The use of a capacitative mat for dynamic weighing of vehicles in normal traffic

A. DE HENAU, BSc, Belgian Road Research Centre

A methodology was developed for the analysis of dynamic road loads using a capacitive weigh-in-motion mat with two inductive loops installed on the road surface in less than 25 min. The dynamic impact caused by this obstacle was assessed by means of a theoretical model. Load spectra were found per type of road. The possible effects of decisions as to vehicle weights and dimensions on traffic aggressivity were demonstrated. They are not always as intended.

1. Introduction

A knowledge of the spectrum of loads applied to a country's road network is important not only to solve problems of an economic nature, but also with a view to managing and developing the asset represented by that network. The accuracy to which the spectrum needs to be known depends on the problems to be solved.

The road manager has to assess the cumulative rate of damage to the road structure under the repetitive impact of traffic loads already carried.
The designer of new roads, overlays and engineering structures has to estimate the loads that will travel during the life which he has chosen for the facility.
These concepts are expressed in terms of traffic aggressivity.

All countries have legal limits for vehicle, axle or even wheel loads transported on their public roads.
The reference loads are measured statically by means of horizontal weighbridges on which the vehicles are stopped.
Check weighings disturb traffic and generally do not yield representative samples of vehicles.
To date no "weigh-in-motion" or "dynamic" system (weighing vehicles travelling at normal speed) has been capable of attaining the physical magnitude defined by :

$$P(N) = M(kg) \ x \ 9.81(m/s^2)$$

Two effects are involved :
- the inertia of the moving parts of the weighing sensor,
- the dynamic actions of the moving vehicle.

The first can be minimized by using modern equipment incorporating sensitive piezoelectric or capacitive elements.
The second depends on vehicle characteristics and motion and on road surface irregularities, which generate random accelerations.

From the point of view of road mechanics, the load applied to the structure is a dynamic load, $P_{(t)}$, having an instantaneous value which varies about the static load, P_s. The average value of $P_{(t)}$ along the journey of the vehicle tends towards the value P_s.
As for the structural behaviour of the road, cumulative damage is caused by the average value of $P_{(t)}$ calculated over a distance reduced to the area of influence of the load at the point being considered.
To convince oneself of this fact, it is enough to consider a few typical surface irregularities such as bridge expansion joints, joints between cement concrete slabs, construction joints, manhole covers and gutters, which give rise to undisputed dynamic action. The loads to be taken into account when assessing cumulative damage to the road structure in such places are bound to be different from the static weight, P_s.

However, what is most important to road network managers or developers is a knowledge of the statistical distribution of the loads that have acted, or will act, on structures, i.e. the "spectrum" of loads.
In this respect, the distribution of dynamic loads applied to roads must be considered.

2. The spectrum of loads

In road construction (ref. 1 and 2) the spectrum of loads acting, or expected to act, at a given point of a pavement surface is an indication, for that point, of the probability of finding in a given traffic a load, P_i, which comes into a preselected interval.
This is expressed in practice by the ratio :

$$f_i = \frac{n_i}{N} \qquad (1)$$

where :

n_i is the number of P_i loads in N transient loads at the point being considered.

The aggressivity of traffic N is expressed by relating the cumulative structural damage caused by the passage of a P_i load to that resulting from $(P_i/P_r)^n$ passages of a selected reference load, P_r, and summing the numbers thus calculated for the whole spectrum :

$$C = \Sigma \ [f_i \ x \ (\frac{P_i}{P_r})^n] \qquad (2)$$

Exponent n represents the type of damage considered and depends on the selected reference load, P_r.
For an 8 tonne axle under which the tyre/road contact areas each have the form of a circle with a radius of 0.1 m, it may be considered that n = 4 for fatigue cracking or permanent deformation in flexible pavements.
If the load spectrum is affected by a dynamic component, the relation becomes :

$$C = \Sigma [f_i \times Ic^n (\frac{P_i}{P_r})^n] \quad (3)$$

Expressions (2) and (3) show the marginal influence of loads smaller than the reference load and, on the other hand, the preponderance of the heavier loads, as well as the influence of the impact factor, I_c, at power n. It will be seen hereafter that this impact factor decreases as load increases.

3. The impact effect of rolling loads

The instantaneous load, $P_{(t)}$, applied by a moving wheel at a given point of a road surface can be expressed as the sum of two terms :
- one is the static weight, P_s (standing wheel) ;
- the other is the dynamic component, $P_{d(t)}$, which varies about 0 and has an average value tending to 0 along any given journey. This can be represented as follows :

$$P_{(t)} = P_s + P_{d(t)} \quad (4)$$

It is customary to define the "impact factor", I_c, as the following quantity :

$$I_c = \frac{P_{(t)}}{P_s} = (1 + \frac{P_d}{P_s}) \quad (5)$$

where
P_d = dynamic load component $P_{d(t)}$ at a given time (t) with an average value equal to zero.

Several theoretical models (ref. 3, 4, 5) have been developed to simulate the dynamic reactions of different types of axle : single, tandem or triple fitted with wheels having tyres and suspensions of varied characteristics and carrying various sprung masses.
These models enable the impact factor to be estimated when known obstacles are passed over by vehicles of given characteristics travelling at a given speed.

Thus it can be demonstrated that :
I_c increases
- with obstacle height,
- with vehicle speed and
- with tyre stiffness ;
I_c decreases
- as the gross weight increases and
- as the ratio between sprung and unsprung masses increases.

Some of these theoretical findings are illustrated by the examples presented in Fig. 1, 2 and 3.

Various experimenters (ref. 5, 6, 7) have confirmed these results. Direct measurements on vehicles and instrumented roads remain, however, very delicate.

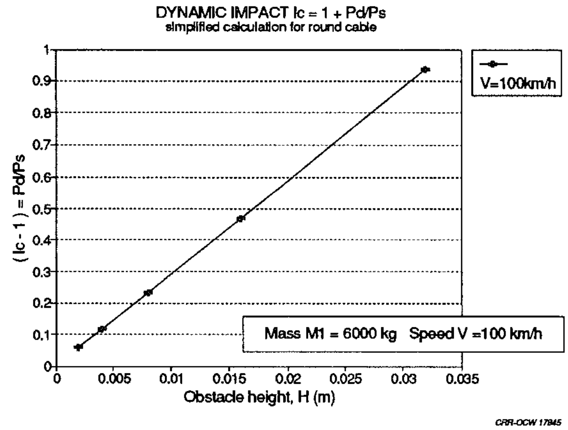

Fig. 1 Theoretical effect of obstacle height on I_c

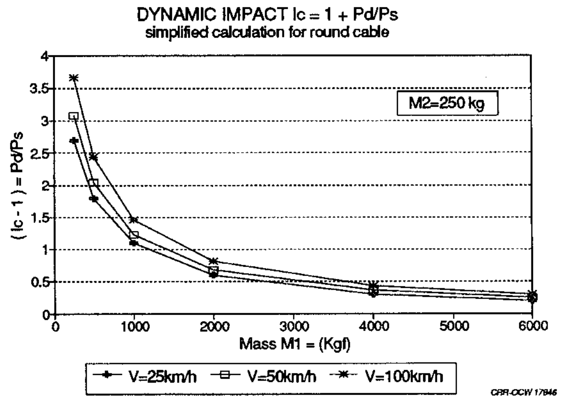

Fig. 2 Theoretical effect of speed at the passage over an obstacle, for different sprung masses

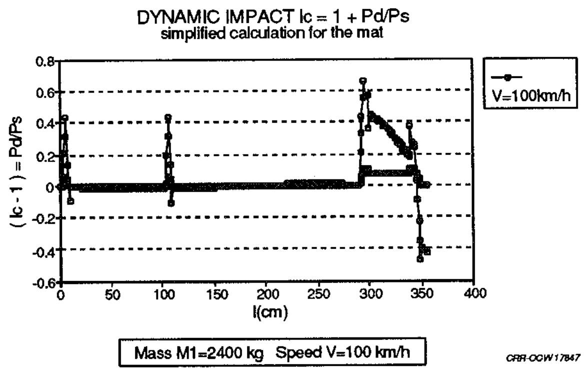

Fig. 3 Theoretical impact effect of the loops and the capacitive mat installed on the pavement surface

4. Measurements of the spectrum of dynamic loads

The Belgian Road Research Centre has examined the possibilities of using a capacitive weigh-in-motion mat to define the load spectra to be considered in flexible and semi-rigid pavement design and strengthening (ref. 1, 2).

The mat is fixed on the road surface during the measurement, together with two inductive loops (Fig. 4). It is connected with a data logger which stores the measurements at the passage of each vehicle axle travelling at normal speed.

Fig. 4. Capacitive weigh-in-motion mat installed on a road surface

The mat is 0.5 m wide, 1.8 m long and 0.008 m thick.

When installed on the surface, it causes an impact that can be assessed theoretically and experimentally (ref. 4, 7, 9).
Obstacles not higher than 10 mm have been shown to produce similar effects as road surface irregularities under normal dynamic traffic loading.
Nevertheless, the equipment is provided with a correction system to adjust the measurements to the characteristics of a reference vehicle integrated with the traffic.
Several series of measurements were made with this mobile equipment, on motorways as well as on regional and municipal roads.

5. Calibration of the weigh-in-motion mat

The capacitive mat for "dynamic" weighing forms an obstacle 0.008 m high and 0.5 m long to the passage of the right-hand wheels of moving vehicles.
The impact effect of this obstacle is additional to the random dynamic component resulting from road surface irregularities and vehicle motion characteristics.
The calibration procedure suggested by the manufacturer aims at empirically determining correction factors to be fed into the TDL 500 data logger in order to find back the static weight of recorded axles.
For this determination a vehicle of known characteristics is run a number of times over the mat installed on site. The factors thus found are applied indiscriminately to all weighings performed.
However, the relevant quantity to road construction engineers is the instantaneous load, $P_{(t)}$, applied by a wheel at a given point of the road surface. That is why attention should be focussed on dynamic rather than static loads.

6. Measurements with the mat out of traffic

With the equipment installed on a motorway pavement not yet opened to traffic, an analysis was made of the responses to successive passages of a tanker having two axles with an allowable mass of 10 t. The object was to show the effect of speed on the impact factor, $I_c = P_{(t)}/P_s$, under various load conditions.
Table 1 below gives an example of results obtained (average values of ten runs for each level) as compared to the theoretical assessment obtained by modelling the lorry and the obstacle.

It can be seen that the theoretical predictions (rear axle) agree well with the measurements for speeds usually encountered on motorways.
This clearly reflects the dynamic effect of an obstacle : at low speeds, the impact effect of the obstacle is outweighed by the random effects produced by surface irregularities, whereas at high speeds it is predominant.

7. Measurements with the mat under traffic

On a motorway in service, vehicles of different types were diverted from traffic and weighed statically before they were allowed to continue their journey.
Once back in traffic, they were recorded when passing at normal speed over the weigh-in-motion mat.

A total of 115 axles having a statically determined mass M_s and belonging to type C2, C3, S22, S23 and S33 goods vehicles - see Fig. 5 - were thus recorded passing over the mat at speeds ranging between 40 and 100 km/h ; it was demonstrated that I_c decreased as static axle load increased - see Fig. 6 -, thus confirming a theoretical result reported above. The following was found without correction applied to the mat :

$$I_c = 5.3 - 1.8 \times \ln(M_s) \qquad (7)$$

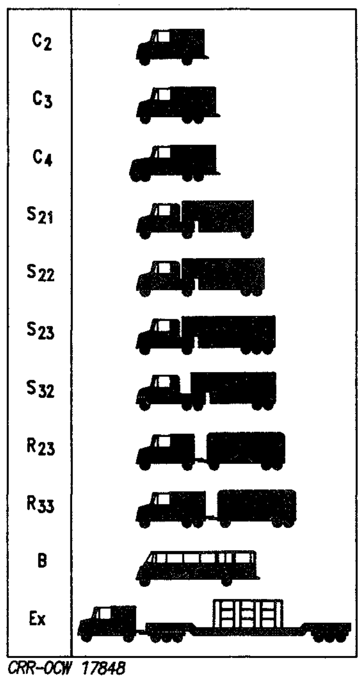

Fig. 5. Classification of goods vehicles

Table 1. Assessment of impact factor I_c with a reference lorry out of traffic

P_s axle	20 km/h	25 km/h	40 km/h	45 km/h	85 km/h	90 km/h
front 3.2 t	1.2	1.4	1.3	1.4	1.4	1.6
rear 7.2 t	1.3	1.4	1.4	1.5	1.5	1.6
model for 7.2 t	1	1	1.2	1.2	1.5	1.6

With an average mass M_s = 5.6 t found for the above set of weighed axles the calculation results in I_c = 2.2.

The application of the simplified model to the reference lorry with a 5.6 t axle passing at a speed of 100 km/h over the obstacle formed by the mat leads to I_c = 1.7 (see Fig. 7).

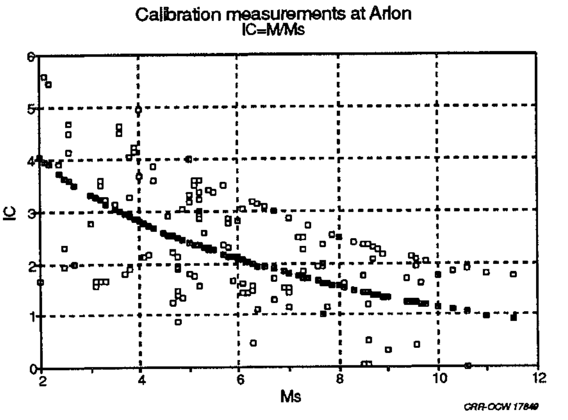

Fig. 6. Measured values of impact factor I_c against axle load

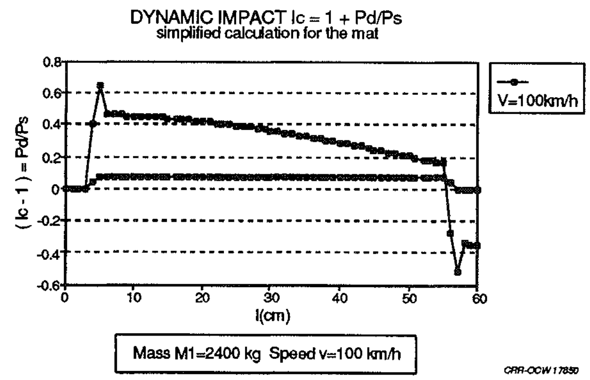

Fig. 7. Impact effect of the capacitive mat assessed from a theoretical vehicle model

From the foregoing it may be concluded that the dynamic effect caused by random movements of the vehicle on the road surface is the difference between these two values (2.2 - 1.7 = 0.5).

A correction factor, defined by the manufacturer of TDL 500 as the ratio between measured static and dynamic mass, i.e. $1/I_c$ = 2, would then be introduced, and the normal dynamic loads applied by the wheels to the road pavement would be stored in memory.
This procedure was used throughout the various series of measurements on motorways as well as on regional and local roads, with a view to determining load spectra that can be used in pavement design.

8. Observed load spectra

By proceeding as described above, load spectra were found on various types of road.
A few examples of load spectra observed before new legal limits for axle load came into force are presented in Table 2, page 5 where the aggressivity has been calculated for each spectrum using relation (2) with n = 4.

This table 2 shows that the load spectra to be considered for the various networks differ in specific aggressivity (see Fig. 8).

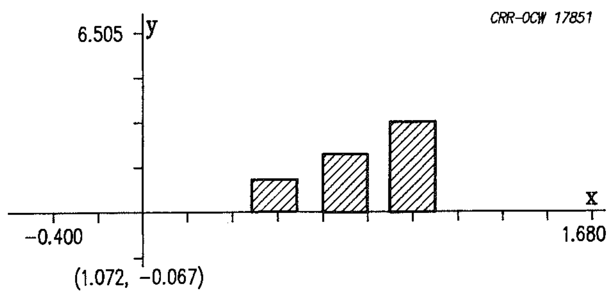

Fig. 8. Aggressivity of load spectra on rural, regional and motorway networks

The average developments in the spectrum of loads on Belgian roads and motorways over a period of more than 25 years are presented in Fig. 9.
It can be seen that the reduction in axle load recommended by European authorities has had the effect of diminishing overloads with respect to the 12.5 t legal limit, but also of

Table 2. Examples of load spectra

Class (t)	Motorways	C (*)	Regional roads	C (*)	Rural roads	C (*)
0.5						
1.5	30.3	0.0004	54.0	0.001	29.66	0.0004
2.5	15.0	0.001	11.4	0.001	11.48	0.001
3.5	10.0	0.004	8.6	0.003	13.68	0.005
4.5	9.7	0.010	7.1	0.007	14.78	0.015
5.5	9.3	0.021	5.8	0.013	8.36	0.019
6.5	6.1	0.027	4.3	0.019	3.40	0.015
7.5	6.4	0.049	2.7	0.021	4.59	0.020
8.5	3.2	0.041	1.7	0.022	5.05	0.065
9.5	2.0	0.040	1.0	0.020	4.13	0.052
10.5	2.0	0.059	0.5	0.015	2.66	0.080
11.5	1.9	0.081	0.5	0.021	1.47	0.064
12.5	1.0	0.060	0.5	0.030	0.73	0.042
13.5	1.3	0.105	0.5	0.041	-	
14.5	0.6	0.065	0.1	0.011	-	
15.5	0.2	0.028	0.1	0.014	-	
16.5	0.2	0.036	0.1	0.018	-	
17.5	-	-	-	-	-	
18.5	0.2	0.057	-	-	-	
19.5	0.6	0.212	1.1	0.388	-	
20.5	-		-	-	-	
21.5	-		-	-	-	
Σ	100.0	0.90	100.0	0.64	100.0	0.38

(*) Formula No.

increasing the frequency of heavy axles.
This has resulted in a greater aggressivity of traffic ! C increased from 0.64 in 1965 to 0.80 in 1991, which is certainly not what the authorities intended to achieve.
In addition, the average number of axles per goods vehicle increased from 2.7 to 4 over the same period. This calls for an adaptation of the design charts used in pavement design and strengthening methods.

This example clearly illustrates the effect of vehicle weights and dimensions on road pavement design and management (ref. 1 and 2).

By way of conclusion, it may be emphasized that decisions on vehicle weights and dimensions can be counter-productive if they are taken without assessing their actual effects on road structures.
It has also been shown that means must be available to monitor developments in the spectrum of loads on roads.

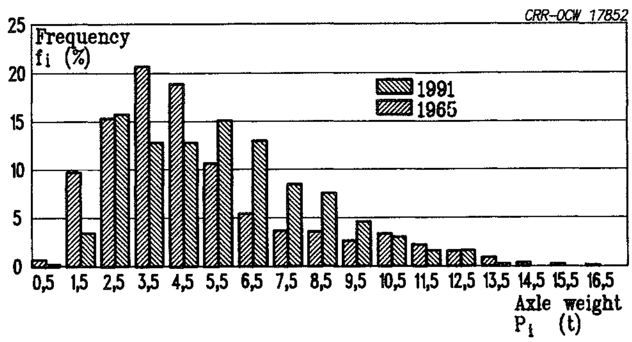

Fig. 9 Developments in the load spectrum on Belgian roads between 1965 and 1991

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