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# Report of Current Studies Performed on Normal Load Model of EC1

## Part 2. Traffic Loads on Bridges

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*ABSTRACT. This report gives results of some new studies performed to validate the european road traffic load model proposed by the Eurocode EC1. Weight in motion has developed greatly in the last ten years and confidence in the accuracy of recorded data has increased significantly. Traffic data recently obtained from a number of representative European sites are used to re-calibrate the codified main load model of the European bridge loading code, Eurocode 1 Part 3. A wide range of real and virtual bridge forms were chosen for the study. Simulations were performed using free-flowing and jammed traffic. Load effects generated were determined and statistical extrapolations were performed, where appropriate, to determine characteristic values for the load effects. Some of the assumptions used in the derivation of the original loading model were re-assessed.*

*KEYWORDS: Eurocode, traffic loads, load effect, bridges, design code, extrapolation.*

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## **1. Introduction**

This report contains the result of some new studies performed to validate the adequacy of the normal load model, LM1, proposed by the draft Eurocode EC1, Part 3, Traffic Loads on Bridges, for the design of highway bridges with spans < 200m and width up to 12m. The normal load model, prescribed by the code, was calibrated in studies performed in the late 1980's. The calibration studies involved the calculation of a set of target values, characteristic load effect values (i.e. bending moments and shear forces) for a variety of bridge configurations. These values were calculated in traffic simulations performed using Weigh in Motion, WIM, traffic data recorded in Auxerre in France in 1986. The simulations were performed for both 'free' and 'congested' flow conditions with subsequent extrapolation of the calculated load effect distributions to yield the maximum expected value of a given load effect during the lifetime of the structure. It was these lifetime maxima which were used as target values for the normal load model.

The draft Eurocode is currently being prepared for conversion from ENV to EN status. In the 10 years since the calibration of the original normal load model, considerable advances have been made in WIM technology leading to increased availability of unbiased traffic data. In addition some questions have been raised concerning the possibility of traffic growth in the intervening period. In response to these and other developments it was proposed, in advance of the conversion of the code to Euronorm, to perform some new studies to validate the adequacy of the Eurocode load model. This report presents the results of these studies.

The first stage in the study was a reassessment of the past work. This was considered essential to this report as before attempting to perform simulations with new traffics it is imperative that one should be able to reproduce the results of the original studies. To this end extensive effort was made at the outset to replicate, within reason, the results of the original calibration studies. Having reproduced these results identical simulations were performed using modern data to determine if indeed factors such as traffic growth had influenced the adequacy of the normal load model prescribed by the code. Finally suggestions are made for further research for future revisions of the code.

## **2. Reassessment of Past Work**

In attempting to reproduce the results of past work this study has initially concentrated on the results of simulations performed in Paris using the simulation software CASTOR-LCPC and the original traffic data recorded at Auxerre in 1986. The simulations performed have followed the scheme outlined published in Annex C of the background studies to the calibration of the main loading model (Calgaro, 1994).

### 2.1. Traffic Scenari

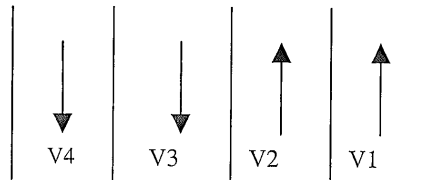
The simulations are performed for both free flowing and hazard (i.e. jammed) scenari as outlined in table 1 and 2 respectively. Where:

V1 refers to traffic effects recorded on the slow lane,

V12 refers to traffic effects simultaneously recorded on both lanes 1 and 2 of the same carriageway ( slow and fast lanes),

V14 refers to traffic effects recorded on two slow lanes 1 and 4 for traffic going in opposite directions,

V1234 refers to the traffic effects of all traffics simultaneously recorded on two carriageways.



**Figure 1.** Schematic representation of measured lanes

No. of Lanes in Bridge	Lane No. 1	Lane No. 2	Lane No. 3	Lane No. 4
1	V1			
2 <sup>1</sup>	V1	V2		
2 <sup>2</sup>	V1	V4		
3	V1	V2	V4	
4	V1	V2	V3	V4

**Table 1.** Type of traffic data used in free flowing simulations

No. of Lanes in Bridge	Lane No. 1	Lane No. 2	Lane No. 3	Lane No. 4
1	V1			
2	V1	V4		
3	-	-	-	
4	V1	V2	V3	V4

**Table 2.** Type of traffic data used in Jammed flow simulations

The traffic jam scenarios were simulated by reducing the inter-vehicle spacing for all vehicles (between subsequent axles) to a standard 5 m. This was chosen as being representative of typical congested or slow-moving traffic conditions in accordance with the original studies.

## 2.2. Influence Surfaces

Identical influence surfaces to those employed in the background studies were used in the simulations. The main longitudinal influence lines are indicated in table 3. In the simulations nine span lengths  $L$  were considered: 5, 10, 20, 30, 50, 75, 100, 150, 200m and four carriageway width  $\ell$ : 3, 6, 9, 12m. In addition to these theoretical influence lines shown in table 3, and in accordance with the background studies an additional influence surface for torsion in a simply supported beam was employed.

Effect	Influence Surface
A) Normal Force	$N(x,y) = 1$ $0 < x < L$ $0 < y < \ell$
B) Bending Moment	$M(x,y) = x/2$ $0 < x < L/2$ $0 < y < \ell$
C) Bending Moment	$M(x,y) = -\frac{x^4}{2L^3} + \frac{x^3}{L^2}$ $0 < x < L/2$ $0 < y < \ell$
D) Bending Moment	$M(x,y) = -\frac{3x^5}{L^4} - \frac{8x^4}{L^3} + \frac{6x^3}{L^2} - x$ $0 < x < L$ $0 < y < \ell$
E) Shear Force	$V(x,y) = x/L$ if $0 < x < L/2$ $V(x,y) = x/L - 1$ if $L/2 < x < L$
F) Torsion	$T(x,y) = (1-x/L)(y-\ell/2)$ $L/2 < x < L$ $\ell/2 < y < \ell$

**Table 3.** Influence lines used in simulation (see table 8)

The simulations were performed using the program CASTOR-LCPC developed at the Laboratoire Central des Ponts et Chaussées. Loads effects were calculated, for the traffic samples described, as the program moved the vehicles along the bridge, lane by lane, preserving the axle loads and spacing as well as the vehicle spacings recorded on site or simulated depending upon the simulation scenario. Level crossing histograms were calculated in real time during the simulations. The histogram is obtained by counting the number of times that the load is recorded exceeding a given value. This is repeated for a complete range of threshold values and the results presented in the form of a histogram. These level crossing histograms are a useful means of extrapolating a load effect to a period longer than the recording period. Level crossing histograms were compiled in this way by the CASTOR-LCPC program for all simulations. Probability density functions were

fitted to the computed load effect histograms and extrapolated using “Rice’s formula” in a procedure which is well known in the field of time varying processes.

### 2.3. Extrapolation

The extrapolation of the all load effects (i.e. both free flowing and jammed) was performed as per the original studies to a return period of 1000 years. This value is determined from equation 1, where a design life  $T = 100$  years and the fractile  $\alpha = 10\%$ .

$$R = R_{y\alpha} \cong \frac{-T}{\text{Ln}(1-\alpha)} \cong \frac{T}{\alpha} \quad [1]$$

### 2.4. Dynamic Amplification

In agreement with the original studies some amplification of the load effects induced by free flowing traffic may be expected due to dynamic interaction between the vehicle and the structure it crosses. Consequently, dynamic amplification factors were applied to the extrapolated load effects as outlined in table 4 and in figure 2. Where:

$E_{stat}$  the static effect of the recorded traffic,

$E_{dyn}$  the calculated dynamic effect of the traffic,

$\varphi_{calib}$  the global dynamic amplification factor resulting from numerical simulations,

$\varphi_{local}$  the complimentary amplification factor related to local effects.

Type of Traffic	Number of Lanes	Length of Influence Line	Dynamic Effect
Congested	1	All Spans	$E_{dyn} = \frac{E_{stat}}{1.10} * 1.10 = E_{stat}$
	2 & 4	All Spans	$E_{dyn} = \frac{E_{stat}}{1.10} * 0.90 = E_{stat}^{\ell}$
Free Flowing	All Lanes	$L > 15$ m	$E_{dyn} = \frac{E_{stat}}{1.10} * \varphi_{calib} = E_{stat}$
	All Lanes	$L \leq 15$ m	$E_{dyn} = \frac{E_{stat}}{1.10} * \varphi_{calib} * \varphi_{local} = E_{stat}$

**Table 4.** Dynamic amplification factors

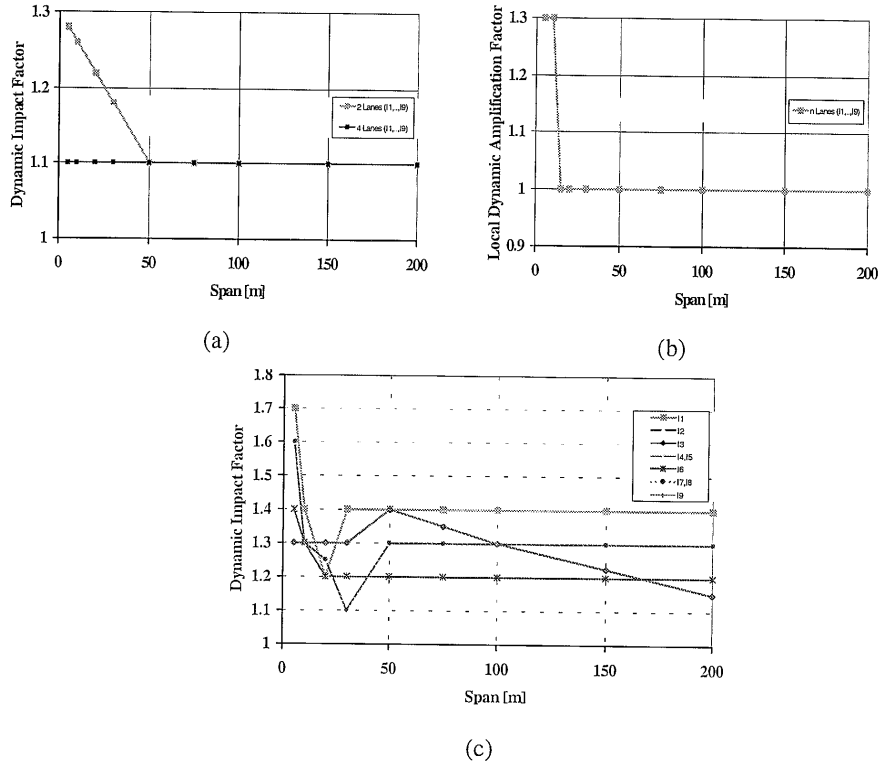


Figure 2. (a)  $\varphi_{calib}$  One Loaded Lane, (b) Two and Four Loaded Lanes, (c) Values of  $\varphi_{local}$

$\varphi_{calib}$  represents the dynamic amplification of the considered effect and is dependent upon the span length and the type of influence surface. The factor was evaluated in the original studies by comparison with the static effect, consequently, the maximum dynamic effect does not necessarily correspond to the maximum static effect.

**2.5. Results**

In the following the results of the simulations outlined in tables 1 and 2 are presented. These simulations were performed using the Auxerre traffic (1986) employed in the original background studies. The simulation and extrapolation procedures outlined in background documents have been followed as closely as

possible in the new simulations. This permits a comparison of the results presented in Annex C (Calgaro, 1994) of the background studies document. However, in some cases details are vague and therefore some objective decisions were made. It is considered important to outline the assumptions made at this point:

(a) As previously stated, the return period for extrapolation was chosen as per the original studies as 1000 years. It was presumed that in each year 50 weeks with traffic similar to that recorded could be expected (i.e. allowing for national holidays, demonstrations etc) as such the 1000 year return period was approximated as 50,000 weeks. It is unclear if a similar assumption was made in the original work, and if so what number of working weeks were presumed per year. It should be noted however that studies by the authors have shown the sensitivity of the extreme to variations in return period decrease with increasing return periods.

(b) In performing simulations using CASTOR-LCPC a 'PAS' or sampling rate for calculation of load effect is required to be specified on input. The PAS rate determines how frequently load effects are calculated for a vehicle train traversing the influence surface. Studies by the authors have shown some sensitivity in the level crossing histogram to the selected PAS rate. No information was available on the PAS rates used in the original studies. In the new studies the rates considered most appropriate to the influence surface shape and length were chosen. Small discrepancies between the predicted extremes in the original and new studies may therefore be expected in some cases.

(c) CASTOR-LCPC requires that the statistical parameters of the Level Crossing histogram be entered for each load effect on input (i.e. the frequency bins for the distribution). Again studies by the authors have demonstrated sensitivity of the extrapolated extreme to the selected frequency bins. This sensitivity may be expected to cause some small discrepancies between the results of the new and old studies.

(d) The new simulations were performed using a new Windows based version of the software CASTOR-LCPC. In addition the extrapolations although performed as in the original studies by fitting the rice function to the level crossing histogram employed a new optimization routine developed in recent times by Dr. Cremona at the LCPC.

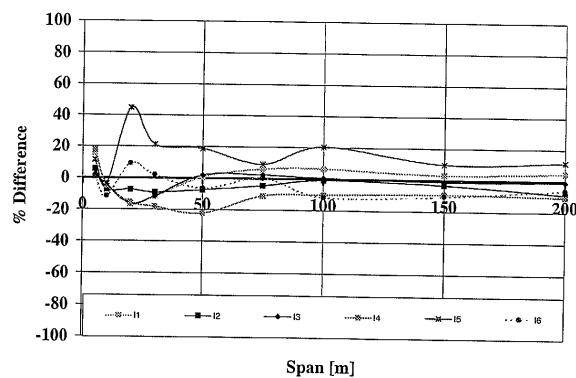


Figure 3. V1 Free Flow

Taking these factors into consideration, some deviation between the results of the new simulations and those of the original work are expected. Figures 3 to 10 present a comparison of the results of new simulations with those performed in the original background studies.

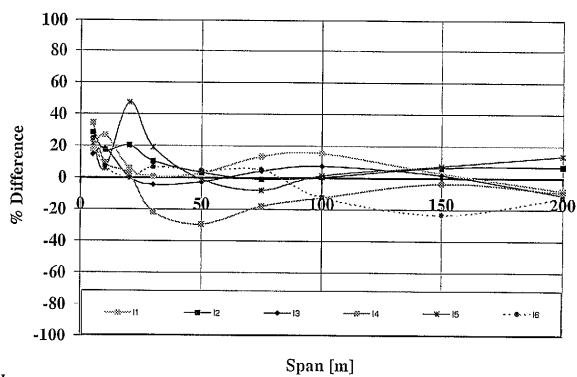


Figure 4. V12 Free Flow

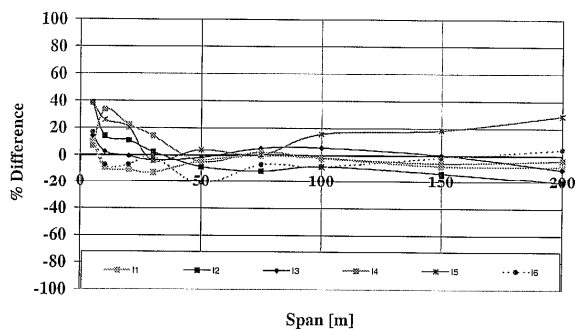


Figure 5. V14 Free Flow

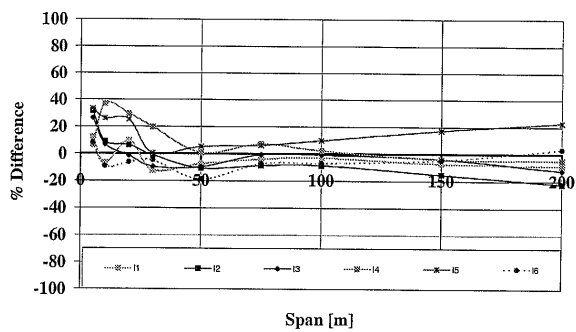


Figure 6. V124 Free Flow

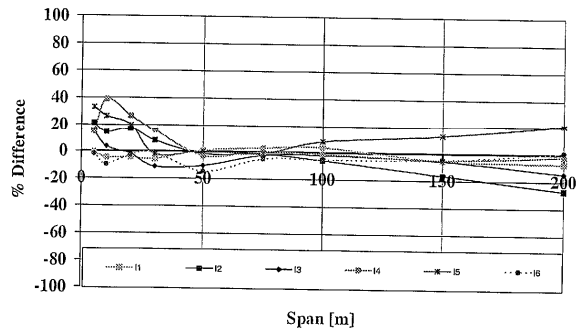


Figure 7. V1234 Free Flow

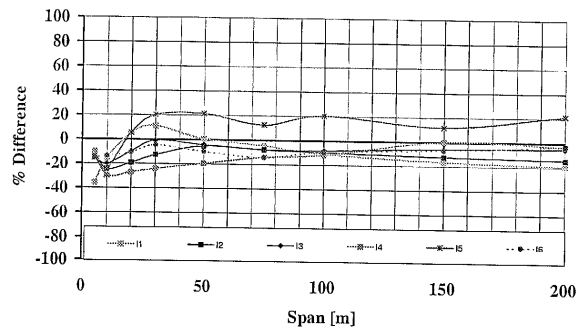


Figure 8. V1 Jammed Flow

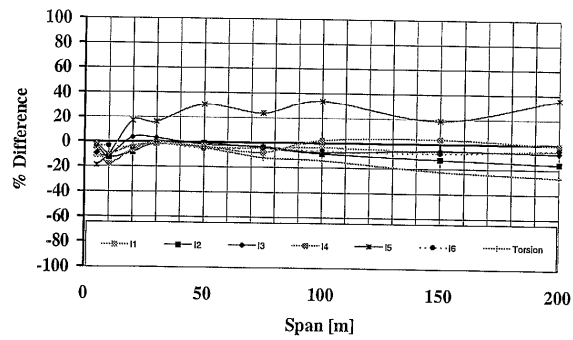


Figure 9. V14 Jammed Flow

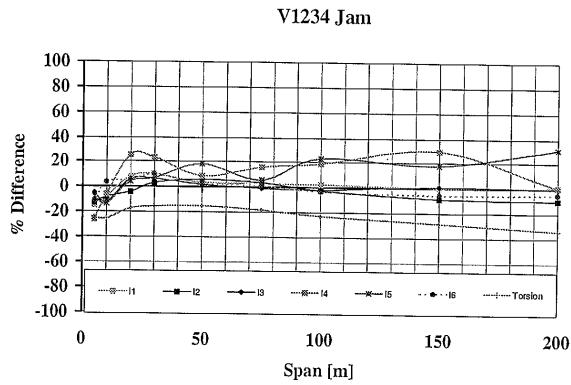


Figure 10. V1234 Jammed Flow

In addition to performing the simulations outlined in tables 1&2 using the Auxerre 1986 data, the simulations have also been performed at this stage using data recorded on the A31 in 1997. This data was used as it comes from a modern WIM site close to the site where the original data was collected on the A6. A comparison of the Gross Vehicle Weight (GVW) distributions of the sites is presented in figure 3. The results of these simulations for each influence surface may be seen in Appendix A. More details of this and the other modern data employed in the new studies will be given in a later section of this report.

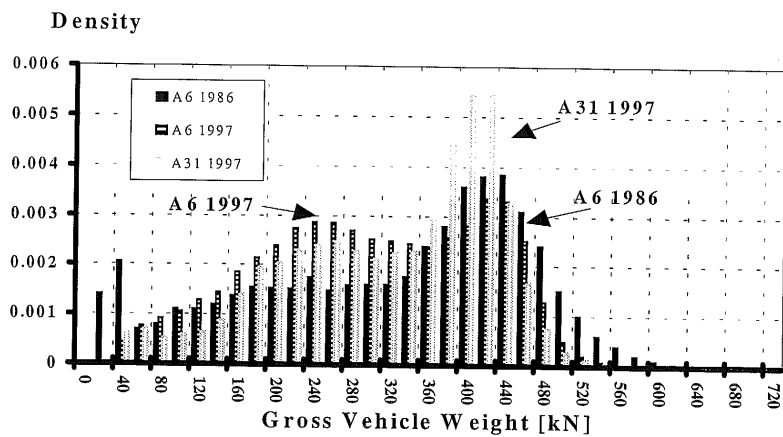


Figure 11. Gross Weight distributions

Clearly, in certain cases significant differences exist between the results of the original and new simulations. As discussed, some deviation was to be expected to perhaps an order of  $\pm 10\%$ . However for certain influence surfaces, differences of 40% are recorded. Analysis of Annex C however would suggest that the traffic as simulated is correct, in that for certain influence surfaces good agreement between the results of the original and new simulations is recorded. It is evident that significant differences exist for influence surface E in particular. It is stated in some background documents that some smoothing of the results of simulations was required, however the mathematical models used are not presented. Perhaps if some smoothing were performed on the results of the new simulations better agreement might be obtained.

### **3. Assessment of LM1 Using Modern Data**

The second stage of this study involved a re-assessment of the target values specified for LM1 in the original calibration studies using modern WIM (weight in motion) data. Significant advances have been made in improving the accuracy of WIM systems in recent years and it was decided to assess the effect that these improvements might have on the target values. In addition it was desirable to assess if changes in traffic patterns might have been experienced in the 10 years since the original calibration studies and if so to quantify if such changes might influence the original target values. As such modern European WIM data was collected from a number of representative sites and used in simulations exactly the same as those employed in the original calibration studies. In addition, once more an attempt was made to replicate the results of the original studies using the Auxerre data. The results of these simulations were compared with the results from the original studies thereby assessing the adequacy of LM1.

#### **3.1. Traffic samples and flow**

The traffic samples obtained, outlined in table 5, consisted of WIM recordings made in France, on the following motorways and national routes :

- motorways A1 and A2 from Paris to Lille and Brussels,
- motorway A31 at Bulgnéville, between Nancy and Dijon carrying the traffic between Benelux and North-West Germany to South-East France, Italy and Spain,
- motorway A6 at Chalon from Paris to Lyon, carrying the traffic of the A31 and from North-West France and the Paris region to South-East France, Italy and Spain,
- main highway RN10 at Trappes, from Paris to Chartres, Tours and Bordeaux.

Site	Year	Lanes		Measured Directions	Date	Recording period (days)	No. trucks	Total flow (trucks/h)
		N	n					
A1	1996	6	4	2	9/9-14/9	6	67482	11935
A1	1997	6	4	2	27/1-30/1	4	48938	
A1	1997	6	4	2	22/10-28/10	7	86455	
A2	1996	4	4	2	9/9-16/9	8	33683	4400
A2	1997	4	4	2	27/1-30/1	4	19149	
A6	1997	6	4	2	20/10-22/10	3	30837	10280
A31	1997	4	4	2	9/10-22/10	14	57106	4080
RN10	1997	4	1	1	17/1-24/1	7	8404	1275 (1 lane)
RN10	1997	4	1	1	19/9-26/9	8	10584	
RN10	1997	4	1	1	3/12-10/12	8	10300	

**Table 5.** Traffic data description (N: number of lanes, n: number of lanes monitored)

For each continuous WIM record, table 2 gives the number of lanes monitored, n, the actual number of lanes at the site, N, the number of measured directions and the total number of recorded trucks. The total observed mean truck flows (i.e., vehicles with gross weight greater than 35kN) are given in Table 2. 1900 to 5000 lorries per day were recorded on the slow lanes, while on the fast lane, these figures dropped to between 100 and 700 vehicles per day, 4 to 8% of the total heavy vehicle flow. In performing simulation and extrapolation to extreme values of load effect, the period of recording is considered sufficient to provide all possible loading patterns to which the structure might be subjected during its design life. Although simulations have been performed for all of the modern traffic obtained, results will be presented here only for the data where at least 1 week was continuously recorded.

### 3.2. Traffic scenarios

Traffic records only give information on normal traffic. It is clear, however, that the most critical situations for long spans appear when the traffic is disturbed while for short spans (i.e. <40 m) or local load effects the heaviest individual axle (or group) or vehicle load is dominant. Therefore, it has been necessary to combine realistic traffic scenarios (arrangements of vehicle, traffic types) such as free flowing and jammed traffic. It is important for subsequent extrapolation to ensure that the duration of each simulated scenario be retained for comparison with respect to its

expected frequency during the lifetime of the bridge. The free flowing and mixed scenarios are detailed in tables 6 & 8 respectively. The scenarios modeled in these re-calibration studies to determine target values are those which were performed originally in Paris.

Number of lanes	Code	Liege	Paris	Pisa	Aachen
1	F1	A6 Slow lane 25% lorries	A6 recorded traffic Slow lane	A6 recorded traffic	A6 Slow lane 100% of lorries V=60-80kmh
2	F2	2*(A6 Slow lane) 25% lorries	2(A6-V1+V2)	1 <sup>st</sup> lane: same as former 2 <sup>nd</sup> lane daily maximum of 1 <sup>st</sup> lane	1 <sup>st</sup> lane Same as former 2 <sup>nd</sup> lane A6 slow lane 32,2% of lorries V=80kmh
3	F3			1 <sup>st</sup> & 2 <sup>nd</sup> lanes: same as former 3 <sup>rd</sup> lane A6 daily maximum of 2 <sup>nd</sup> lane	
4	F4	2(A6-V1+V2) 10% lorries		1 <sup>st</sup> , 2 <sup>nd</sup> & 3 <sup>rd</sup> lanes same as former 4 <sup>th</sup> lane A6 2 <sup>nd</sup> lane daily average	1 <sup>st</sup> & 4 <sup>th</sup> lanes A6 slow lane 32,2% of lorries 2 <sup>nd</sup> & 3 <sup>rd</sup> lanes A6 2 <sup>nd</sup> lane 9,2% of lorries V=10kmh

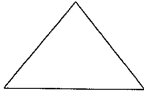

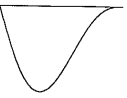
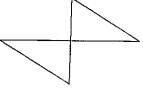
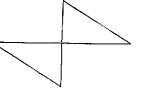
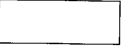
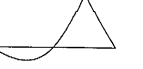
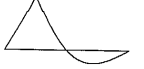
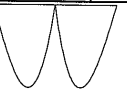
**Table 6.** Free flowing scenarios

Number of lanes	Code	Liege	Paris	Pisa	Aachen
1	C1	Maximum of: -A6 slow lane 100% of lorries d=5m  -A6 traffic jam with 25% of lorries	A6  100% of lorries  d=5m	A6 Slow lane  100% of lorries  d=5m	A6 Slow lane 100% of lorries  V=10-20kmh
2	C2	2*(A6 traffic jam) 25% lorries  d=5m	1 <sup>st</sup> lane: same as 1 <sup>st</sup> one  2 <sup>nd</sup> lane: F1	1 <sup>st</sup> lane: same as 1 <sup>st</sup> one  2 <sup>nd</sup> lane: maximum of: -A6 daily max  -medium traffic jam with cars	
3	C3		1 <sup>st</sup> & 2 <sup>nd</sup> lanes: same as the former ones  3 <sup>rd</sup> lane: F2-F1	1 <sup>st</sup> & 2 <sup>nd</sup> lanes: same as the former ones  3 <sup>rd</sup> lane: A6 slow lane daily maximum	
4	C4	4*(A6 slow lane)  10% of lorries  d=5m	1 <sup>st</sup> , 2 <sup>nd</sup> & 3 <sup>rd</sup> lanes: same as the former ones  4 <sup>th</sup> lane: F2-F1	1 <sup>st</sup> , 2 <sup>nd</sup> & 3 <sup>rd</sup> lanes same as former  4 <sup>th</sup> lane A6 2 <sup>nd</sup> lane daily average	

Table 7. Congested flowing scenarios

### 3.3. Influence Surfaces

Identical influence surfaces to those employed in the background studies were used in the simulations. The main longitudinal influence lines are indicated in table 8. In the simulations nine span lengths were confirmed: 5, 10, 20, 30, 50, 75, 100, 150, 200m. In addition to these theoretical influence lines shown in table 8, although not employed in the original calibration studies the influence surface for torsion in a simply supported beam was also employed.

Influence Line Number	Representation		Description of the Influence Line
I1, I2			Maximum bending moment of a simply supported and double fixed <sup>1</sup> span, respectively.
I3			Maximum bending moment at the support of the former double fixed beam <sup>1</sup> .
I4, I5			Maximum and Minimum shear force at midspan of a simply supported beam
I6			Total Load
I7, I8			Minimum and maximum bending moment at midspan of the first of two spans of a two span continuous beam (the critical span only is loaded).
I9			Continuous support moment of the former two span beam.

1. With an inertia strongly varying between mid-span and the ends

**Table 8.** Influence lines used in simulation (representation)

### 3.4. Extrapolation

Extrapolation of the level crossing histograms was performed as before to a return period of 1000 years presuming 50 working weeks per year. All traffic scenarios were extrapolated.

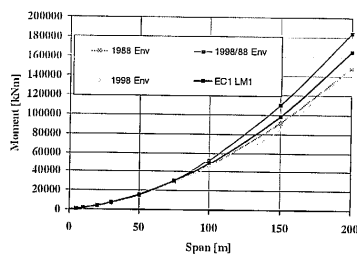
### 3.5. Dynamic Amplification

Dynamic amplification factors specified in 'Calibration Objective Effects for Characteristic Values', Prat 1991, have been employed. Where in the case of mixed (congested/free) flow the amplification factors were applied to the influence surface in the free lane. No dynamic amplification of congested traffic was performed.

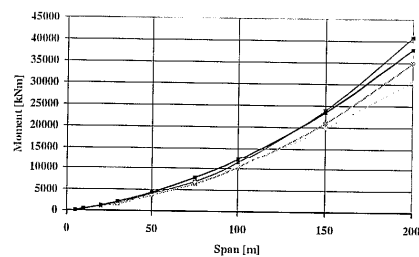
### 3.6. Results

The following results present a comparison between:

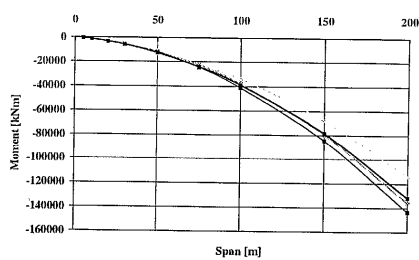
1. the initial target values calculated in the original calibration in 1988 using the Auxerre 86 data in the scenarios outlined in tables 6 & 7;
2. a re-estimate of those target values using the same data and attempting to re-perform the aforementioned scenarios;
3. an envelope of target values calculated using modern WIM data;
4. the design values prescribed by LM1.



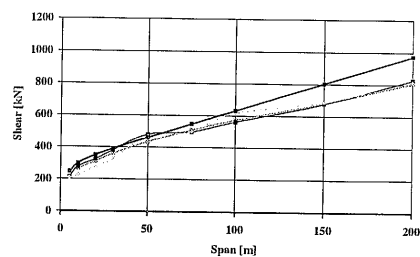
Influence Surface I1



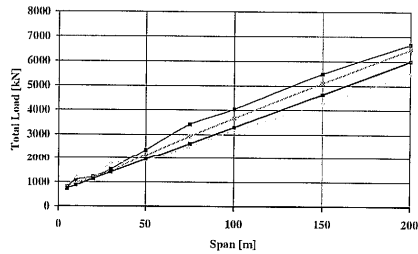
Influence Surface I2



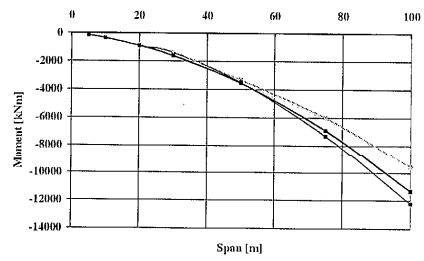
Influence Surface I3



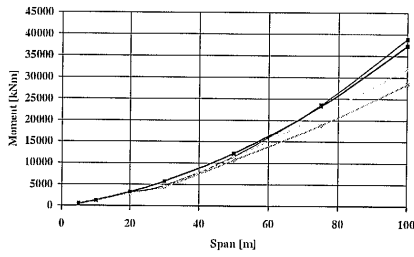
Influence Surface Max(I4,I5)



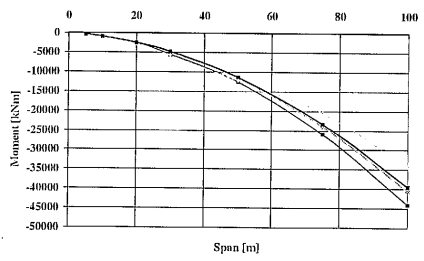
Influence Surface I6



Influence Surface I7

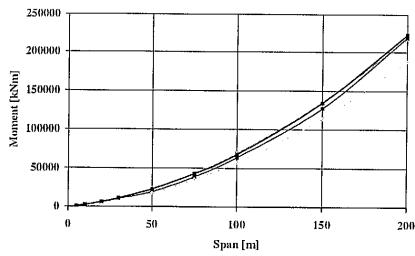


Influence Surface I8

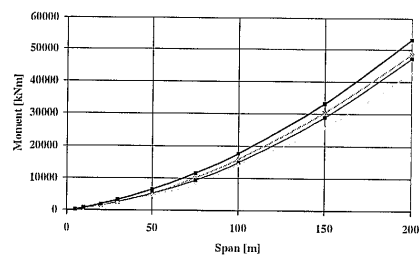


Influence Surface I9

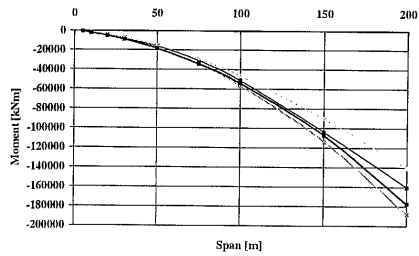
Table 9. Lane 1 (Influence surfaces I1 to I9)



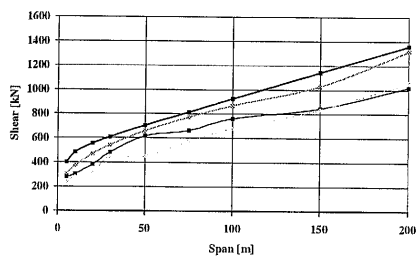
Influence Surface I1



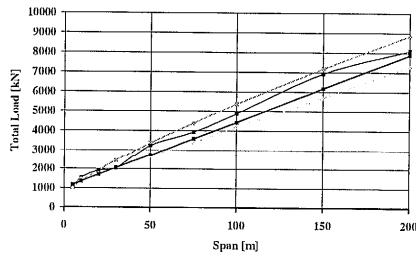
Influence Surface I2



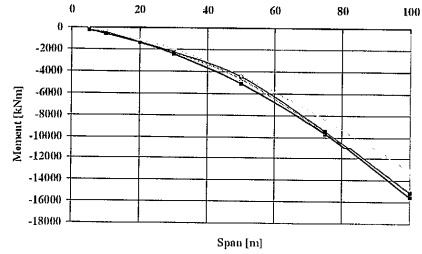
Influence Surface I3



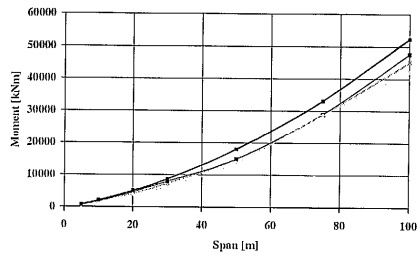
Influence Surface Max(I4,I5)



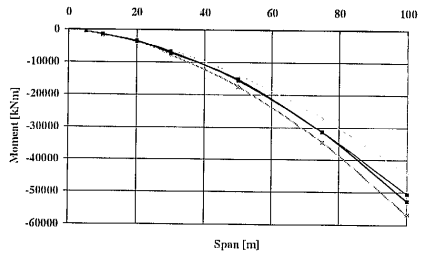
Influence Surface I6



Influence Surface I7

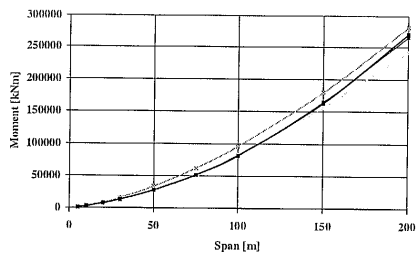


Influence Surface I8

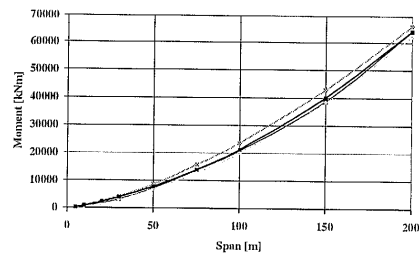


Influence Surface I9

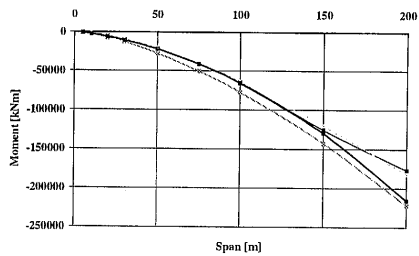
Table 10. Lane 1+2 (Influence surfaces I1 to I9)



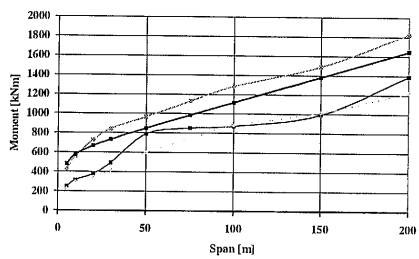
Influence Surface I1



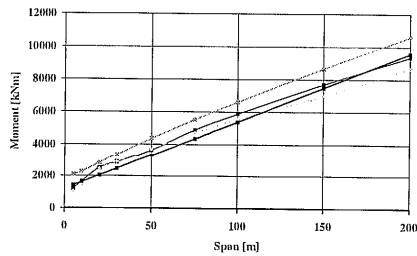
Influence Surface I2



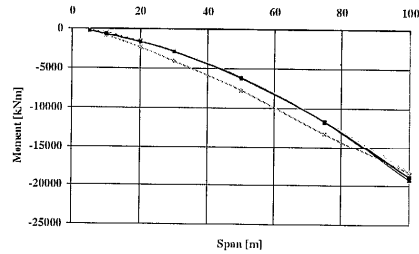
Influence Surface I3



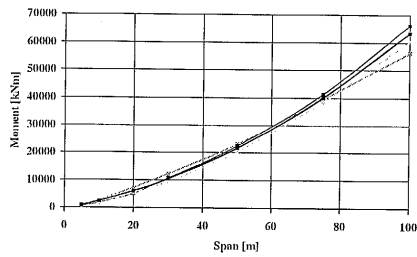
Influence Surface Max(I4,I5)



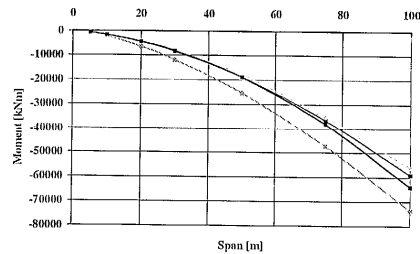
Influence Surface I6



Influence Surface I7



Influence Surface I8



Influence Surface I9

**Table 11.** Lane 1+2+3+4 (Influence surfaces I1 to I9)

It is clear from the results of these simulations (tables 9, 10, 11) that the LM1 is sufficient for modern traffic. It should be noted that the comparison has been made with LM1 using the results of the simulation regime proposed in Paris in tables 6&7. However LM1 was calibrated against mean values from all simulations. The difference between the results of simulations using 1988 results and data and for modern data is significant. Further analysis of this difference for each traffic, may suggest that it would be appropriate to eliminate the need to divide the results of simulation by a factor 1,1 to allow for inherent dynamic effects. The factor is clearly inappropriate where using modern WIM data. The full results of simulations with modern WIM data are presented in Annex B.

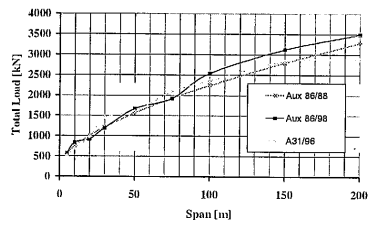
#### 4. References

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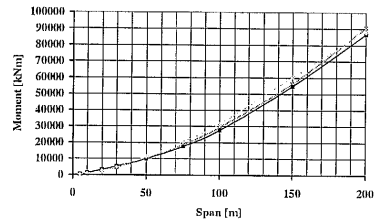
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**Annex A. Comparison of attempted reproduction of results from simulations performed in background studies with Auxerre 1986 data**

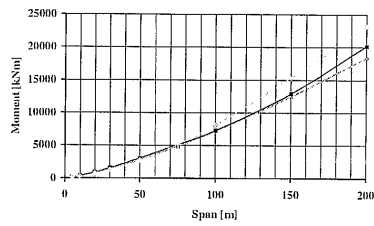
**V1 FREE FLOWING**



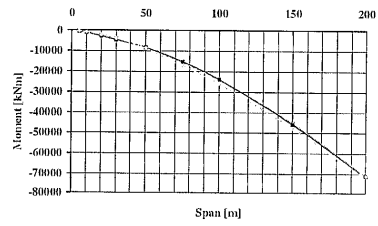
Influence Surface A



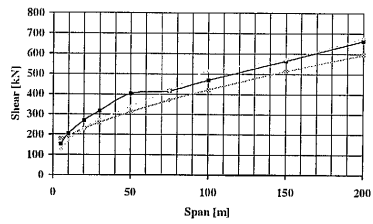
Influence Surface B



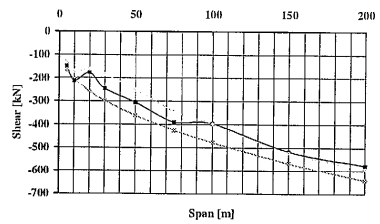
Influence Surface C



Influence Surface D



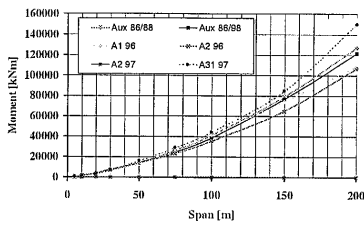
Influence Surface E (>0)



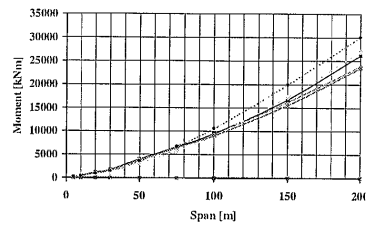
Influence Surface E (<0)

**Annex B. Reproduction of EC1 simulation results (Paris) using Auxerre 1986 data. Results of similar simulations performed with modern WIM data**

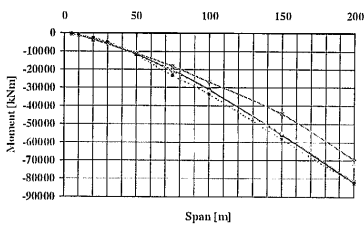
FREE 1 (F1)



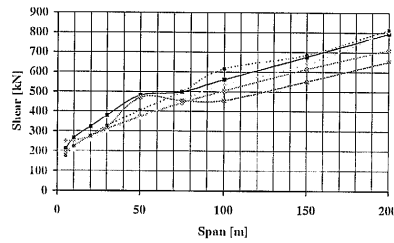
Influence Surface I1



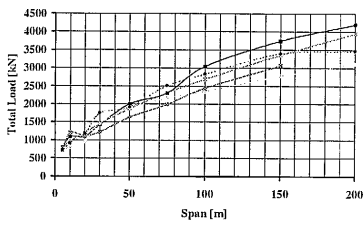
Influence Surface I2



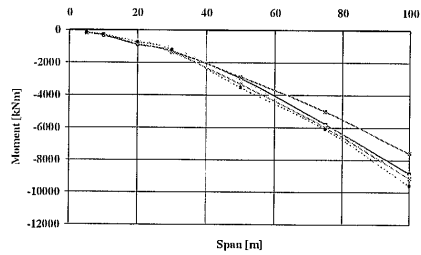
Influence Surface I3



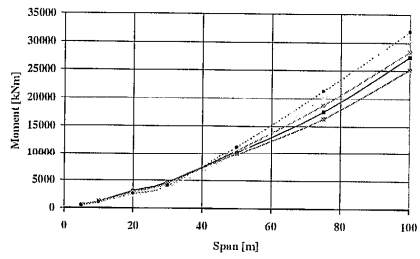
Influence Surface I4



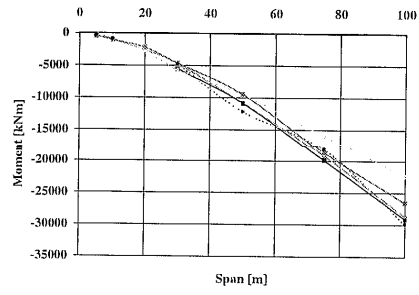
Influence Surface I6



Influence Surface I7



Influence Surface I8



Influence Surface I9

