

# WIM and dynamic loading on pavements

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The axle load of a heavy freight vehicle is not constant but varies at each point because of the dynamic effects of a vehicle and its suspension and the roughness of the road. Weight-in-motion (WIM) measures the axle load in one point. The effect of dynamic loadings on WIM is discussed in this paper.

## 1. INTRODUCTION

The accuracy of WIMs depends on the WIM itself and on the dynamic axle loads. The axle loads are not constant but because of the roughness of the road the real axle load is oscillating around the static axle load. The dynamic axle loads depend on the roughness of the road and on the vehicle, especially on its suspensions. Usually only the accuracy of the WIM itself has been studied and the effects of dynamic axle loads have been neglected. Its effect has been tried to minimise in certain few cases by using multiple WIMs in a row.

Axle loads may vary +/- 15 percent on good roads (it means that eg if the static load is 10 ton the real dynamic axle load may be any value between 8.5 and 11.5 tons). It is known that the same vehicle at the same speed causes highest dynamic axle loads at the same point of the road (spatial concentration) but little is known about the effects of the whole vehicle fleet. These dynamic effects can be avoided to certain degree with multiple sensors but very little research work has been done in this area.

The dynamic axle load effects for WIM can be studied with computer simulation and with dynamic axle load measurements in a vehicle.

## 2. COMPUTER SIMULATION

The computer simulation was made with ADAMS (Automatic Dynamic Analysis of Mechanical Systems) which is a commercially available multibody system analysis software. Today it is the most widely used software package of its kind. ADAMS is used in a large variety of industrial applications throughout the world, automotive, aerospace, general machinery etc.

ADAMS offers an extendable library of modelling elements. The elements are very general, so they do not restrict the type of mechanism being modeled. In fact they are kind of basic building blocks of dynamics i.e. forces, parts, joints. By selecting and combining these elements, the user can build up a dynamic model in the required level of detail. Because most of the ADAMS elements match very closely to their counterparts in the real world, the model

is, indeed, defined by imputing the real physical properties of the system.

In this study the dynamic loads on pavement were studied using computer simulations. The original truck model was created in cooperation with the manufacturer, Oy Sisu-Auto Ab, which is specialized on heavy transport equipment under extreme driving conditions. The model was first used in ride comfort analysis. This presentation concentrates on dynamic axle loads, especially by varying the number of axles, spring types, damping and speed of the truck, the repeatability of road-vehicle interaction forces on different road profiles were examined.

Originally a four-axle truck was chosen to be studied, because of its complex dynamic behaviour. There are also three-axle trucks available quite similar to the one being studied. The four-axle versions are used in heavy duty and they are common especially in lumber transportation in Finland. The equipment of a truck varies very much depending on the intended usage of it. For the truck model the equipments needed to carry logs was chosen in order to represent typical use of such a truck in Finland.

In this truck the first two axles steer and there are single tyres on them. On the both axles of the bogie there are twin tyres, so altogether the truck has 12 tyres. The first axle is suspended by parabolic leaf springs, the second by air springs and on the bogie there are two multileaf springs. The two rear axles are kinematically coupled by swing arms, so that one multileaf spring on each side of the bogie can suspend both of the axles. The second and the fourth axle can be lifted off the ground in order to save fuel and tyres, when the truck is driven without load.

The original four-axle truck model was created in cooperation with the manufacturer to be used in studying the ride comfort. In Fig. 1 a side view of the model is shown. It consists of 35 inertial masses, which are connected to each other with kinematical joints and nonlinear force elements. Each joint reduces the amount of active degrees of freedom in the

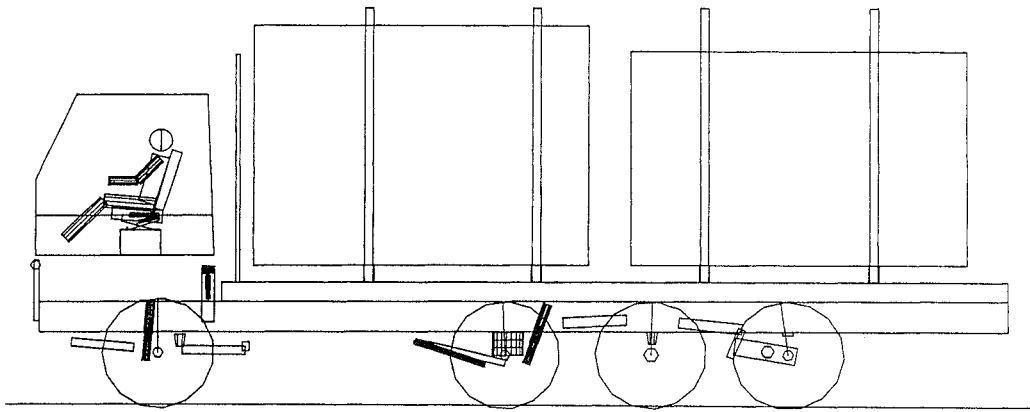


Fig. 1. The side view of the truck model.

model. After adding the kinematic couplings there are still 32 of them left. Altogether the model forms a set of 1166 differential-algebraic equations, which are solved iteratively by ADAMS. The other models used in this study were derived from the original one by varying chassis characteristics such as number of axles, spring types and shock absorbers.

The geometry and kinematics of different parts were derived from drawings. The mass and inertial properties needed were measured as far as possible. For complex structures, as the frame, the inertial data were calculated by dividing them in smaller pieces. The properties of each piece were found by using a separate computer program, after which they were put together to represent the whole structure.

The characteristics of shock absorbers, rubber mountings and bump stops, tyres and springs are based on the data derived from the manufacturer in question. Most of those dynamic properties, which were not directly available, were measured during the project. Some data, which was difficult to achieve through measurements, had to be approximated. Every approximated value was first carefully considered to have a minor effect to the dynamic behaviour of the whole truck.

The three road profiles studied were measured by the Road Surface Monitoring Vehicle fabricated by Technical Research Centre (VTT). It measures the profiles by accelerometers and

lasers and thus the wavelength is limited approximately to 30 metres.

The first, called Road 6, represents a rather good highway (IRI value 1.52). Its profile consist of long waves and there are not very severe local unevenness. The Road 7 (IRI value 2.40) includes much more short radical changes in its profile, especially in the end part of it. The third profile used, Road 8 (IRI value 1.89), the first 100 metres is the worst part (IRI value 2.73) used in this study. Unfortunately even the Road 8 is not an extreme example of existing roads, because most of the measurements have taken place on national highways.

The lengths of the Roads 6 and 7 were about 100 metres and the Road 8 about 200 metres.

The dynamic properties of only one truck was available. It was realistic, however, to take off one axle and the second type was available. The parabolic springs could be replaced by realistic multileaf springs. Because the number of trucks was very limited three different speeds (70, 80 and 90 km/h) were used especially for the studies concerning the spatial concentration of dynamic axle loads. The legal speed limit for trucks, 80 km/h, was chosen to be the most frequently used speed. In this study the other speeds were used only with one model version on two different road profiles. The combinations are shown in Table 1.

Table 1. Simulated combinations. 4L = four axle leaf spring, 4P = four axle parabolic spring, 3P = three axle parabolic spring.

ROAD	Suspension type								
	4 L			4 P			3 P		
	Speed km/h			Speed km/h			Speed km/h		
	70	80	90	70	80	90	70	80	90
6		*		*	X	*		X	
7		*			*			*	
8				*	*	*			

X = with three shock absorbers

The simulations were run on Sun 4/390 - workstation. CPU-time used for a 100 metre simulation with 200 output steps per second was 1-1.5 hours depending on the speed and the model version. The total number of time steps during the simulation varied between 1000-1500 and the number of cumulative corrector iterations needed were roughly 4000.

Fig. 2 shows dynamic axle loads of the front axle as a function of the road station at three speeds and the longitudinal profile of the road (note, wavelengths over 30 metres are neglected). The small frequency due to the pitch of the truck body dominates and the higher frequency from the axle bounce is much smaller. All the frequencies are in the same phase in the beginning because the road before the beginning of the simulation is perfectly smooth and it takes some time before the truck body begins to oscillate. From about 40 metres the dynamic axle loads begin to separate as a function of the space but not in time (the frequency is the same). A stronger unevenness at 75 metres is in pitch phase and gets the dynamic loads in about the same phase. This happens even the IRI-value is only 1.52.

The dominating frequency in Fig. 3 (the driving bogie axle on the same Road 6) is higher because it is due to the bounce of the axle and not to the pitch of the truck body. However, the phenomenon is the same, the dynamic axle loads separate in the beginning but a single, a slightly greater unevenness gets them back into the same phase.

Fig. 4 presents the front axle on the Road 8 which is rougher (IRI 2.73) and consequently greater dynamic axle loads exist. It is possible to distinguish both lower frequencies due to truck body pitch and higher frequencies from axle bounce. Higher frequencies are more important than those in Fig. 2. The dynamic axle loads at different speeds begins to separate but a sharp and short unevenness gets them in the same phase. The spatial repeatability is perfect at the 40 - 60 metres but then begins to separate. At 90 metres the forces get once again in the same phase.

The dynamic axle loads of the driving axle in the bogie (Fig. 5) shows similar behaviour but the repeatability is clearly stronger.

The axles 2 (the second axle) and 4 (the carrying axle in the bogie) behaved like the axle 3 (driving axle in the bogie).

The effect of the road roughness and the speed can be seen in Figs. 6 (Road 6) and 7 (Road 8). The Dynamic Load Coefficients (DLC = standard deviations of dynamic axle loads divided by the mean dynamic axle load) vary between 0.03 and 0.11.

The DLC of the front axle on the Road 6 is relatively high because of the pitch but because there are only few smaller unevennesses the DLCs of the tridem axle are small. The small, sharp unevenness increase all DLC values but because the pitch is smaller the DLC of the front axle is even smaller than that on the Road 6.

The DLC of the air suspension is relatively better on the Road 8 which is more uneven.

As the speed increases, the DLC increases linearly.

The three-axle version of the vehicle behaved exactly like the four-axle vehicle and thus it is not handled here.

The basic idea of the use of simulation was to find the effect of dynamic loading and its repeatability in order to estimate the errors due to dynamic axle loads and to find criteria for optimum place for WIM.

The relative dynamic axle loads of the driving axle on Road 6 are presented in Fig. 6 (total axle loads in Fig. 3). Limits for +/- 3 percents has been drawn in the Fig. 8. The longitudinal profile between stations 30 and 80 has been drawn in Fig. 9 for further analysis. The dynamic axle loads are presented as earlier, all three speeds separately and added the difference between the dynamic loads of 70 km/h and 90 km/h (bold line).

Those parts of the Road where the dynamic load differs less than three percent are marked in the lower part of the figure, separate marks for each speed and the combination of them. WIM should be installed in place where all three speeds are marked which is marked as the "combination".

The road is relatively smooth between 30 and 40 metres and even the axle loads begin to separate most of the part is acceptable for WIM. Second good point is after 40 metres which is still acceptable because the top of the "hill" is smooth and its radius great. The rough area between 50 and 70 metres is not acceptable even it is not very rough.

The smooth part of the road could be surprisingly short if the road is relatively smooth everywhere.

Only very few profiles have been analyzed. General rules have not been found yet.

### 3. MEASUREMENTS

Technical Research Centre (VTT) has measured dynamic axle loads with strain gauges glued to the axle. Inertial effects can be corrected by accelerometers. The calibration has been only static but it is estimated that the errors in dynamic axle loads are less than +/- 10 percent if corrections from accelerometers are used. Thus it is not possible to make any exact comparisons between measured values in the vehicle and those from the WIM. The phases are, however, correct and if various speeds and several vehicles are used the effect of spatial distribution can be estimated and the results from the simulation validated to certain degree.

The following research was planned in 1991 but the financing was delayed. It will be carried out during summer season 1992 and more detailed plans will be made in near future.

One instrumented vehicle will be taken in the first phase, the dynamic axle loads will be measured and the exact moment as the vehicle The signal from the electric eye is exact and the place of the dynamic axle load can be exactly determined (Fig. 10). passes WIM will be monitored with electric eye. Various speeds as well as loads will be used on several WIMs. The profiles will be measured. In the second phase more instrumented vehicles will be used.

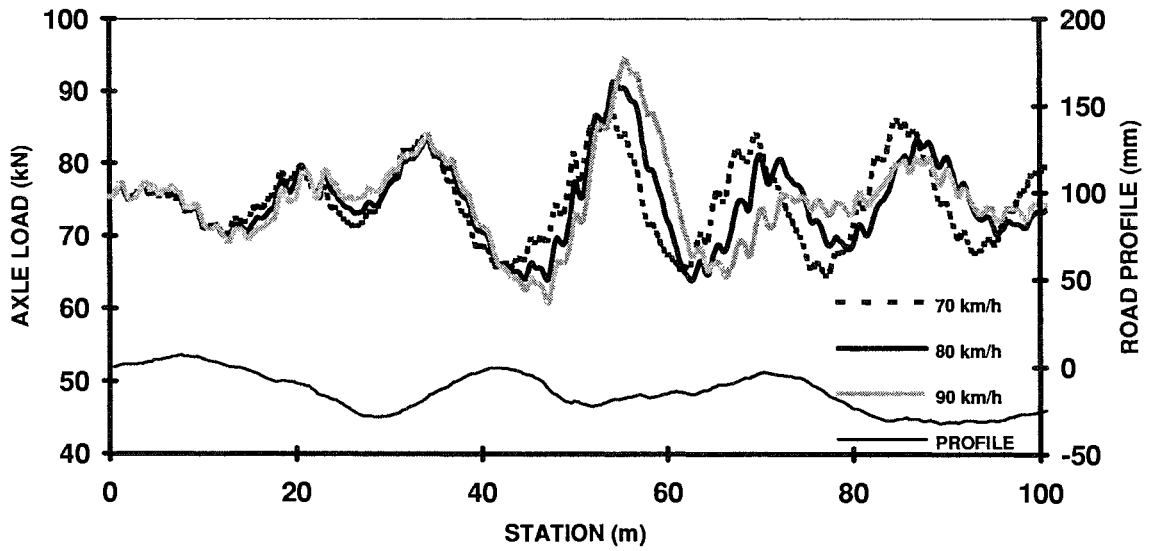


Fig. 2. The dynamic axle loads of the driving axle on road 6.

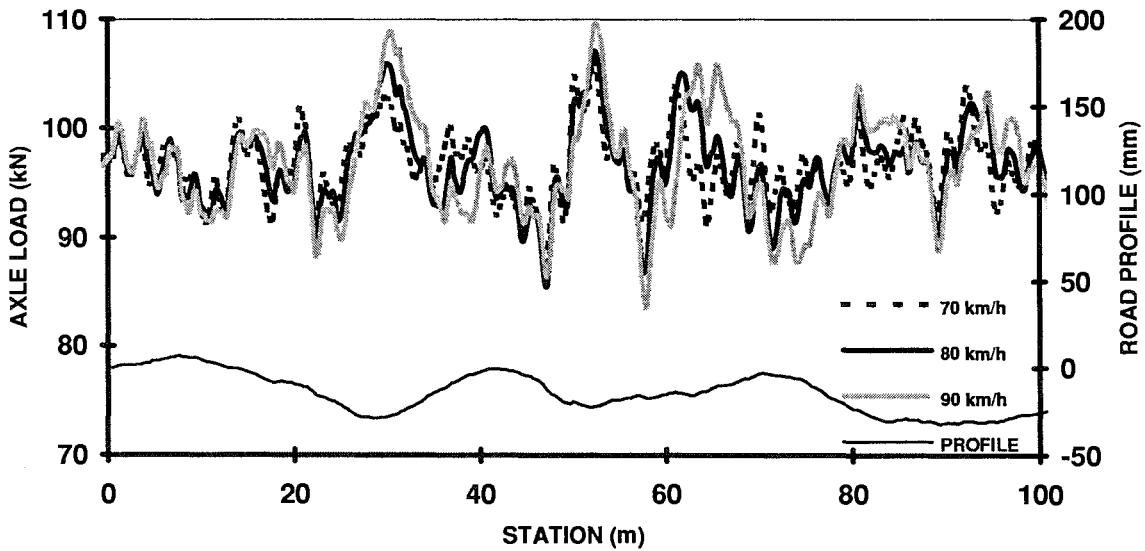


Fig. 3. The dynamic axle loads of the driving axle on road 6.

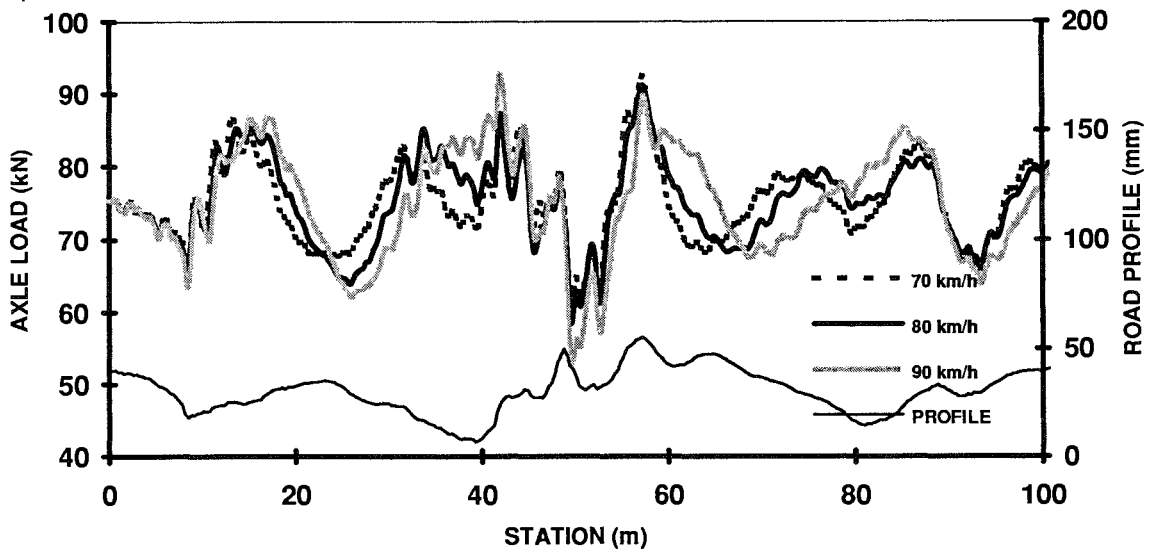


Fig. 4. The dynamic axle loads of the front axle on road 8.

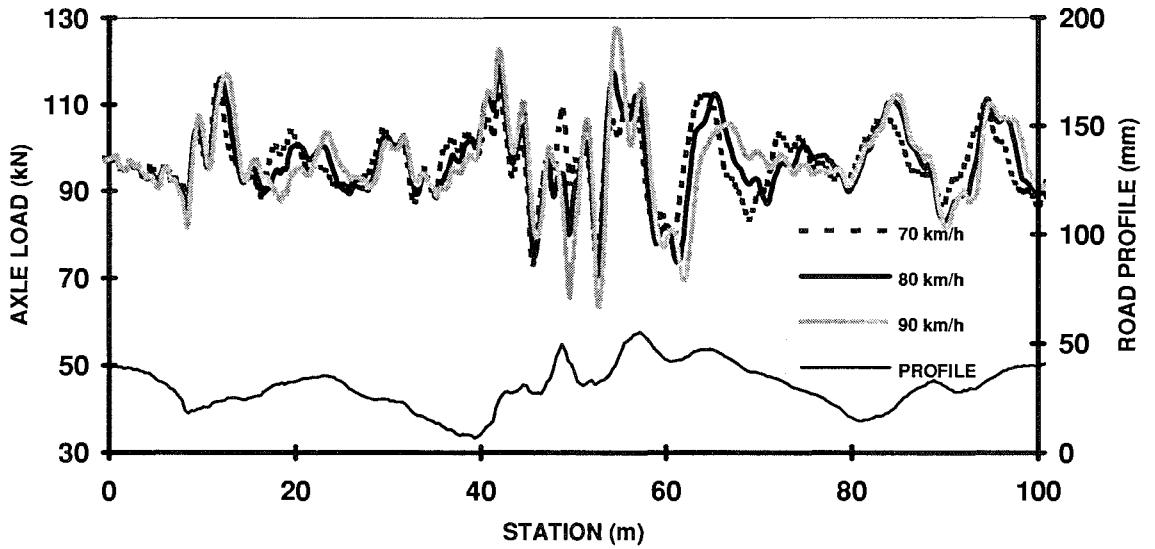


Fig. 5. The dynamic axle loads of the driving axle on Road 8.

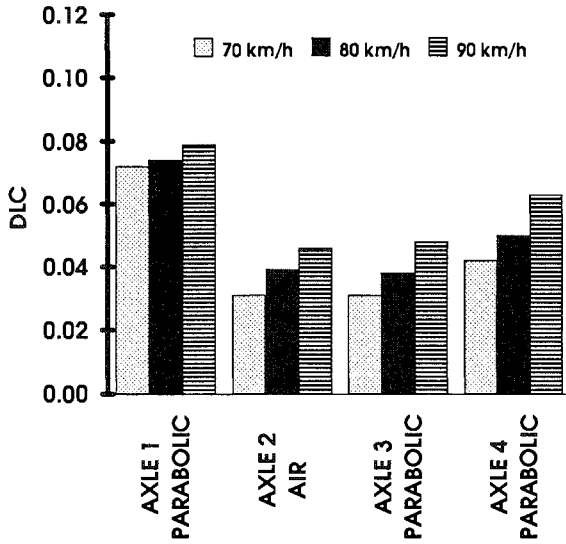


Fig. 6. The Dynamic Loading Coefficients (DLC) on Road 6.

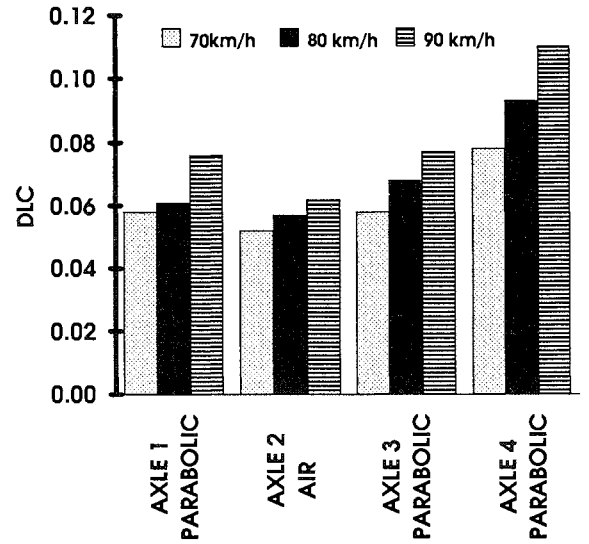


Fig. 7. The Dynamic Loading Coefficients (DLC) on Road 8.

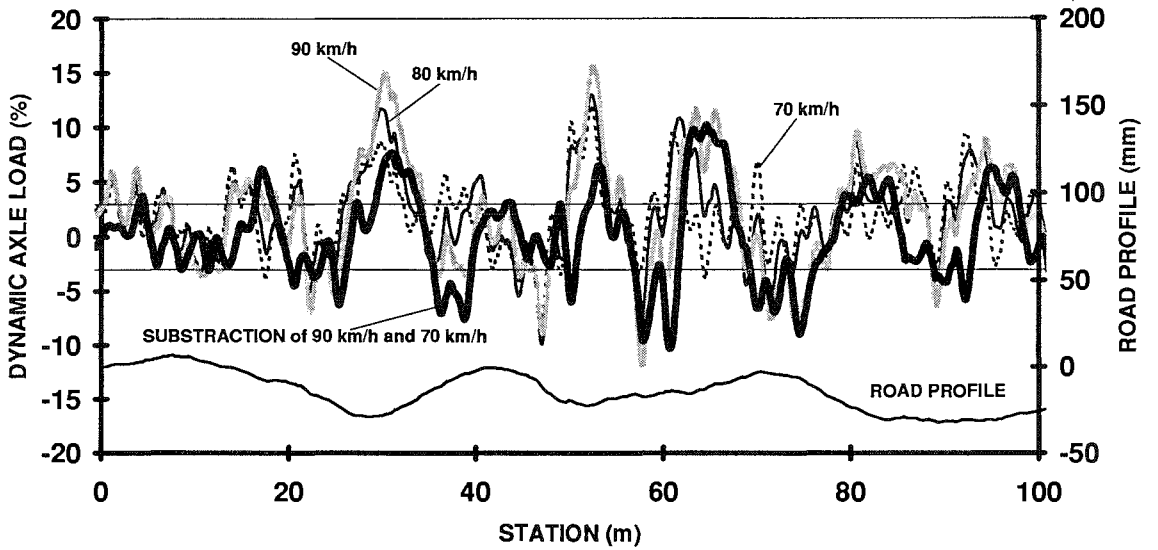


Fig. 8. Dynamic axle loads at various speeds and the difference at speeds 90 km/h and 70 km/h.

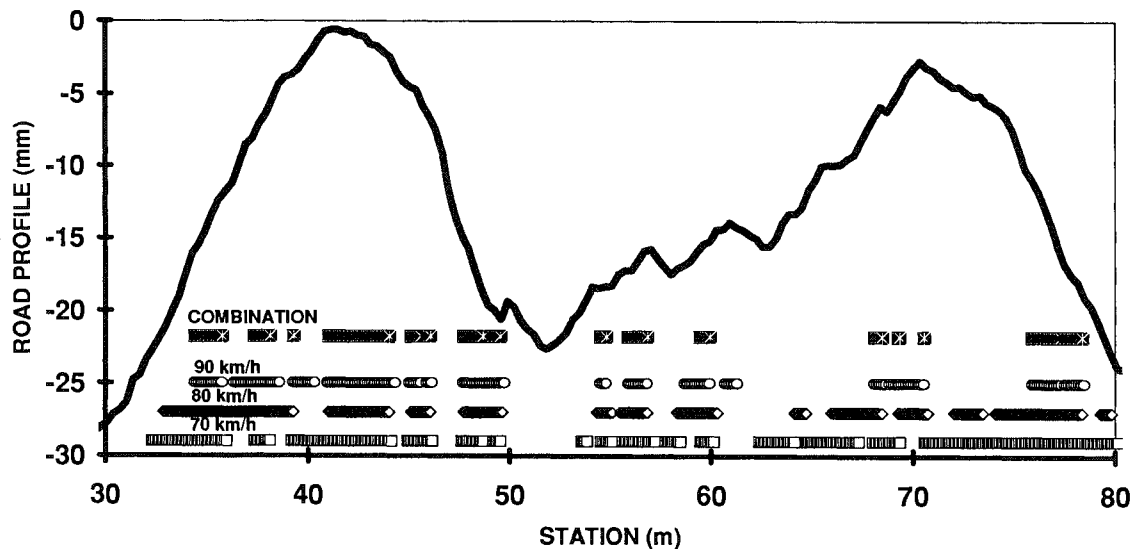


Fig. 9. The longitudinal road profile and place where WIM could be installed.

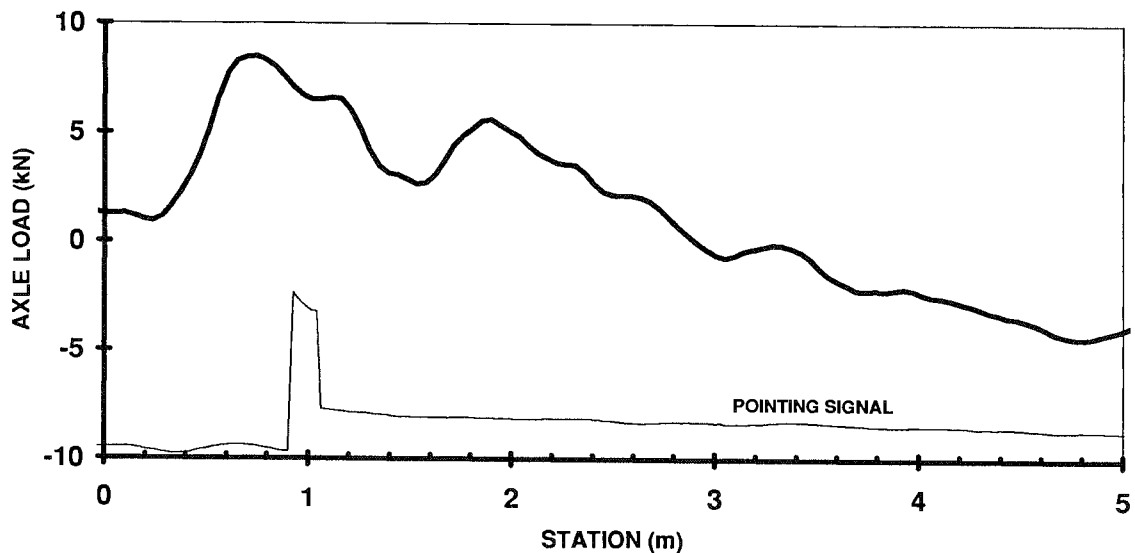


Fig. 10. Dynamic axle load measured in a vehicle and a signal from an electric eye.

#### 4. CONCLUSIONS

It has been found that if a truck passes the same road at the same speed the dynamic loadings occur at the exactly same points, so the repeatability or the spatial concentration of dynamic pavement loads is perfect. Very little is known if the speeds and vehicles are different, that is to say what is the spatial concentration of the dynamic axle loads of the whole vehicle fleet.

The spatial concentration of dynamic axle loads was simulated driving the same vehicle at different speeds. Each axle has its own specific frequency. If the speeds of a vehicle are different the maximum axle loads should occur at different points. The results were shown as a function of the station of the road; not as a function of time as usually.

The results showed that if the road is very smooth there is no spatial concentration of dynamic loadings but only a very small unevenness in the road put the dynamic loadings in phase and the spatial concentration of dynamic

loadings is very clear. The same phenomenon was found on all the axles and on both roads.

Simulation was used in order to find criteria for best possible position for WIM and to estimate errors due to dynamic axle loads in WIM measurements.

The smooth part of the road could be surprisingly short if the road is relatively smooth everywhere. Even long radius "hills" are acceptable if they have no short wave irregularities.

Only very few profiles have been analyzed. General rules have not been found yet.

Dynamic axle load measurements can be used for the same purpose and a research program will be realized during this summer season.