ENV 1991 part3: the main models of traffic loads on road bridges: background studies

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ENV 1991 Part 3 : The main models of traffic loads on road bridges Background studies

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SUMMARY

Part 3 of Eurocode 1 defines the traffic load models to be used for the design of road bridges, footbridges and railway bridges, for serviceability, ultimate resistance and fatigue verifications. For road bridges, several load models are proposed for serviceability and ultimate resistance verifications : one of them (Load Model 1 or LM1) is the main system. The background studies related with the calibration of this main system are presented.

Introduction

The work for the definition of traffic loads on road bridges and footbridges started in 1987. A working group was appointed by the EEC, convened by Ir. Gl. H. Mathieu. At the end of 1991, the work for the development of what is now included in ENV 1991 Part3 was transferred to the CEN and allocated to a project-team (SC1/PT6), the composition of which is given in Table 1.

Members	Associated experts
Ir. Gl. H. Mathieu (Convenor)	Pr. Calgaro
Ir. Gulvanessian (SC1 Technical secretary)	Dr. Ir. Croce
Pr. Bruls	Dr. Ir. Jacob
Dr. Flint	Ir. Gilland
Pr. Sanpaolesi	Dr. Ir. Merzenich
Pr. Sedlacek	Ir. Prat

Table 1 - SC1/PT6 for road bridges

For road bridges, Part 3 of ENV1991 defines :

- Four load models for serviceability and ultimate resistance verifications (noted LM1 to LM4) : LM1, completed by LM2 for some specific local verifications, is the main model, LM3 includes a set of abnormal vehicles and LM4 represents the load due to a crowd on a bridge deck. These two last models are used, for a particular project, only if required by the client.
- Five models for fatigue verifications (noted FLM1 to FLM5) [6]

The present contribution gives information on the background studies wich led to the definition of LM1 and LM2.

1. Basic data on road traffic

When studies started, the available road traffic data consisted of :

- old data collected from 1977 to 1982 in France, Germany, Great Britain, Italy and The Netherlands ;
- recent data mostly collected in 1986 and 1987 in several countries. Four countries (France, Germany, Italy and Spain) had full records of traffic, including all the needed information about the axle weights of heavy vehicles, about the spacing between axles and between vehicles, and about the length of the vehicles.

Most of the recent data were recorded on the "slow lane" only (supporting the heaviest traffic) of motorways or main roads. The duration of the records varied from a few hours to more than 800 hours.

1.1 Traffic composition

The observed flow of heavy vehicles varied from 1000 to 8000 vehicles per day on the slow lane of motorways, from 600 to 1500 per day on the other roads. On the fast lanes of motorways or on secondary roads, this medium flow dropped to 100 or 200 vehicles per day.

The distribution of the distance between lorries appeared to follow a "gamma" type law with a mode between 20 and 100 m, a mean value varying from 300 to more than 1000 m and a large variation ratio (2 to 4). The most frequent types of vehicles were the double-axle vehicles and the articulated vehicles. The number of axles per vehicle, depending on the constructor, varied widely, but the histograms of their spacing showed three persistent modes with peak values particularly constant :

- 1,30 m for double and triple axles with a very small standard deviation,
- 3,20 m for the tractor axles of the articulated lorries, with a small standard deviation,
- 5,40 m for other spacings but with a widely scattered distribution.

1.1.2 Axle and vehicle weights

The axle weight was very scattered, with an average value around 60 kN, but the maximum weight corresponding to a mean return period of one day was not very different from a location to another one. Table 2 shows the range of the maximum weight per axle type, corresponding to a mean return period of one day.

	Single axles	Tandems	Tridems
Range of the maximum weight per day (kN)	130 to 210	240 to 340	220 to 390

Table 2

Even the maximum total weight of vehicles corresponding to a mean return period of one day was not very different from one location to another one, mostly in a range 400 - 650 kN. And all statistical distributions had two modes : the first one around 150 kN and the second one around 400 kN.

Finally, and in spite of some variations in the result of the measurements from one country to another one (these variations resulted mostly from the choice in traffic samples), the road traffic parameters turned out to be rather homogeneous, especially for the maximum daily values of the axle and vehicle weights.

2. Procedure for the definition of LM1

Preliminary studies were performed to compare different results obtained from the various load models of the existing European standards. They all demonstrated qualities and failings, and it was therefore decided to build an original main load model such that :

- its effects reproduce accurately the total utmost effects (local and global) due to the actions of the real traffic for various shapes and dimensions of influence areas representative of the bridge construction in Europe, including the dynamic magnification ;
- its effects could not vary too much if the system only partially applies on the relevant influence surfaces, so that the unfavourable location (loading arrangement) can be easily determined both transversally and longitudinally ;
- its application rules should be as simple and unambiguous as possible.

From a global point of view, the procedure adopted for the development of LM 1 consisted of the two following major steps :

1. Definition and assessment of « target values » for various effects ;
2. Reseach of the best fitted model, able to reproduce the « target values » with accuracy, by the use of operational research.

The definition and the assessment of target values needed several choices :

- Traffic samples and pavement roughness,
- Traffic situations,
- Set of influence areas,
- A level of probability for the assessment of characteristic values,
- Extrapolation methods.

2.1 Trafic samples

The first idea was to mix all the traffic records in order to get an "European sample", but some extrapolation methods, based on mathematical simulations of traffic, needed samples of homogeneous traffic. Considering that the traffic recorded on the A6 motorway near the French city Auxerre was already an "European" traffic, it was decided that all the statistical manipulations would be done only with this traffic and that other traffics might be taken into account to bring, possibly, some corrections.

The Auxerre traffic is rather heavy for one loaded lane, but it is not the heaviest observed traffic : for example, the traffic on the slow lane of the Brohltal bridge in Germany was the most "aggressive", and the recorded daily maximum axle weight was equal to 210 kN on the Ring of Paris while it was equal to 195 kN on the slow lane of A6 motorway (these values are in conformity with the technical capacities of industrial tyres). Taking account of the method of measurement (by piezo-electric cables and a weigh-in-motion system) it was agreed to consider that the real traffic records included an inherent dynamic effect characterised by a magnification factor of 1,10.

Many numerical simulations considering the dynamic behaviour of the vehicles and of the bridges were performed, which were based on some hypotheses about the roughness quality of the carriageway. The corresponding studies are detailed in [6]. Target values of the extrapolated traffic effects were determined for a set of influence areas (see 2.3) on the basis of numerous dynamic calculations.

2.2 Traffic situations

Traffic records give information only on usual traffic conditions. But it is clear that the most critical situations appear with disturbed traffic conditions. Therefore, it has been necessary to define and to combine realistic traffic scenarios (arrangements of vehicles, traffic types) such as free flowing traffic, condensed traffic, traffic jam, special situations due to social demonstrations ("snail" operations), etc. The assessment of the target values, previously mentioned, to be used for the calibration of LM1 needed the selection of traffic situations (or scenarios) on the various lanes of a bridge, i.e. combinations of basic traffics depending on the location and the number of lanes.

The studies for the definition of traffic situations were rather complex and it is only possible to give a general overview in the present contribution. The considered basic traffics were :

- flowing traffic, as recorded on the slow and fast lanes of A6 Motorway, or simulated (random distribution of lorries and cars) on the basis of traffic records and possible manipulations on the number of lorries ;
- congested traffic, that is simulated flowing traffic, moving at very low speed (5 to 10 kph);
- jam situation taking into account vehicles with a conventional distance of 5 m between them.

Several contributors proposed various traffic situations (hazard scenarios), combining flowing and congested traffic and corresponding to deterministic[1] processes. They are summarized hereafter.

2.2.1 Hazard scenarios with flowing traffic

On the *first* (most heavily loaded) *lane*, all contributors proposed to consider the extrapolated traffic corresponding to A6 motorway slow lane, as recorded or simulated with a percentage of lorries of 25%, and speeds about 80-100 km/h.
On the *second lane*, the propositions were more varied : same traffic as on the first lane, traffic on A6 slow lane but corresponding to the daily maximum (no extrapolation), or traffic on A6 fast lanes with 10% of lorries.
On the *third and fourth lanes*, it was mainly proposed to take into account the recorded traffic on A6 fast lanes corresponding to the daily mean loads, or with limited percentages of lorries.

2.2.2 Hazard scenarios with congested traffic or jam situations

On the *first lane*, all propositions were based on A6 slow lane traffic without cars, corresponding to a congested traffic or a jam situation as previously defined.
On the *second lane*, it was envisaged A6 flowing traffic as recorded on the slow lane (extrapolated to 1000 years or daily maximum) or simulated jam situations both on first and second lanes with a distance of 5 m between lorries.
On the *third and fourth lanes*, it was generally proposed to take the daily maximum and the daily mean of A6 slow lane, respectively.

Considering that all points of view were pertinent, the target values defined by each contributor of the Project Team were used to some extent for the calibration of the load model.

2.3 Set of influence lines

Numerous influence areas (for beams as for slabs) were used for the calibration work of the main loading system. The main (cylindrical) influence areas used to assess the effects of the loading pattern are represented in Table 3.

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[1] This method was the only one that could be used considering the time constraint of the Project-Team, and was considered as sufficient at the considered step, being conscious that adaptations should be fitted for bridges with traffic lighter than A6 traffic.

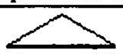
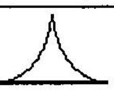
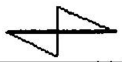
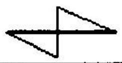
Nr.	Representation	Description of the influence line
I1		Maximum bending moment at mid-span of a simply supported beam.
I2		Maximum bending moment at mid-span of a double fixed beam with an inertia that strongly varies between mid-span and the ends.
I3		Maximum bending moment on support of the former double fixed beam.
I4		Minimum shear force at mid-span of a simply supported beam.
I5		Maximum shear force at mid-span of a simply supported beam.
I6		Total load.
I7		Minimum bending moment at mid-span of the first of the two spans of a continuous beam (the second span only is loaded).
I8		Maximum bending moment at mid-span of the first span of the former continuous beam.
I9		Bending moment on central support of the former continuous beam.

Table 3 : Desciption of the influence lines

For all these influence lines, 9 span lengths were considered : 5, 10, 20, 30, 50, 75, 100, 150 and 200 m. In fact, influence lines I1 and I9 turned out to be the most important lines for the calibration of the load model.

2.4 Level of probability

The target values of the traffic effects were determined such that the probability of exceeding in 50 years was less than 5% (or, in other words, such that they correspond to a mean return period of $\frac{50}{0{,}05} = 1000$ years). This choice was based on the following considerations :

- The chosen probability had to be small enough so that combinations with LM1 or with exceptional convoys (LM3), as dominant variable actions, could be based on the same reliability format.
- The probability for several exceedances of irreversible serviceability limit states during the period of reference should also to be strongly limited.
- It is rational to think that the loads will increase in future and the difference between return period values of 1000 years and of 200 years is small because the distribution of the traffic utmost effects is weakly scattered.

Note that there is no discrepancy in the reliability level between the design effects of LM1 and of LM3 : in other words, the effects of the lightest exceptional convoys are covered by those of LM1. Note also that the approach adopted for road traffic loads started from assessments of load effects and not, as for climatic loads, from a natural parameter representing partially the action.

3. Calibration of LM1

3.1 Principles

The aim of the works was to build a model that would include the dynamic magnification with simultaneous concentrated and distributed loads, so that it covered all traffic scenarios and that both general and local verifications could be simultaneously performed. The minimum intensity of the distributed load was set to 2,5 kN/m^2 on the basis of existing national standards. The calibration tests later confirmed this value.

These calibration tests were carried out at the SETRA with methods of the operational research. Noting :

- S_{1i}, the target values of the selected effects for the various span lengths and the various influence lines or areas[2] ;
- S_{2i}, the corresponding values deriving from the load model under calibration ;
- d_i the gap between S_{1i} and S_{2i} defined by : $d_i = \left|\frac{S_{1i}}{S_{2i}} - 1\right|$;

the following functions were considred :

$$d_{max} = \mathrm{Max}\left|\frac{S_{1i}}{S_{2i}} - 1\right| \qquad d_m = \frac{(\Sigma d_i)}{n}$$

The optimisation method consisted of finding, for various models depending on various parameters, a function S_2 calibrated on the basis of the following criteria, considered separately :

- d_m is minimum,
- d_{max} is minimum as well,
- d_{max} and d_m are minimum and $\frac{S_{1i}}{S_{2i}} \geq 1$ or 0,95

3.2 Calibration procedure and major results

The calibration of LM1 was performed step by step, by the successive consideration of a single loaded lane, two loaded lanes, and finally four loaded lanes. From a general point of view, it appeared that, in the longitudinal direction :

- The best fitted model was composed of both concentrated and uniformly distributed loads;
- It was possible, for the assessment of general effects, to have only a single concentrated load in each lane, but its magnitude made impossible the definition of realistic rules for local verifications.
- The introduction of more than 2 concentrated loads was superfluous because it did not really increase the accuracy of the results.
- The intensity of the uniformly distibuted load should be a decreasing function of the loaded length, noted L.

Table 4 shows LM1 as it resulted from the first calibrations.

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[2] Index i = 1 to n is an identification index of the values obtained for the 9 span lengths, the 8 influence lines and the 3 loading systems (1 lane, 2 lanes, 4 lanes) ; thus n = 9 x 8 x 3 = 216 values.

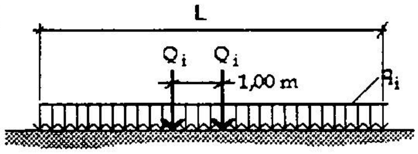
	Loaded lane(s)	Q_i (kN)	q_i (kN/m)
	1	$Q_1 = 185$	$q_1 = 29{,}3 + \frac{375{,}6}{L}$
	2	$Q_2 = 100$ kN	$q_2 = 0{,}487\, q_1$
	3+4	$Q_3 + Q_4 = 150$ kN	$q_3 + q_4 = 0{,}56\, q_1$

Table 4

This solution was progressively modified for the purpose of simpler application. The accuracy of the calibration was slightly decreased in order to obtain a load model of very simple use and unambiguous application. Consequently, it was agreed to give a constant magnitude to the uniformly distributed load.

3.3 The final Load Model 1

Further studies about the influence lines and areas with a length smaller than 5 m led to increase the intensity of the concentrated loads on the first and second lanes, to correlatively decrease the intensity of the distributed load on the same lanes and to remove the concentrated loads after the third lane. Besides, the distance between concentrated loads in lanes 1 to 3 was increased up to 1,20 m. This value seemed to fit better the real spacing between two axles of lorries (the aim being to define realistic local verification rules), although the concentrated loads were not initially supposed to represent the axles of actual vehicles. The final model is represented in figure 1.

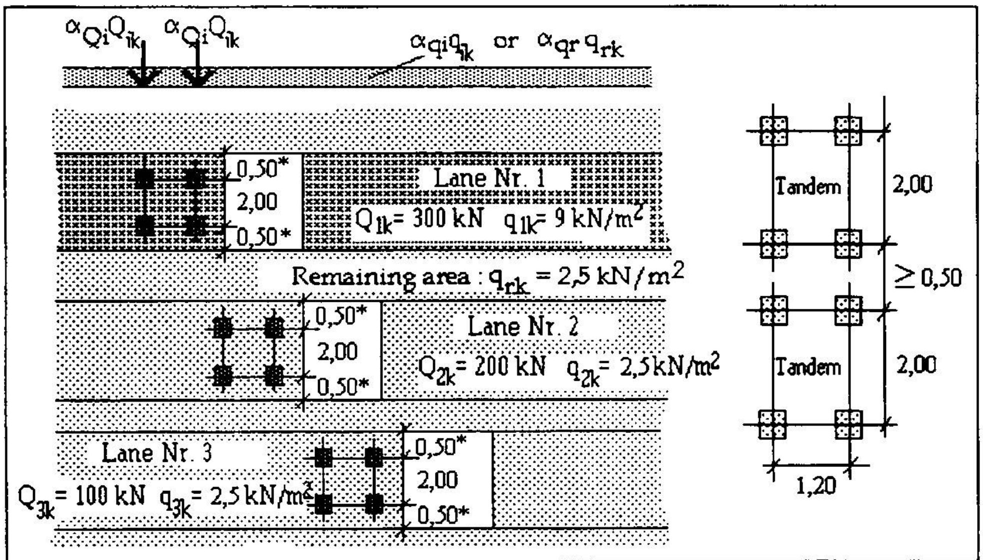


Fig. 1 : Description of LM1

As formerly explained, the calibration of LM1 was performed with the effects of a rather "heavy" traffic (Auxerre traffic). For bridges intended to carry a lighter traffic, special loading classes may be defined in the various NADs by using adjustment factors on concentrated loads (factors α_{Qi}) and on distributed loads (factors α_{qi} or α_{qr}).

3.4 Choice of the wheel contact area shape

On the basis of a detailed study performed by Mr. Prat [5] on local loads transmitted to the carriageway by heavy vehicle wheels, the contact area of the concentrated loads is a square of 400 x 400 mm (fig. 2), corresponding to realistic wheel contact areas of wide tyres.

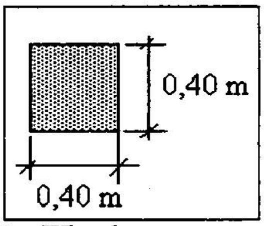


Fig.2 : Wheel contact area

Two main tyre achitectures are met : diagonal carcass, for aircraft and farm tractors, and radial carcass, for almost all road vehicles. In the case of lorries, the use of simple wheels is widely developed : radial tyres deform by crushing only in the longitudinal direction. Therefore, the footprint of such a tyre is a rectangle of constant width and all studies showed that the contact area of tyres with the road pavement is rather square (in all cases, the transverse dimension is less than, or equal to, the longitudinal dimension). With the adopted dimensions, the contact pressures on lane 1 are equal to 150/0,16 = 937,5 kPa (for adjustment factors equal to 1), which corresponds to the dynamic pressure of a tyre on the road pavement (equal to the inflation pressure plus the structural reaction of the tyre).

3.5 Additional considerations

3.5.1 Definition of the loadable width of a bridge deck

For the sake of simplicity, it was agreed that the loadable width of a bridge deck was equal to the net width of the carriageway, measured between the kerbs where they are higher than 100 mm or between the inner limits of relevant road restraint systems.

3.5.2 Definition of the lanes

Considering that, in the most critical traffic situations, vehicles can be driven close to each other, and considering also transient situations (e.g. for maintenance and/or repair), it was agreed that the loads resulting from the calibration tests should apply on strips of 3 m width. So are defined the so-called "*notional lanes*" of 3 m width, that are independent of the marker strips on the road surface. These notional lanes can be located anywhere on the drivable surface : their ***maximum*** number is thus the integer part of the division by 3 of the carriageway width (where this width is more than 6 m).

3.5.3 Definition of Load Model 2

Some calculations showed that the tandem systems of LM1 did not cover all local effects of vehicles of various configurations. Therefore, for some local verifications (in particular in case of orthotropic slabs), it was agreed to complete this model with a

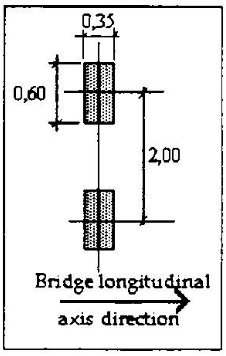


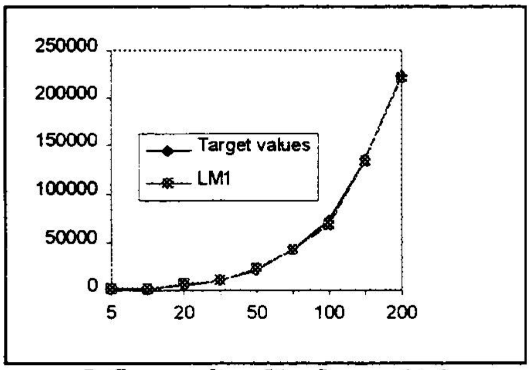
Fig. 3 : LM2

loading system (LM2) which also allows to take into account other contact areas than the ones corresponding to wide tyres (in case of double wheels) and to correct the effects of LM1 for very short influence lines. It consists of a single axle corresponding to a load of 400 kN to which can be applied an adjustment factor β_Q depending on the class of the expected traffic for a particular project (fig. 3).

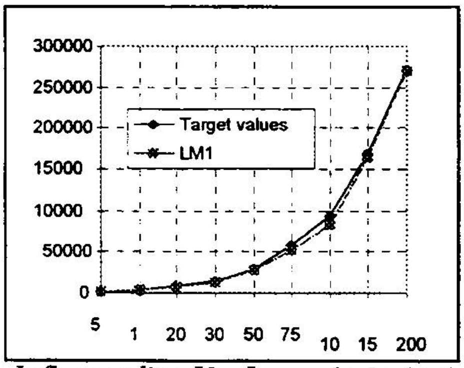
4. Comparisons between the effects of LM1 and the corresponding target values

Some typical curves are given hereafter to show the quality of the adjustment between the target values and the effects of LM1.

4.1 Influence line I1

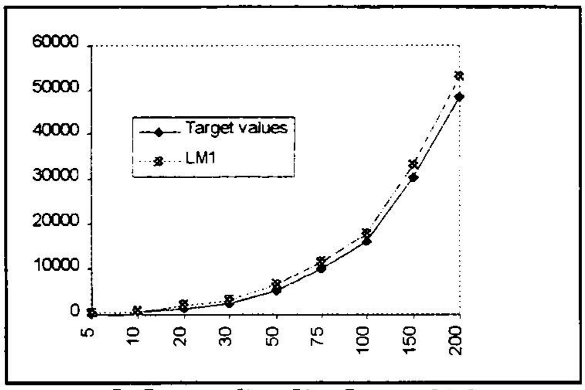


Influence line I1 - Lanes 1+2

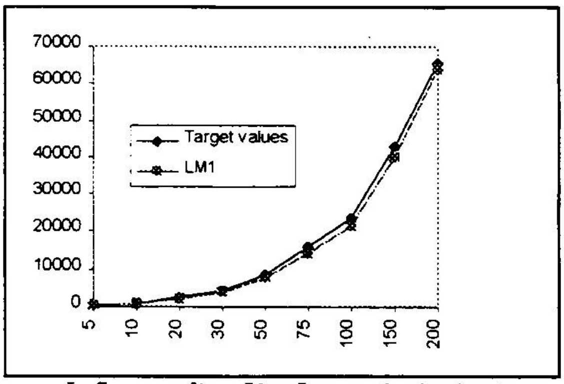


Influence line I1 - Lanes 1+2+3+4

4.2 Influence line I2

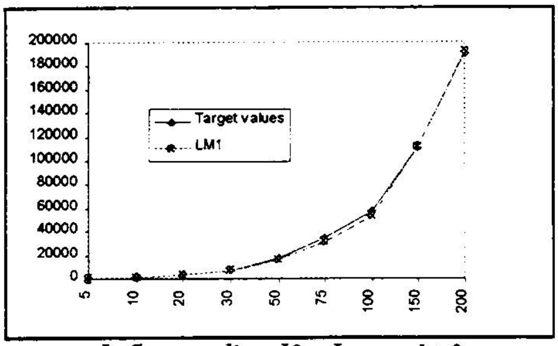


Influence line I2 - Lanes 1+2

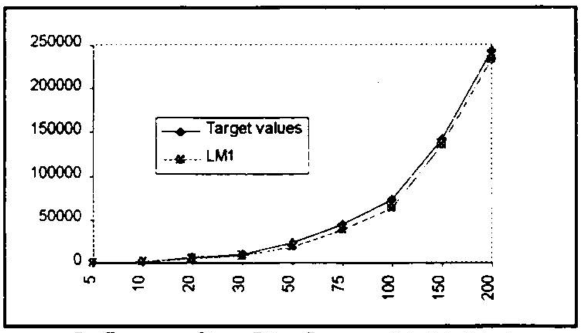


Influence line I2 - Lanes 1+2+3+4

4.3 Influence line I9



Influence line I9 - Lanes 1+2



Influence line I9 - Lanes 1+2+3+4

The major differences are obtained with influence line I2, which is a very particular influence line because the ratio between the moment of inertia of end cross-sections and cross-section at mid-span is very high. The values obtained from the model are bigger than the calibration values for one and two loaded lanes, but not for four loaded lanes. For loaded lanes 1+2, the deviation varies from 27 % for L = 50 m to 9 % for L = 200 m.

5. Representative values of traffic loads and groups of loads

5.1 Representative values of traffic loads

The various representative values of traffic loads are :
- the ***characteristic values*** (which were calibrated as previously described) for the ultimate limit states ;
- the ***infrequent values***, corresponding to a mean return period of one year ;
- the ***frequent values***, corresponding to a mean return period of one week.

The ***quasi-permanent values*** of the actions due to the road traffic are in general practically zero. In case of bridges that support a heavy and continuous traffic, a non null quasi-permanent value of the uniformly distributed load of the main loading system might be considered, with a likely uniform or unique distribution in the transverse direction.

Infrequent values had been required by drafters of EC2.2. They were intended for verifications concerning some serviceability limit states that correspond to an imperfect reversibility of the effects, and were assessed on the basis of a mean return period of 1 year. The infrequent models derive from the characteristic models by means of a reduction factor ψ'_1 equal to 0,8. This means consequently that the traffic effects corresponding to a return period of 1000 years are only 20% higher than those corresponding to a return period of 1 year. For more details concerning the calibration of frequent and infrequent values, see [6].

5.2 Definition of groups of loads

On a bridge deck, various kinds of loads, represented by specific models, may be more or less simultaneously applied : road traffic loads, pedestrian loads, abnormal vehicles, crowd, etc. These loads are multi-component and give rise to vertical and horizontal forces.

In Part 3 of ENV 1991, various models are defined to represent all kinds of loads : vertical forces due to vehicles or pedestrians, braking and acceleration forces. In order to facilitate the work of designers, and in accordance with ENV 1991-1 « Basis of design », groups of loads are defined, each of them being considered as one variable action in combinations. The major group of loads is group Nr. 1, which includes the vertical forces due to LM1 and vertical forces due to a load on footways and cycle tracks with a reduced value of 2,5 kN/m^2. For this group :

- the infrequent values are obtained as previously explained by applying to the characteristic values of LM1 and LM2 a ψ'_1 factor equal to 0,80 ;
- the frequent values are obtained by applying a ψ_1 factor equal to 0,75 to the concentrated loads of LM1 and LM2, and equal to 0,4 to the uniformly distributed load.

In the ultimate limit state combinations, the partial safety factor for road traffic actions is equal to 1,35 (as for permanent actions).

6. Possible evolution of traffic load models

Most of the background studies was scientifically performed. Based on real traffic records, the calibration of the main loading system resorted to probabilistic techniques and to the methods of operational research. Only one step was deterministic : the choice of traffic scenarios on the various lanes of a bridge deck.

In the future, if more refined calibrations are undertaken especially for the EN stage, it would be probably more satisfactory to reconsider the problem of traffic scenarios on the basis of a probabilistic approach, as far as statistical bases can be found for this.

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