The Effect Of Wheel Loads On Pavements

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ABSTRACT

The effects of wheel loads on pavements are important for technical reasons (pavement design and bituminous mixture design), for administration (regulation of legal axle and total loads of vehicles), for economical calculations concerning transport economy and for taxation. The most famous effort was the AASHO Road Test which gave the basic information on the effects of axle loads on pavements. Important but much less extensive research has been made later, nowadays also in close cooperation between vehicle and pavement experts. There are many technical and scientific problems which are presented in this paper as well as a short review of ongoing international research.

INTRODUCTION

The knowledge of the effects of vehicle wheel loads on pavements is needed

- for technical purposes (for pavement design and bituminous mixture design)
- for administration (regulation of legal axle and total loads of vehicles)
- for economical calculations concerning transport economy
- for taxation.

All this should lead to the most economical transport system if also all the costs of other transport modes can be calculated. However, there is also question of politics and decision making. If certain regulations have been decided, it may be very difficult to make changes in them even the scientific, technical and economical basis have been unsound or clearly erroneous. This may be frustrating for researchers.

Road pavements may be

- bituminous pavements or flexible pavements
- cement concrete pavements or rigid pavements
- bituminous pavements including cement-treated base course or semirigid pavements.

Bituminous pavements are by far most common and this presentation will concentrate on them but deal also semi-rigid pavements. Rigid pavements are omitted here.

The exact behavior of pavements under wheel load is very difficult to handle correctly theoretically and many simplifications must be made. That is due to

- properties of materials
- nature of loadings and
- nature of failure modes.

Bituminous layers (asphalt concrete is the most common) can be described as a viscoplastoelastic material. It means that its elastic modulus is very dependent on temperature and loading time. An asphalt concrete is a compromise between many aspects, for instance if it is very stiff its load bearing capacity is good but fatigue properties are poor. Stiff asphalt concrete may crack during cold periods. If it is not stiff enough there may be plastic deformation or rutting during hot summer days. Water resistance and skid resistance for the wearing course are also important.

It is essential for cement-treated materials that they are so weak that there will be many thin cracks. If they are strong there will be only a few cracks which are not any more thin. Those cracks will cause reflective cracks through bituminous layers. Because of cracks the cement-treated course is not homogenous which cause severe limitations for laboratory measurements.

The structural properties of unbound materials are stress dependant. It means for instance that the modulus in the same material decreases with distance down and sideways from the loading point. The structural properties depend on the properties of the underlaying layer, too. The stress is not simply pulsating but the main stresses circulate.

The traffic load is distributed to the pavement through tires. Tires may be single or dual, their size and tire pressures vary. The axles may be single, tandem or tridem and the load distribution is not always ideal. The axle load is not always the nominal axle load but it may be considerably smaller and overloads are not uncommon.

The vertical load is not steady axle load but because of unevenness of the road there is variation in these dynamic loads. The roughness of the road and the properties of the vehicle suspensions have effect on these dynamic loads.

Vehicles cause not only vertical loadings but also horizontal loadings. Shear forces between the tires and the pavement may be considerable, too.

Pavement may crack due to fatigue in bound layers. Temperature and rest period between loadings have effect on the fatigue resistance of bound layers. There may be also permanent deformation in bituminous layers due to traffic loadings during hot summer days. Because bituminous layers are always compromise between many variables this kind of permanent deformation may occur also in cold and moderate climate.

There may be permanent deformation in unbound layers or in subgrade which can be seen as ruts or longitudinal unevenness. The structural properties of unbound materials and subgrade vary due to water content. Variation in subgrade may be especially large in cold climate because of frost.

A failure in road means very seldom a catastrophe. Thus no safety factor is used but it is common to speak about probability level of failure. If lower level of service will be tolerated the repair or the overlay can be postponed.

Basically there are only two criteria for pavement; evenness and skid resistance, everything else is irrelevant from the point-of-view of the user.

The text before tries to explain that the effect of wheel loads on pavements is very complicated and very exact answer cannot be given. However, the importance of those effects makes the estimations very important.

RESEARCH APPROACHES

The basic approaches to study the effects of wheel loads on pavements are:

- pavement performance
- pavement response.

Pavement performance means how the quality of pavement changes due to repeated traffic loadings and environmental reasons. Pavement response means that the effects of a single vehicle pass on pavement is measured of calculated. This means that there are no changes due to that one single vehicle pass but transient phenomena are measured or calculated.

Thus if pavement performance is used as an approach enough loadings are needed to cause change in the quality of pavement. Because of the nature of pavement deterioration, which often can be described as fatigue, pavement condition changes first very slowly and only later before the failure there are more changes. That means that it will take long time before any results are available. It is also difficult or impossible to distinguish the effect of various loading factors.

If pavement performance is used as an approach stresses, strains and deflections are measured or calculated in various parts of the pavement. One vehicle pass is in theory enough but for many practical reasons a few more is needed, from ten to twenty is common.

The use of response measurement or calculations is based on an assumption that response/performance function is known. Unfortunately that is not true but because their effects on pavements are compared to each other the exact response/performance functions are not necessary.

The nature of response measurements and calculations makes possible to study the effects of several variables in a short time. Because the responses are measured exactly and their signals are saved it opens possibilities to understand the basic phenomena in pavement behavior; in other words the approach is analytical.

Pavement performance can be monitored on

- test road network (like SHRP/LTPP),
- test roads,
- road tests (like AASHO Road Test) or
- accelerated full scale facilities (like ALF, HVS, Captif).

In the first case the traffic is real which means that the differences in the characteristics can only be monitored. The differences in the quality of traffic between test sections is usually very small (difference in quantity is often large). In test roads the traffic itself is the same but there are different pavements which limits also the possibilities for analyzing the effects of various loading factors. Accelerated full scale loading facilities allow direct comparison of usually two kind of wheel loads at the same time in nearly equal conditions. The effects of different axle loads, tires and suspensions have been compared or are compared at the present time. The acceleration effect causes certain problems and thus the results are not always reliable.

Pavement responses are based on theoretical calculations or on direct response measurements. They may be usually strains in bound layers, stresses or strains in unbound layers and subgrade or deflections of the total pavement or within certain parts of it. The measurement technology itself is relatively simple but it is very difficult to develop sensors which measure the correct value without disturbing the stress or strain distribution.

The behavior of most road materials and the wheel loading are very complex and therefore many simplifications must be made. The effect of these simplifications on results is difficult to estimate.

Different approaches are important, none of them alone can solve the problems. Therefore a combination of research approaches is often used. The real results come from real roads; unfortunately the possibilities to analyze them is often very limited.

MAIN RESULTS CONCERNING EFFECTS OF WHEEL LOADS

AXLE LOADS

From the data of the AASHO Road Test in 1958-60 the following formula was later developed:

$$\left(\frac{P_x}{P_y}\right)^4 = \frac{N_y}{N_x}$$

where P_x and P_y are axle loads and N_x and N_y are the corresponding number of load applications.

This formula implies that if an axle is twice as heavy as another, their relative effect on pavement performance or aggressiveness is in the ratio $(2)^4$, i.e. sixteen. Thus the pavement trafficked by the heavier load has a life only one sixteenth that of the pavement trafficked by the lighter load.

This formula is called the **fourth power law**. The exponent in the fourth power law is not constant but was found even in the AASHO Road Test to vary from about 3.6 to 4.6.

One example is the OECD/FORCE project where the effect of two axle loads were compared. The value "x" has been calculated for different levels of deterioration and the values "x" vary between 1.8 to 8.8 increasing linearly with the degree of cracking.

The power of the fourth power law is different if it is based on cracking or rutting or on rutting in bituminous layers. It depends also on the structure of the pavement.

Experimental and theoretical research has indicated important variability in the power, but has not been conclusive. However, the value **four** is generally used **for bituminous pavements**. It is important to note that the value **for cement-treated base courses** is about **8 - 10** and **for cement concrete roads** it is still higher, perhaps **15 to 20.**

AXLE CONFIGURATIONS

One of the main results from the AASHO Road Test was the equivalency of single and tandem axles. The result was quite complicated but to make it simple one can say that a 100 kN single axle load has the same effect as a 180 kN tandem axle.

There are no direct comparisons of tridem axles to single or tandem axles but the equivalencies are more or less extrapolations of the results from tandem axles to tridems. One difficulty is the fact that there are usually wide single tires on tridem axles but tandem axles have often dual tires.

Response measurements and calculations have confirmed the basic results but have given possibilities to more detailed comparison of for instance slightly different tandem axles.

TIRES

Tires transmit traffic loads to the pavement. The traffic load is assumed to be evenly distributed on a circular area. In reality the shape is more rectangular and the highest vertical stresses are in the middle and/or on the sides of the tire imprint (Figure 1). The stress distribution depends on the relation wheel load / tire inflation pressure. Different tire brands have different stress distribution. It depends also on the speed of the vehicle.

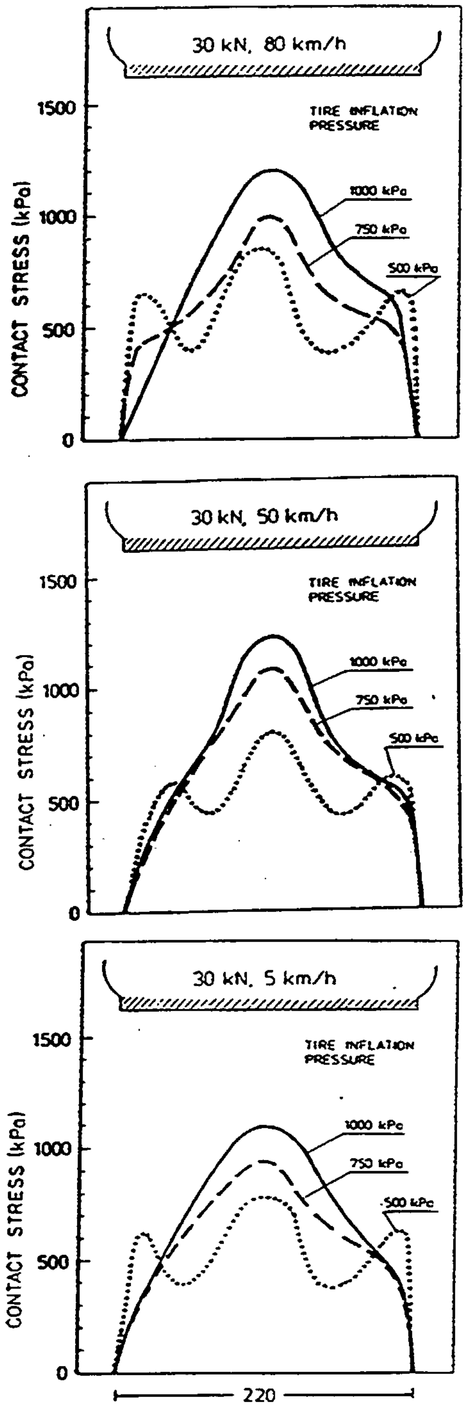

Figure 1. Vertical stress distribution between a tyre and pavement

The uneven vertical stress distribution has effect only close to the surface of the pavement or mainly only in bituminous layers.

Tires are round and as they are pressed flat against the pavement there are small movements between the tire and pavement surface and corresponding shear forces. These surface stresses may be strong enough to start cracks from the surface in certain cases and not like according to the basic theory of pavement design from the bottom of the bituminous layers. This theory is based more on assumptions because there are not reliable measurements on the shear forces.

Tire industry has no interest to make the distribution even. If they have made vertical or horizontal stress distribution measurements they have no interest to publish the results. Their interest is to make long lasting tires which means for instance that the wear of the tires should be even. Wear is related to the movements between the tire and pavement which is affected also by the vertical stress.

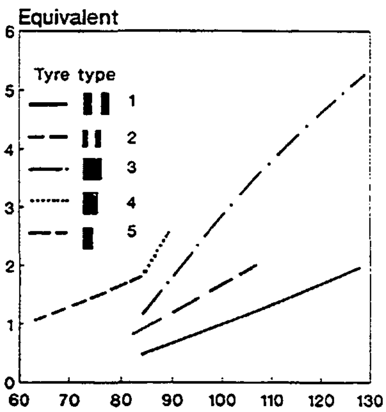

Figure 2. The aggressiveness of different tyres.

Wide base tires are according to that research more aggressive than dual tires by a factor 2.5 - 4.0 in ideal conditions for dual tires. Because the load is very seldom evenly distributed on both dual tires, the uneven load was simulated by tire pressures (500 kPa in one and 1000 kPa in another tire). Despite this wide base tires were more aggressive by a factor 1.2 at least if they were compared to the most common dual tire. If they were compared to the small size dual tires, single tires were in certain cases less aggressive by a factor 0.7.

Within wide base tires there are differences, factor up to 1.6 and within them wider tires are less aggressive.

If the tire is smaller in diameter and the load is the same the contact surface is shorter and stresses correspondingly greater. Thus it is easy to understand that smaller dual tires are more aggressive than normal size dual tires, in that research project by a factor 1.5 - 2.0.

The effect of different tires on pavements depends on the pavement structure. All the differences are greater if the bituminous layers are thinner and smaller if thicker.

As the tire inflation pressure increases the stress distribution changes as presented in Figure 1. According to VTT measurements an increase of 20 per cent in tire inflation pressure increases the aggressiveness 1.1 - 1.4 times.

The preceding figures are based on response measurements in pavements. Based on relatively few research projects it seems that the effect of tires on plastic deformation in bituminous layers is less severe or the power of the fourth power law is smaller than four. However, the stress distribution between the tire and pavement may play much greater roll than in cracking or rutting of the pavement.

It is easy to understand that dual tires are better to the pavement than wide single tires carrying the same load because the load is divided into two areas. VTT has made an extensive study in order to compare the effects of three wide base tires and two dual tires on pavements. The main results are presented in Figures 2 and 3.

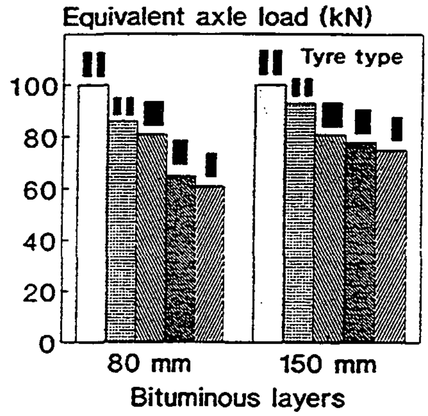

Figure 3. Equivalent axle loads.

DYNAMIC EFFECTS

The axle load of a heavy vehicle is not steady but it varies because the road is not even. This variation may easily be +/- 20 percent which means that the axle load varies between 80 kN and 120 kN if the nominal static axle load is 100 kN. Not only the unevenness of a road but also the quality of suspensions and the structure of the vehicle have effect on this **dynamic axle load**.

The main movements are the **body bounce**, specific frequency usually between 1.5 and 3 Hz and **axle hop**, specific frequency about 10 Hz. Body bounce is usually dominating. An example of dynamic axle loads is presented in Figure 4.

The dynamic axle loads may concentrate on certain spots along a road or there exists **spatial repeatability** of dynamic loadings. If the same vehicle runs at the same speed the repeatability is nearly perfect. Relatively little is known by the present time about spatial repeatability of the whole vehicle fleet driving at different speeds on roads of different unevenness.

The dynamic axle loads depend on the evenness of the road and on the properties of suspensions and especially on dampers. Air suspensions have been usually thought to be better because they are good for the load (and passengers). The reality is not necessarily the same. If the damping is not adequate the stresses to the pavement may great. Thus at the present time it is not known very well what kind of suspensions are really "**road friendly**".

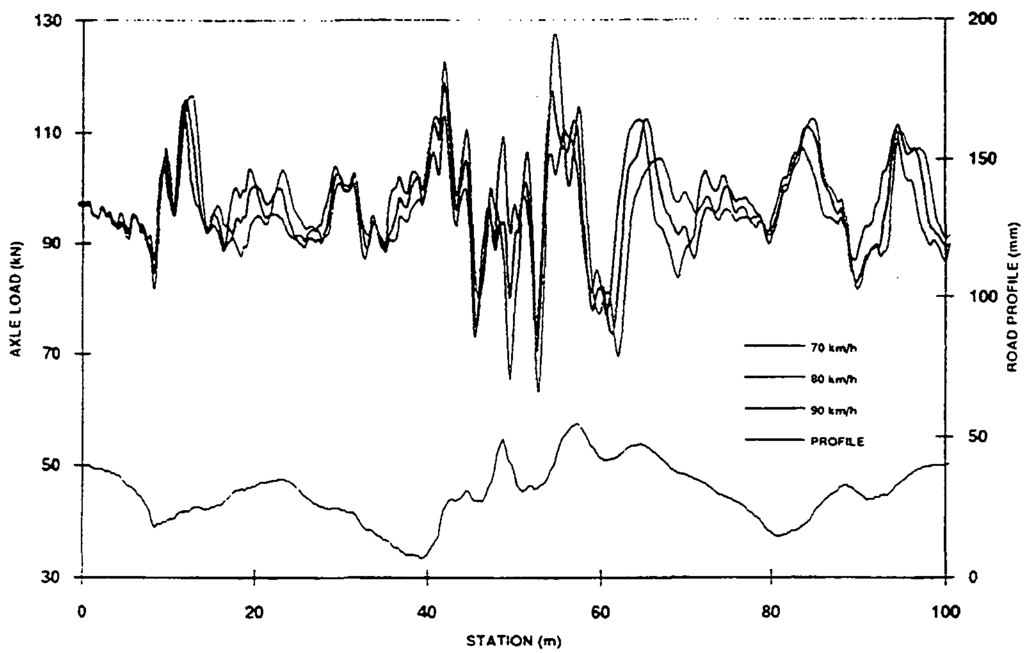

Figure 4. Dynamic axle loads.

PROBLEMS IN LOAD EQUIVALENCIES

The most important research has been the AASHO Road Test. Its problem was that it was accelerated, most pavement failures occurred during the spring thaw seasons and that the same vehicles run at the same speed; the spatial repeatability was perfect. A comparison of the effects of two vehicles on several test sections is being made at the low volume road of the Minnesota Test Road (MnRoad). The OECD/Force accelerated test at the circular test track at Nantes gave more detailed information on the effect of two axle loads. Analyzing of several test roads (World Bank) has given more information.

Other research is mainly based on response measurements and calculations.

In most of the research only the effect of one axle has been studied and not the total vehicle or vehicle combination. The following wheels do not drive the same path. Some patterns of vehicles and vehicle combinations used by VTT is presented in Figure 5. Only the right-hand side of the vehicle is drawn in the figure, note also the very different scales. The wheels are not following each other but especially the transverse position of the front tire is different from others. The phenomena will be even more complicated as the vehicles run like a dog, not exactly straight but slightly sideways. That depends further to certain degree on the crossfall of the road. Thus it would be important not to calculate only the effect of different axles but the effect of total vehicle or vehicle combination.

This phenomenon is not important on strain on subgrade but it is important on the strains at the bottom of the bituminous layers because the critical points are relatively close to the tire.

Another reason, the nature of the strains are different in longitudinal and transverse direction. The preceding wheel has little effect on the strain under the following wheel (Figure 6) because the strain becomes always to the zero level after the pass of the wheel. The transverse strain does not come to the same level and it may accumulate or because the transverse strains are very sensitive to transverse position may it may behave very surprisingly (Figure 7).

Vehicles do not drive like trains but there is always some lateral wander. The shapes from wide base tires and dual tires are, however, different (Figure 8). Because the strains from wide base tires are much more peaked than the peak values due to dual tires they are divided on wider area. Thus as the wander is taken into account the "multiplying" the wander and strain distributions. Based on a VTT data it was found that the aggressiveness factors of wide single tires should be multiplied by 1.4.

One simple example is the difficulty in the comparison of wide base and dual tires is that the load in dual tires is usually assumed to be divided evenly on both tires. That is very seldom true and less load is allowed for a tire in dual tires than if the same tire is a single tire. The uneven load distribution between dual tires may be due to:

- tires have not worn similarly; for instance, one is older than the other,
- the manufacturer or the brand is not the same,
- the tire may be new or retreaded,
- there is more or less fatigue in the carcass,
- different tire pressures,
- different tire temperatures and, due to that, different tire pressures,
- uneven road (ruts, crown),
- the camber angle or the bending of the axle.

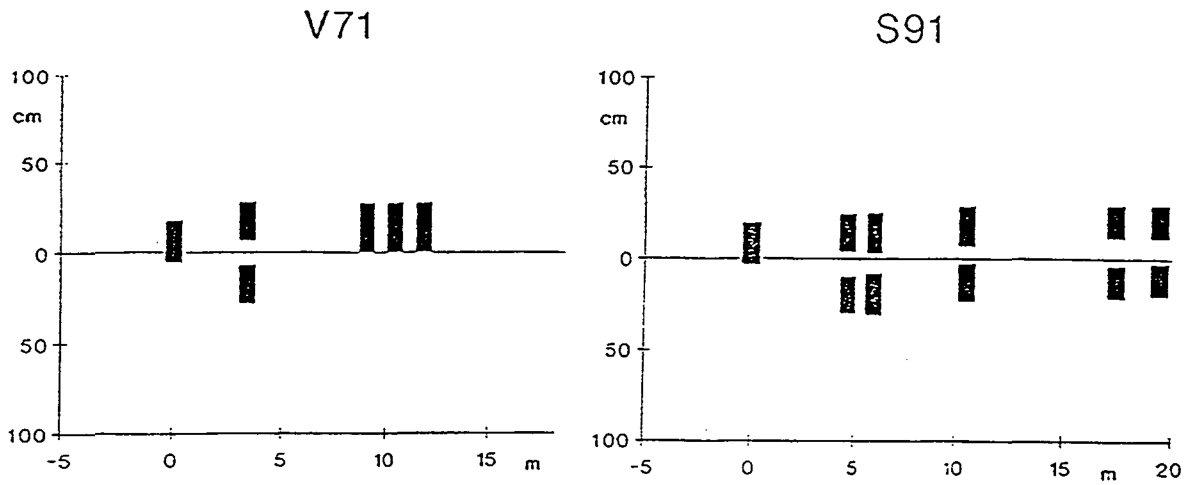

Figure 5. Patterns of vehicles.

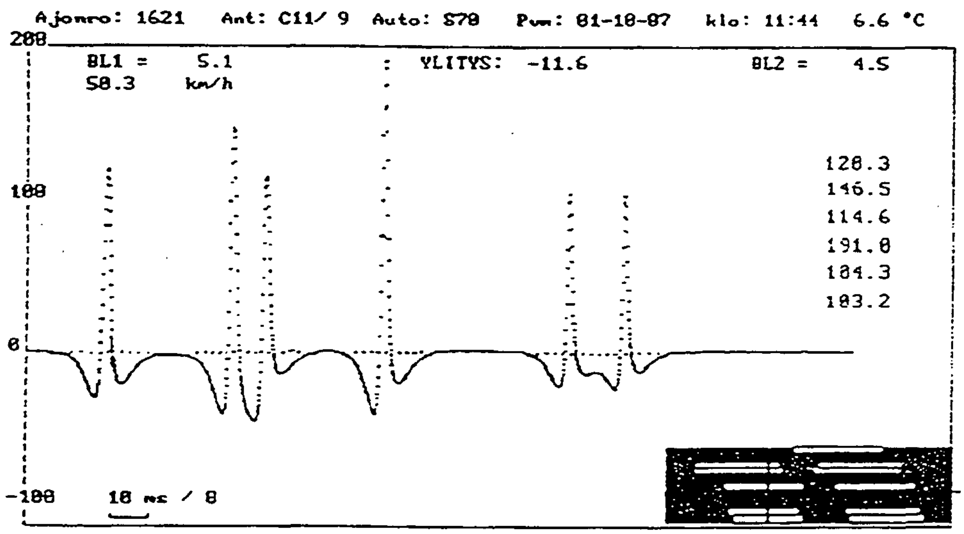

Figure 6. Longitudinal strain at the bottom of the bituminous layer.

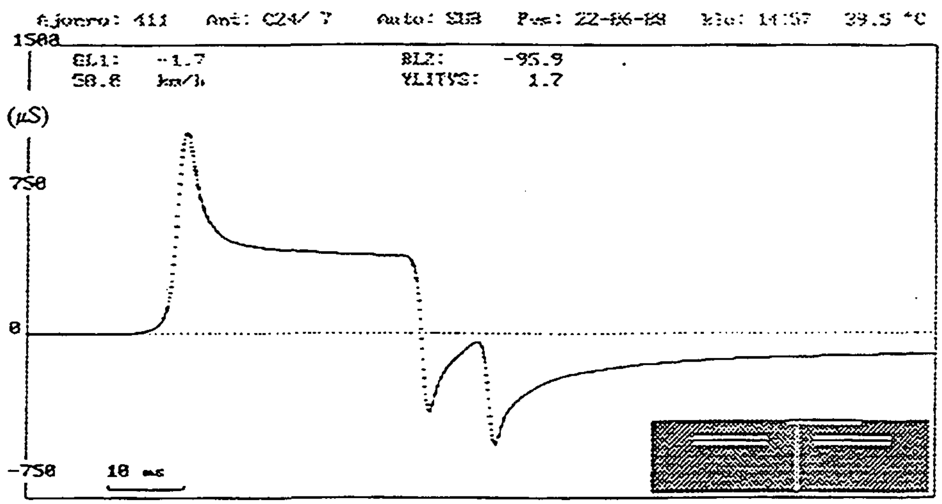

Figure 7. Cumulating transverse strains, tandem axles not passing over the gauge.

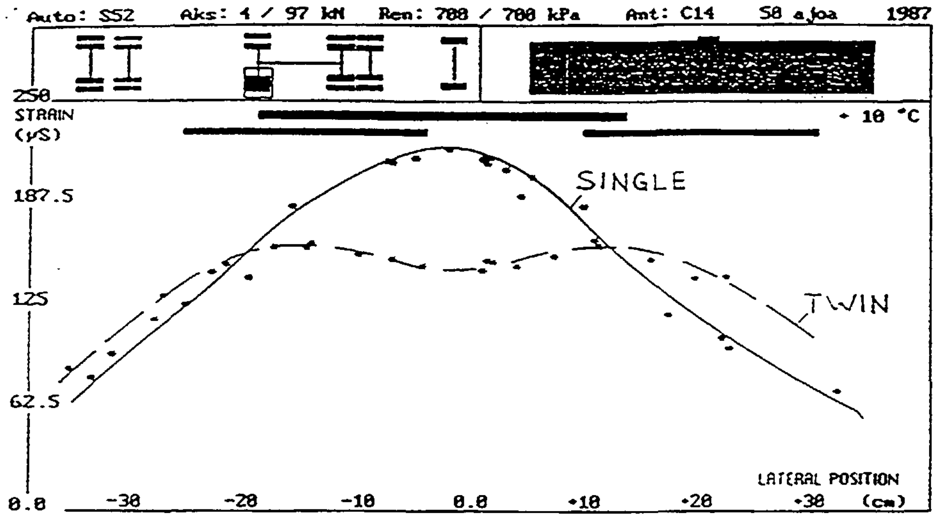

Figure 8. The peak strains of a single and dual tyre.

The effect of dynamic loadings is relatively unknown. One reason for it is that there has been in fact no cooperation between vehicle and pavement experts. OECD has started international research project which is called DIVINE (Dynamic Interaction Vehicle-Infrastructure Experiment). It is divided into six research elements: (1) Accelerated Dynamic Pavement Test, (2) Pavement Primary Response Testing, (3) Road Simulator Testing, (4) Computer Simulation of Heavy Vehicle Dynamics, (5) Spatial Repeatability of Dynamic Loads, (6) Dynamic Loading of Bridges.

The effects of two different suspensions, a good and a poor one, are compared simultaneously in an accelerated testing facility under controlled conditions. The test is made at CAPTIF located in Christchurch, New Zealand.

The basic idea in response measurements is to use two different bumps in order to excite body bounce (specific frequency 1.5 - 3 Hz) and axle hop (specific frequency about 10 Hz) and measure the strains and stresses in pavements. The dynamic axle loads in the instrumented vehicles are measured simultaneously and will be compared to the response measurements. The response measurements have been made at Virttaa Test Site in Finland (a Canadian, a British and a Finnish instrumented vehicle) and in USA (a Canadian and an American instrumented vehicle).

In road simulator testing two vehicles are set on Canadian and American vehicle shakers or road simulators where vehicle wheels are moved hydraulically up and down in order to simulate the unevenness of roads. The ability of computer models to predict heavy vehicle dynamic loading is being compared and evaluated by TNO in the Netherlands to provide recommendations for validated and usable models. Spatial repeatability is studied on two highway sections of flexible pavements, one in France and one in England, which have been fitted with multiple sensor WIM stations. It seems that "road friendly" suspensions may not necessarily be "bridge friendly".

CONCLUDING WORDS

The importance to know the effects of wheel loads on pavements have been recognized. The cooperation between vehicle and pavement engineers has been very limited, in fact the first Symposium of Heavy Vehicle Weights and Dimensions in 1986 at Kelowna, B.C. seemed to start this cooperation. International research has been important within OECD, especially the test at Nantes and ongoing DIVINE-project. A project concerning wide base and dual tires is going to start within EU-countries.

It must be noted also that all the vehicles do not run always fully loaded or for instance the vehicle is fully loaded but the load is not placed well, some axles are overloaded and some underloaded which is not good for pavements nor for the vehicles. The driver has often difficulties because there are no load sensors in vehicles; they do not work well in the hostile environment.

The effect of traffic loads is not only needed for pavement design but also for developing legislation. There are strong pressure groups, vehicle industry, road transporters, environmentalists, competing transporters like railways etc which like to have different kind of legislation for the weight and dimensions of vehicles. Although these decisions are often very political they should be based on sound scientific knowledge. One example, the vehicle industry pressed for higher axle loads based that air suspensions (and corresponding other suspensions) are better for pavements and therefore they should be allowed to use higher axle loads. Nowadays in certain cases vehicles equipped with air suspensions or corresponding other suspensions are allowed to use 115 kN axle loads instead of former 100 kN in EU-countries. This decision was not founded on real knowledge of the effects of the suspensions.