The global dynamic coefficient, related most directly to the total load, must be compared to the factor of 2.5 likely to affect the loads as a whole. On the other hand, the local coefficient, related most directly to the rigidity of the tyre, can be compared to the factor 1.4.

4.5 - Summing up

Considered from the standpoint of the tyre alone, the foregoing considerations confirm the type and extent of the dynamic loads. But the action of a vehicle is not limited to the action of a single axle. Whence the idea of measuring the aggressiveness of a train of axles by comparison with the aggressiveness of a reference axle.

Not counting the direct action on the pavement of the bridge, to a first approximation, we note that, under regulation loading conditions, the aggressiveness of tandems and tridems is at least comparable to that of heavy axles acting alone. Similarly, a 10 % overload of an axle leads to twice the aggressiveness of the axle loaded in conformity with regulations.

Knowledge of tyres and of the use made of them in consequence gives a good approximation of the loads that can be mobilized on bridges. But this knowledge adds, to the complexity of the loads, the complexity specific to the tyres. Many more studies will be needed to correctly delimit the domains.

5 - DISTRIBUTION OF MEASURED LOADS

The determination of the local loads to be taken into account in the design of structures must, in addition to the conceptual aspects developed above, be based on the available actual data. This is in particular a matter of gathering and processing data on the important descriptive parameters. It happens that since 1980, weigh-in-motion systems have been considerably developed, in particular in France with the use of piezoelectric sensors and the associated weighing stations [11]. This has made it possible to collect an enormous mass of information on the weights and dimensions of heavy vehicles and their axles. This has also been done in other countries of the European Community. On the occasion of the work of preparation of Eurocode 1 part 3, a summary of these data was prepared [1] that reveals the main parameters and their distributions.

5.1 - Parameters measured

The flows (of trucks or axles) provide information for the quantification of the aggressiveness of a traffic in terms of fatigue of pavements or bridges, but also of the number of occurences of some loads, useful for extrapolations. The composition of the traffic in types of vehicles or of axles is used to characterize the traffic and its aggressiveness. It is also important to know the distances between axles for each type of vehicle for local effects, in particular for tandem and tridem axles (groups of axles), which act simultaneously on short distances. Finally the weights of these axles or groups of axles are essential to the calculation of the effects. Their extreme values are used, after extrapolation, for calibration of the characteristic values or of models.

As an illustration, table 7 gives, for various traffics, the distribution of axles between single, tandem, and tridem axles, while the following figure gives, for 4 countries, the distributions of the distances between consecutive axles of vehicles. The peak, invariably located near 1.2 m, corresponds to the distances between axles of the same group, while the modes centered around 3.3 m and 5 m are for single-body and articulated vehicles, respectively. The next figure shows the distributions of weights of tridem, tandem, and single axles, the last two of which are bimodal (similar results are found in the other European countries).

TABLE 7 - Proportions of axles of each type

Traffic		Axle	Double	Triple
Highways	Brohltal (D)	64.7	19.8	15.5
	Fiano Romano (I)	55.3	26.7	18.0
	Auxerre v1 (F)	56.2	16.2	27.6
	Auxerre v2 (F)	57.5	16.2	26.3
Nat. road	Angers (F)	58.5	20.4	21.1
Urban way	Lyon (F)	80.9	12.8	6.3

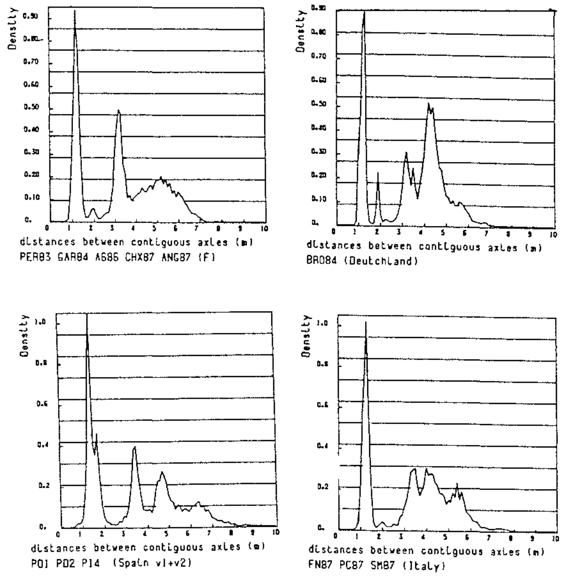


Figure 3

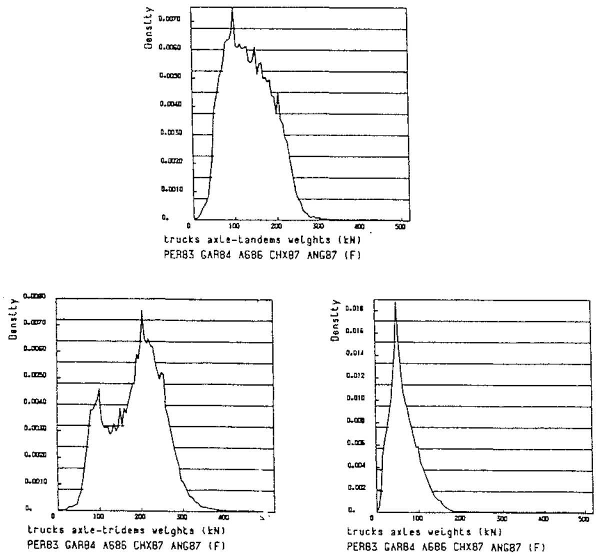


Figure 4

5.2 - Characteristic axle loads

Various methods of extrapolation have been proposed within the working group of Eurocode 1 part 3 in order to determine the weights of axles having specified return periods; they yield rather similar results [12]. These results are given in table 8 for single, tandem, and tridem axles. The values having short return periods are useful for fatigue loads, while those with long return periods are used to define the characteristic loads.

Tableau 8 - Extrapolated loads (in kN) obtained by various methods

Return period	Item	Extrapolated maximum loads
20 weeks	Axle	224 - 226 - 234 - 252
	Double	356 - 353 - 348 - 332
	Triple	469 - 436 - 439 - 442
2000 years	Axle	245 - 278 - 264 - 295
	Double	397 - 442 - 403 - 379
	Triple	527 - 487 - 508 - 517

5.3 - Dynamic coefficient included in the measurements

The studies conducted for Eurocode on the dynamic effects of traffic [13] have made it possible to quantify the share of dynamic loads included in the measurements (weigh-in-motion) and their incidence on the extreme weight values. For isolated axles a coefficient of 1.15 can be adopted, which means that 15% of the proposed extreme load is in reality a dynamic load related to the vibrations of the vehicles due to pavement evenness defects. The absolute dynamic coefficients to be used in the calculation of structures must therefore take this into account. For groups of axles, this coefficient can be estimated at around 1.10, close to that found for the total weight of trucks. So there is approximately 10% dynamic load assigned to the extremes. For cases involving static loads (as in traffic jams), it is therefore necessary to reduce the effects calculated from the measured traffics proportionally.

6 - MODELS OF LOCAL LOADS - CONCLUSIONS

The calibration of heavy traffic load models on bridges has been conducted [14] using the techniques of operational research. The effects F of the extrapolated true traffic, a traffic having a return period of x years, on some number of characteristic bridges are defined. The calibration then consists of minimizing the difference in absolute value between the effects G of a model and the values F, assuming that the model can be broken down into a certain number of parameters (number of axles, load per axle, distance between axles, etc.), transformed for the occasion into structural variables of a linear problem.

6.1 - Extrapolated axle load

The local effects of the true traffic are determined from extrapolated typical vehicles, of which the most aggressive are semi-trailers [12]. They account for about 60% of heavy traffic.

If we consider a single loaded travel lane, the maximum axle load measured extrapolated to the normal quasi-static traffic configuration without congestion does not exceed 220 kN. This value corresponds moreover to extreme axle loads measured on some routes, on trucks that are non-uniformly loaded, in violation (210 kN). The dynamic load is in this case obtained by multiplying this load, in the worst of cases, by 2.1 for the study of the general bending of short-span bridges (1.8 for the study of shear) and by 1.3 for the purely local study [13].

If we now consider two loaded two-way travel lanes, the maximum axle load is again equal to 220kN but since the mean speed is lower in this case, the dynamic load for the calculation of the general effects is obtained by multiplying the static load by 1.7, with no change of the local coefficient.

6.2 - Loading models - Validation

For bridge spans greater than 3 metres, the optimizations show that the extrapolated true local traffic, applied to the main travel lane, can be reduced, from the standpoint of the equivalent extreme effect, to a TEC1-3 tandem. The axle load, dynamic load included, is 300 kN. The longitudinal distance between axles is 1.2 metres, the transverse distance between wheels 2 metres. This tandem therefore induces on bridges extreme effects close to those of the true traffic.

Applied to two main traval lanes, contiguous or not, the true traffic is modelled by 2 tandems acting simultaneously on 2 lanes:

- first lane, the above-mentioned TEC1-3 tandem,
- second land, the TEC1-3 tandem with two-thirds load.

The contact surface of the wheels is represented by a square measuring 400x400mm2. The pressure on the ground is not more than 11 bars.

The diffusion through the concrete follows a slope of 1/1 above the midplane of the structure.

This load model has been validated on a large number of bridges. It is on its way to being adopted as the main model of local characteristic loads under Eurocode 1 (Part 3), road loads on bridges.

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