Effects of Tires and Tire Pressures on Road Pavements

MATTI HUHTALA, JARI PIHLAJAMÄKI, AND MARKKU PIENIMÄKI

The Road and Traffic Laboratory of the Technical Research Center of Finland has developed gauges to measure strain and stress in bituminous and unbound layers and in the subgrade and has also developed a sophisticated microcomputer system for collecting and handling data. These gauges have been used in research concerning pavement design and to measure the response due to moving vehicles at the Virttaa test field. The aggressiveness of different axle loads; single, tandem, and tridem axles; single, twin, and wide-base tires; and tire pressures have been compared at speeds of 50 or 80 km per hour. This paper describes the effects of tires and tire pressures. Two twin tire and three wide-base tire types were compared. Three axle loads were used for each type. Three tire air pressures were used for each axle load and tire type. The load was seldom evenly distributed on both twin tires. That condition was simulated with different tire pressures (500 kPa and 1000 kPa) in the twin tires. Certain tire/pavement contact pressure distribution measurements were also made.

The importance of road transportation has grown everywhere in the world during the last several years—not only as the result of the development of the road infrastructure but also as a result of the technical development of trucks. Vehicles are heavier and their load-carrying capacity is greater. Engines are more powerful, cabs more comfortable, and important developments have been made in axles, tires, and suspensions.

The increased traffic and heavier vehicles cause much more distress to roads than ever before. The regulations of weights and dimensions are even more important in the wake of substantial pressure from the transportation industry to allow heavier and larger vehicles on the highways. The recent developments in tires, axles, and suspensions are important from the standpoint of the road engineers.

Most of the new developments seem to increase distress to the pavements. New regulations often come only after technical development—or may, in some cases, hinder technical development. The technical basis for regulations has often been vague. One reason is that the regulations require special knowledge somewhere between the expertise of mechanical engineers and civil engineers. The following lists perhaps the most important technical changes in vehicles, as they relate to roads:

- Tridem axles,
- Tandem axles with different tires and loads on axles,
- Radial tires,
- Increased tire pressures,
- Wide-base tires instead of twin tires,
- Smaller tires capable of carrying the same load, and
- New suspensions, especially air suspensions.

In order to study the effects of different tires, axles, and suspensions, four approaches can be used: (a) full-size road tests, (b) measurements of stresses and strains in pavements (response measurements), (c) theoretical (mechanistic) calculations of stresses and strains in pavements, and (d) measurements of dynamic axle loads in the vehicle.

In the first approach, the road is damaged by repeated loads. If moving trucks are used as loads, the test is quite expensive. The most famous and complete test run was the AASHO Road Test from 1957 to 1961, from which the basic formulas for the effects of different axle loads and the equivalency of the single and tandem axles have come (and are still used, even though vehicles and tires have changed considerably in 30 years). The circular or linear test tracks are important to pavement research but have only limited use for this purpose. Road tests give the only real and reliable results and the results received by other means should be compared to actual road tests.

The mechanistic calculations by multilayer or finite element computer programs are inexpensive and easy, but because the basic assumptions of the behavior of tires and pavements must be simplified, the results may be erroneous and should be verified. However, the scope of the results received by other means can be extrapolated with these calculations.

The stresses and strains in the pavement due to a passing vehicle can be measured (response measurements). The results are turned into equivalency factors using appropriate failure criteria. Because the equivalency factors are compared with each other, their exact validity is not important. The results may reveal, for instance, the behavior of different tires and uneven distribution of the load within tandem axles or twin tires, which is seldom taken into account in mechanistic calculations. The results are clear and easily explained, which is important because of the economic and political pressure groups.

In the above approaches, the road is even or it is assumed to be even. The effect of suspensions is mostly neglected. The effect of suspensions can be studied by measuring the dynamic axle loads in the vehicle. Corresponding response measurements can be done simultaneously in the pavement.

The Road and Traffic Laboratory of the Technical Research Center of Finland (VTT) began developing gauges to measure strains and stresses in bituminous and unbound layers and in the subgrade in the early 1980s. Field measurements were made at the Virttaa test field, which is a 3-km-long, 40-m-wide part of a highway that is used as a temporary airfield by

Technical Research Center, Road and Traffic Laboratory, 02150 Espoo, Finland.

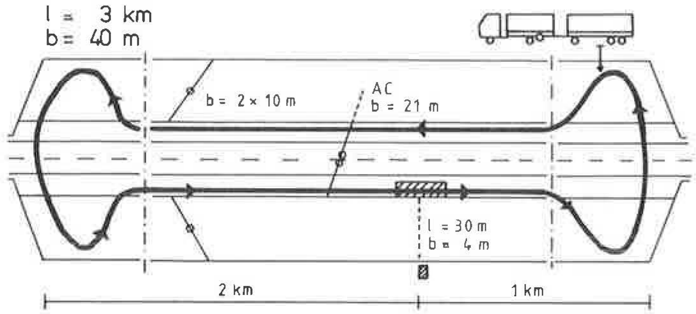

FIGURE 1 Virttaa test field.

the Finnish Air Force (Figure 1). Any truck or vehicle combination can easily attain the maximum legal speed of 80 km per hour and drive back on the other side. The circling time is 5 to 6 min. The test section currently has two pavements; the thicknesses of the bituminous layers are 80 and 150 mm.

The Virttaa test field has been used for both developing pavement design, and measuring the response of different vehicles (loads, axles, tires, suspensions, etc.).

The first measurements were made at Virttaa in 1983. Five truck combinations were compared (*1*). In 1984, practically all 12 axle combinations (single, tandem, tridem, wide-base tires, etc.) that were used in Finland were compared (*2*). The results have impacted directly on the Finnish legislation concerning axle load limits of tandem and tridem axles.

Eleven countries from three continents participated in a common, full-scale pavement test in Italy in April 1984 (*3–5*), which compared strain measurements in bituminous layers. The strain gauges developed by VTT performed well.

During the following years, the measurements were concentrated on pavement design problems, as well as further development of both the gauges and a sophisticated microcomputer program to collect and handle the data. Measurements of the dynamic axle loads in a vehicle, the effects of unevenness on the strains and stresses in the pavements, and the effects of suspensions have also been started.

VTT made measurements concerning the effects of tire types and tire pressures in 1984 and 1985. A more systematic research program was realized in 1987. The project included the comparisons of two twin tires and three wide-base tires, all with three axle loads and three tire pressures. Uneven tire loads within twin tires were simulated with air pressure differences. All together, 51 combinations were measured.

VTT also measured static contact pressure distributions between the tire and the pavement. A new device for measuring dynamic contact pressure distribution has been constructed, and the first results at speeds of 5 to 80 km per hour (3 to 50 mph) are quite promising.

This paper handles the effects of tire types and tire pressures and the first results of contact pressure distribution measurements.

MEASUREMENT METHODS

The main measurement system consisted of strain gauges glued to 6-inch core samples that fit into a hole in the pavement with a tolerance of less than 1 mm. The samples were glued to the bituminous pavement. The gauges acted as an integral part of the bituminous layer and had no strengthening effect (the flexibility was the same as that of the bituminous layer) and thus did not disturb the stress distribution. The gauges had no elastic part, and thus plastic deformation and relaxation could also be followed (up to 30 min). Installation of the gauges demanded meticulous work.

Strain gauges are placed in longitudinal or transverse positions at the bottom of bituminous layers or on the surface, or they can be installed in cores at different depths. Longitudinal gauges at the bottom of the bituminous layers have been used to compare the effects of different axles or tires.

The diagram-type pressure cells were manufactured by VTT. They were installed at five depths; however, only those at −250 mm, −400 mm, and −700 mm were used in these measurements.

In 1987, the field had two test sections, bituminous layers 80 and 150 mm, 58 working strain gauges in bituminous layers, and 25 working pressure cells in unbound layers and subgrade. The longitudinal section of the test area is presented in Figure 2.

The measurement system is shown in Figure 3. Ten strain gauges and six pressure cells were attached to amplifiers, a/d units, and a microcomputer. An electric eye started the operation.

A typical signal of a passing vehicle combination (six axles) is presented in Figure 4 (directly from a computer display). The computer measured the peak values, which are shown on the right side of Figure 4. The transversal position of the right side tires was measured and is shown in Figure 4 in relation to the gauge line in the lower right corner. In this figure, the front tire was outside the line, the right edge of the left twin tires of the tandem axles went over the line, the front left twin tire of the trailer went over the line almost in the middle, and the left tires of the trailer tandem axles were exactly in the middle. Note, too, that the vehicle ran similar to a dog—slightly sideways.

The peak values of the first axle of the trailer are presented as a function of the transversal position in Figure 5 (directly from a computer display). The vehicle is the same as in Figure 4. It can be seen that there are too few points between the transversal positions −10 and −20 cm, which was why the driver was asked to drive the following passes between these values. After the shape in Figure 5 was well-defined, the peak value was determined by using the computer's mouse accessory.

The strain values in Figure 5 were temperature corrected. The same figure can be drawn without temperature correc-

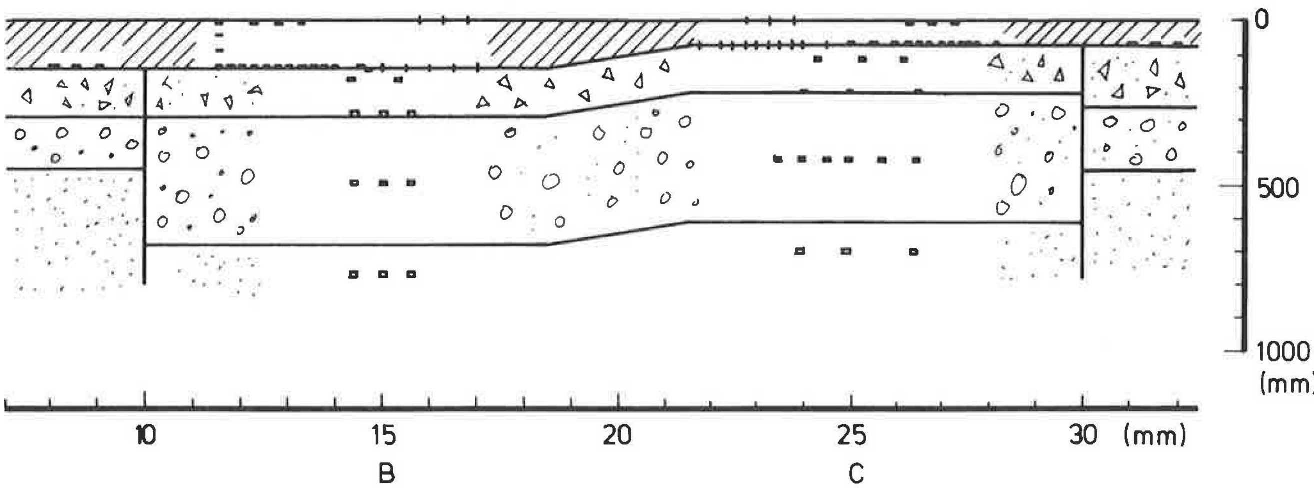

FIGURE 2 Longitudinal section of the test area.

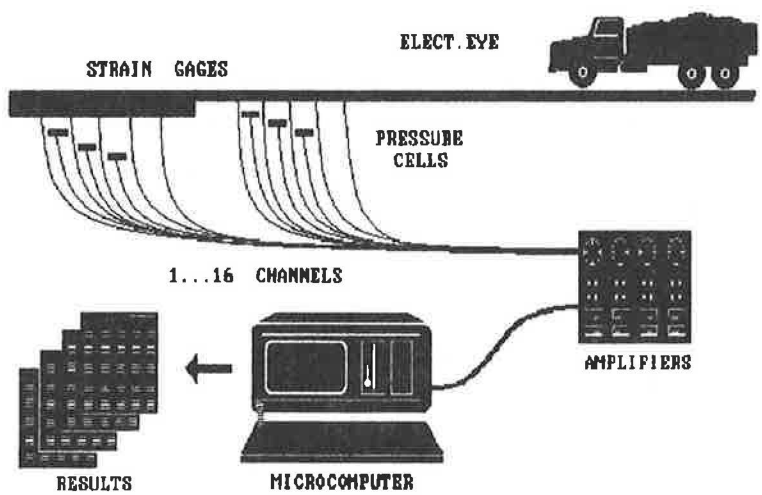

FIGURE 3 Measurement arrangements.

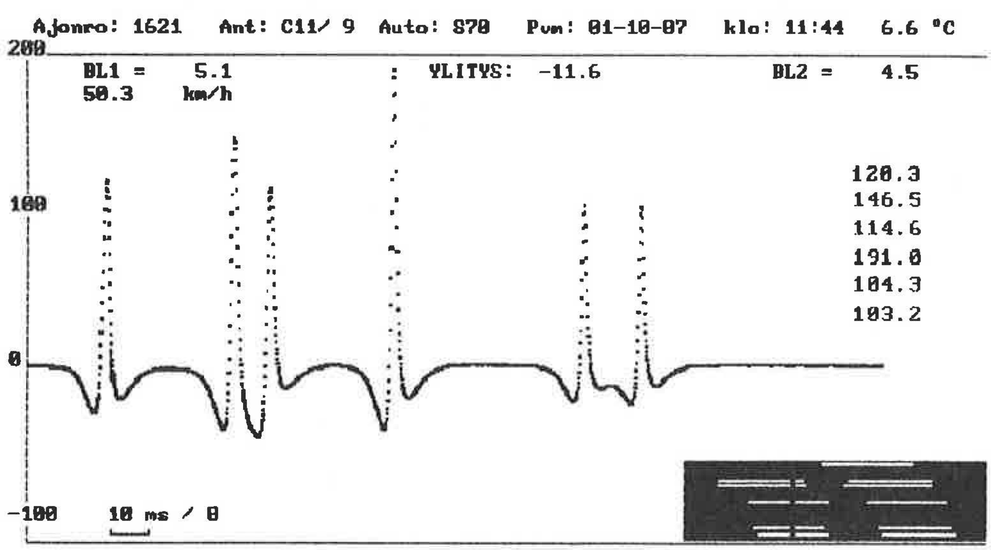

FIGURE 4 Typical signal from a strain gauge.

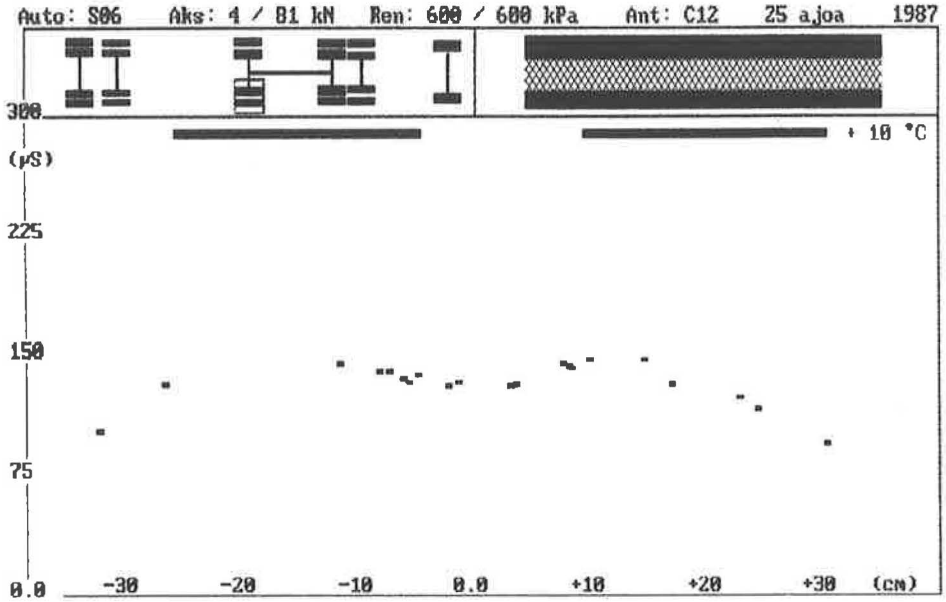

FIGURE 5 An example of strains as a function of the transversal position.

tion; the temperature is shown in that case at each point for closer analysis.

The strain or stress values were turned into an equivalent number of axle passes using appropriate failure (fatigue) criteria (the exponent of the fourth power law is 4.2). Equivalent numbers were compared to those of a standard (reference) axle, which carried a 10-ton, single axle with twin tires 12R22.5 and having the 700 kPa tire pressure. That value is called the equivalency factor and describes the damaging power or the aggressiveness of the axle. If the equivalency factor is 2, for example, the pavement will last only half as long as with a standard axle. Because the equivalency factors are compared, the exact validity of the failure criterion is not important.

The bending of axles corresponded well with the dynamic axle forces and was easy to measure with strain gauges. Accelerometers on the axles and in the vehicle gave more information about the forces (16 channels could be measured simultaneously). Measurements have been made on artificial bumps and on ordinary highways.

The contact pressure distribution between the truck tire and the pavement was measured in the laboratory. The tire rolled slowly over a measuring point and the force was measured. Axle loads and tire pressures were varied. Wide base tires could not be measured because of the restrictive dimensions of the apparatus.

A dynamic contact pressure measurement device was constructed by VTT, with 16 measuring points, the distance *c/c* 20 mm, and total width of 300 mm. The microcomputer continuously measured all 16 channels as the tire rolled over and a three-dimensional, contact-pressure/longitudinal-and-transversal-dimensions figure was drawn automatically on the computer display. The transversal position of the tire was measured. A computer program that could superimpose consecutive passes on the same figure is being developed.

Special attention was paid to the construction of the measuring points in the design of the device. Measurements were made at speeds up to 80 kmph and the results have been promising.

RESEARCH PROGRAM

Five types of tires were used in this research: (a) 12R22.5 twin tires, (b) 265/70R19.5 twin tires, (c) 445/65R22.5 wide base tires, (d) 385/65R22.5 wide base tires, and (e) 350/75R22.5 wide base tires.

The markings were inconsistent, however. The letter *R* denotes radial tire, the number following the *R* is the diameter of the rim or the inner diameter of the tire (in inches). The first number gives the width of the tire in inches (Type 1) or in millimeters (Types 2 through 5). In the past, the height and width of a tire was about the same (the aspect ratio is 100 percent), but now, the tires may be flatter. The height is 65 to 75 percent of the width in Types 2 through 5 (the percentage is the number after the slash).

The tires are typical (but not necessarily those most used) in Finland, because the number was limited and enough variety in dimensions was needed. All are radial tires. Tires 1 and 3 can carry 11 to 12 tons (the legal axle load limit for single axles is 10 tons), and tires 2, 4, and 5 can carry 8 to 8.5 tons (the legal limit for tandem axles is 16 tons). The diameter of Type 2 is 20 percent less than Type 1, and the Type 2 tire was used to provide more height for the load or to lower the trailer platform.

All the tires were measured with three axle loads—in most cases, 10 tons (or the nominal maximum), 20 percent more, and 20 percent less.

For each load, three tire pressures were used. The tire pressure recommended by the tire manufacturer for that tire and load was used as the base (optimal) tire pressure. The other tire pressures were, in most cases, 20 percent more and 20 percent less. The tire pressures varied from 480 to 1080 kPa, most common for optimal loads were 700 to 850 kPa.

A special difficulty in comparing wide-base and twin tires is that the load in twin tires is usually assumed to be divided evenly on both tires, which is seldom true. The uneven load distribution between twin tires may be a result of several factors:

- Tires did not wear evenly; for instance, one was older than the other,
- The manufacturer or the brand was not the same,
- The tire may have been new or retreaded,
- There was more or less fatigue in the carcass,
- Tire pressures differed,
- Tire temperatures differed and, as a result, tire pressures differed,
- Uneven road pavement (ruts, crown), and
- The camber angle or the bending of the axle.

The uneven load distribution between twin tires was simulated in a series of measurements where one tire had a tire pressure 500 kPa and the other 1000 kPa.

The vehicle consisted of a truck and a trailer. The front axle of the trailer was in a dolly, and the measured tires were installed in that axle. The load in the truck was kept constant all the time and was used as a reference for temperature corrections.

Hour-to-hour and day-to-day temperature variations are smallest during the fall, which is why measurements were taken in September and October. About 30 passes are usually needed to obtain a well-defined shape of the strain/transversal position (Figure 5), which required about 1600 vehicle passes.

During the measurements, 16 channels were used (five strain gauges for both pavements and three pressure cells at three levels for both pavements)—25,000 peak values for the tires to be compared. In addition, the strains due to the reference vehicle (front and tandem axles) were measured and handled. That means about 100,000 peak values of signals were stored and handled (all the signals were saved on diskettes for possible later use). The number of strain/transversal position figures of tires to be compared (Figure 5) was 852, and the total number (including the figures of the reference truck) was 3,300. Fortunately, not all of the reference truck figures were needed. To store and handle this data, sophisticated microcomputer programs were developed during the earlier research programs.

RESULTS

The main results are shown in Figures 6 and 7 as equivalencies as a function of axle loads. If the equivalency is, for instance, 2, the damaging power (aggressiveness) of that axle is twice that of the reference axle (a carrying 10-ton single axle with twin tires 12R22.5, the tire pressure 700 kPa) or the pavement lasts in that case only half as long as with the standard axle.

Figures 6 and 7 show that the traditional twin tire 12R22.5 causes the least stress on the pavement (least aggressive). The next best is the smaller twin tire 265/70R19.5. The wide-base tires are also more aggressive than twin tires. Within wide-base tires, wider tires are less aggressive than narrower tires.

The wide-base tires are relatively more aggressive on thin bituminous pavements than on thick pavements. All the tire types seem to have relatively the same sensitivity for the change of relative axle loads. For instance, 20 percent overload doubles the aggressiveness.

The axle loads that correspond to an equivalent value of 1.0 have been taken from Figures 6 and 7 and are presented in Table 1. The tire pressures are optimal.

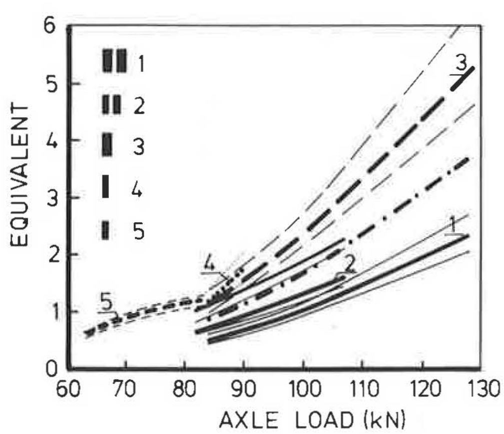

FIGURE 6 Equivalencies as a function of the axle load (bituminous layer thickness, 80 mm).

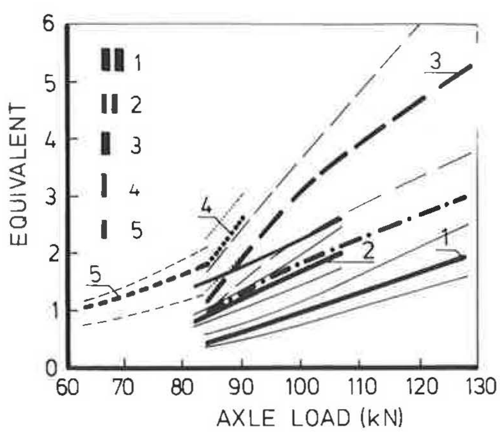

FIGURE 7 Equivalencies as a function of the axle load (bituminous layer thickness, 150 mm).

TABLE 1 AXLE LOADS CORRESPONDING TO REFERENCE AXLE AND EQUIVALENT VALUES CORRESPONDING TO 84-kN AXLE LOAD

	Equivalent Axle Load (kN) by Thickness of Bituminous Layers (mm)		Equivalent (84-kN) Values by Thickness of Bituminous Layers (mm)	
Tire Type	80	150	80	150
12R22.5 twin	100	100	0.33	0.35
265/70R19.5 twin	86	93	0.87	0.58
445/65R22.5	81	81	1.23	1.14
385/65R22.5	65	78	2.34	1.22
350/75R22.5	61	75	2.37	1.28

A vertical line was drawn in order to have equivalent values that correspond to the same axle load of 84 kN (Table 1). The 84-kN axle load was selected because it is the only load that has been used on all the tire types. The same kind of comparisons can be made for the whole area of Figures 6 and 7, but interpolation and extrapolation are needed, which may give misleading results.

The approximate effect of tire pressure can be seen in Figures 6 and 7. The equivalencies of all tire types as a function of tire pressure have been drawn in Figure 8 (the axle load is 84 kN).

It can be seen from Figure 8 that no optimal tire pressure exists from the standpoint of the pavement, which is contrary to the opinions of some tire manufacturers, but the equivalencies increase with tire pressure.

The effect of tire pressures and axle loads is presented in Figure 9 (reference twin tire 12R22.5). The comparisons between twin tires and wide-base tires are always theoretical to a certain degree, because the load is assumed to be evenly distributed on both twin tires. The uneven load distribution is simulated with tire pressures 500/1000 kPa, which increases the equivalencies by 60 percent.

The effect of tire pressures is shown in Figure 10. The values have been calculated so that the value is 1.00 with full-axle load and optimal tire pressure. The tires behave in different ways. Relative changes in the tire pressure give different changes in the load values.

The contact pressure distribution of some personal car tires is seen in Figure 11. The highest pressures are at the sides of the tires. It seems that pressure distribution differs among brands (those in Figure 11 are from different manufacturers). The measurements here are static.

It is often assumed that the contact pressure distribution of truck tires is similar. According to our few measurements, both static and dynamic, the highest pressure is always in the center, as seen in Figure 12 (static measurements).

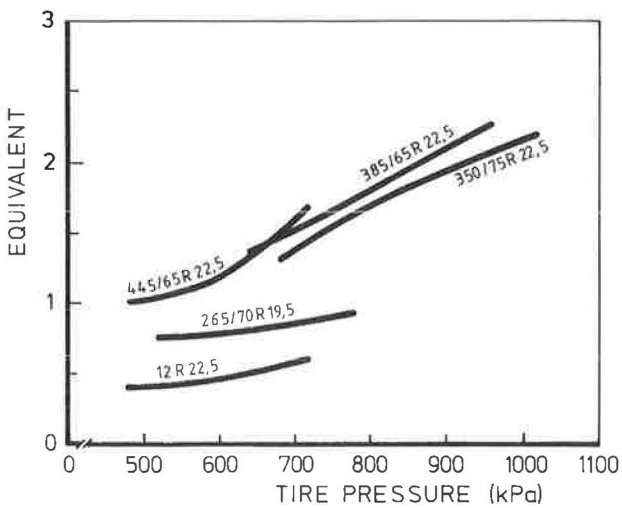

FIGURE 8 Equivalencies as a function of tire pressure (axle load, 84 kN; bituminous layer thickness, 80 mm).

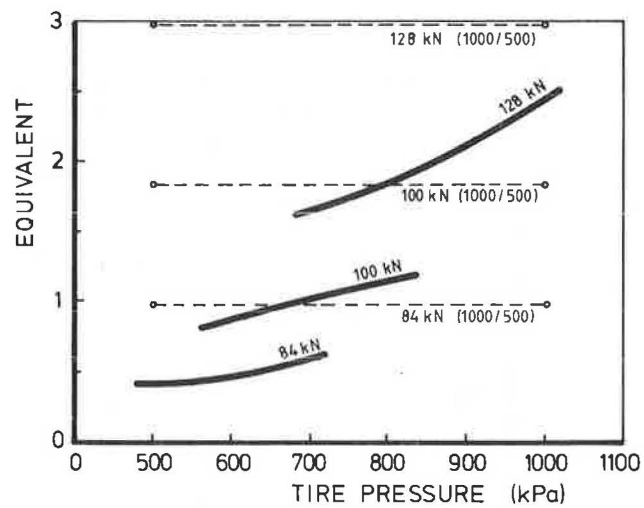

FIGURE 9 Equivalencies as a function of tire pressure (reference twin tire 12R22.5). Simulation of uneven load by tire pressures 500 to 1,000 kPa.

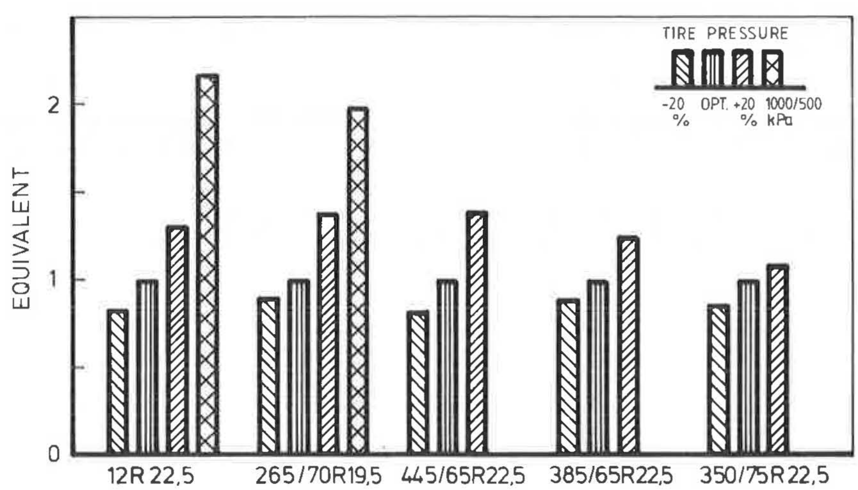

FIGURE 10 Relative values for the effect of tire pressure.

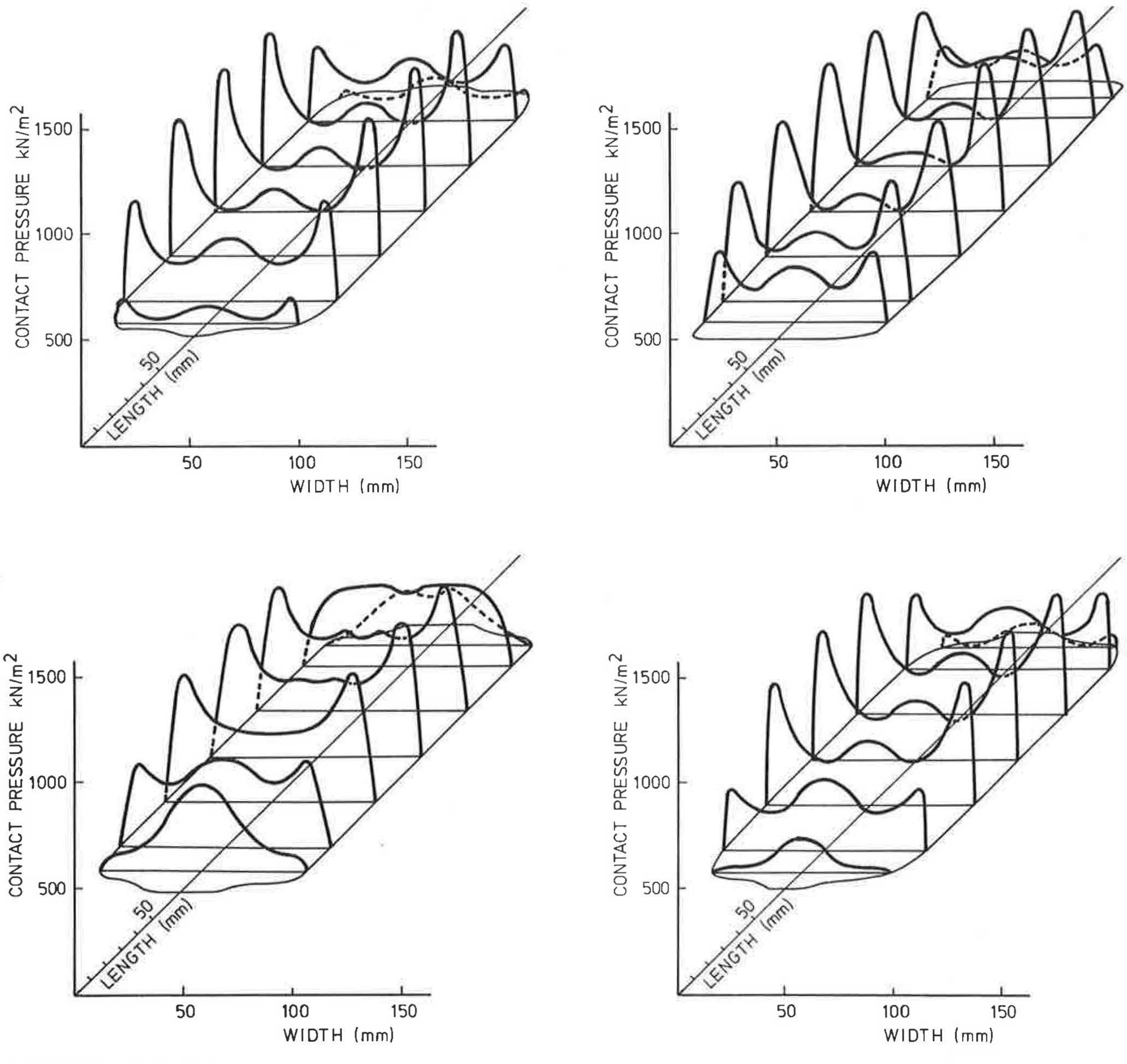

FIGURE 11 Static tire/pavement contact pressure distributions of different personal car tires.

CONCLUSIONS

The following conclusions concerning radial truck tires can be drawn:

1. Clear differences between tires and tire pressures could be found by response measurements. The response was changed to aggressivity, using fatigue curves (the exponent 4.2).
2. Wide-base tires are more aggressive than twin tires by a factor of 2.3 to 4.0 in ideal conditions for twin tires.
3. The load is seldom evenly distributed on both twin tires. The uneven load was simulated by tire pressures, 500 kPa in one and 1,000 kPa in another tire. Despite this, wide-base tires were more aggressive by a factor of 1.2 to 1.9 if they were compared to the most common twin tire. If they were compared to the small size twin tires, single tires were, in some cases, less aggressive by a factor of 0.8.
4. Among wide-base tires, there are differences by a factor up to 1.6.
5. Among wide-base tires, wider tires are less aggressive.
6. Smaller twin tires are more aggressive than normal size twin tires by a factor of 1.5 to 2.0.
7. All the differences are greater if the bituminous layers are thinner, and smaller if the layers are thicker.
8. As the tire inflation pressure increases, the aggressiveness increases; there is no optimum. An increase of 20 percent increases the aggressiveness 1.1 to 1.4 times.
9. The tire/pavement contact pressure distribution depends on the structure of the tire (for instance from different manufacturers), tire inflation pressure, and driving forces (driving

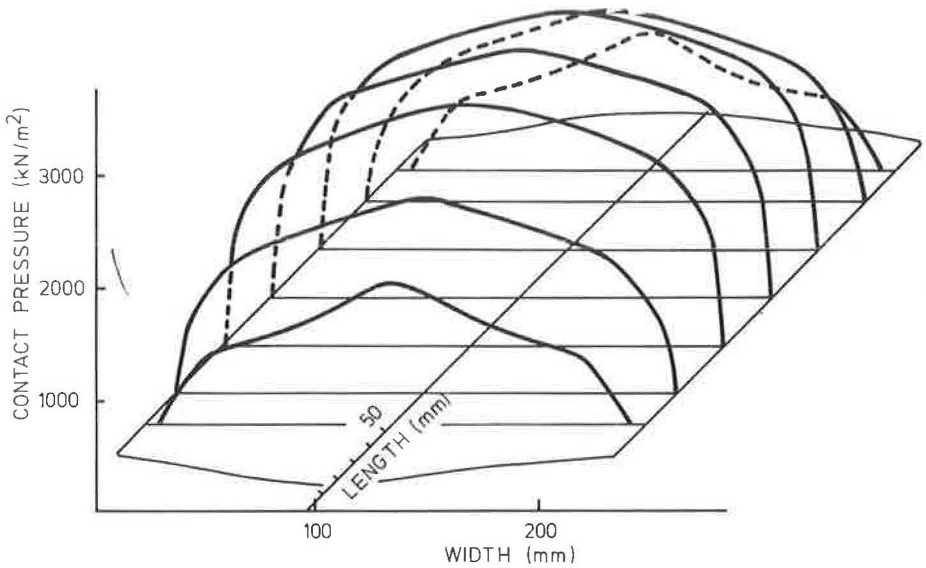

FIGURE 12 An example of static tire/pavement contact pressure distribution of a truck tire.

or carrying). The data are insufficient at this time for further conclusions.

10. The contact pressure between the tire and the pavement is greatest in the center for truck tires. In personal cars, the pressure is greatest on the sides (limited data are available at this time).

11. Only the aggressiveness to the road was studied in this research project. Other factors such as rolling resistance, safety, and economy will be considered in future studies.

SUMMARY

The results from the tire and tire pressure measurements have not been thoroughly analyzed yet, and the results presented here should be taken as preliminary conclusions. The final results will be published in 1989, also in English.

The research programs have always begun with a pilot study. The system for the dynamic axle load measurements has been developed (all axles in a vehicle simultaneously). The dynamic forces are correlated with the strains and stresses in the pavements. Measurements concerning the effect of unevenness have been made on artificial bumps and on ordinary highways. The comparisons of different suspensions have also been started. Data handling is time consuming, although the data-handling system is sophisticated.

A dynamic contact pressure measurement has been continued, but the data are limited at this time.

Although only the aggressivity to the road has been studied as yet, other aspects have not been forgotten, and it is likely they will be considered later. For example, as twin tires and wide-base tires are compared, other factors such as rolling resistance, safety, and economy should be considered.

ACKNOWLEDGMENTS

The Roads and Waterways Administration of Finland sponsored the development of the measurement system and most of the research. The Transport Research Commission (Sweden) sponsored most of the research concerning tires and tire pressures.

REFERENCES

1. M. Huhtala. The Effect of Different Heavy Freight Vehicles on Pavements. Presented at the Tenth International Road Federation World Meeting, Rio de Janeiro, October 1984.
2. M. Huhtala. The Effect of Different Trucks on Road Pavements. *Proc., International Symposium on Heavy Vehicle Weights and Dimensions*. Kelowna, British Columbia, Canada, June 8–13, 1986.
3. Organisation for Economic Co-operation and Development. *Full-Scale Pavement Tests*. OECD, Paris, 1985. 101 pp.
4. Swiss Federal Office of Highways. *Strain Measurements in Bituminous Layers*. Research Report No. 103, Bern, Switzerland, 1985.
5. I. F. Scazziga, A. G. Dumont, and W. Knobel. Strain Measurements in Bituminous Layers. *Proc., Sixth International Conference on Structural Design of Asphalt Pavements*, University of Michigan, Ann Arbor, 1987, pp. 574–589.

Publication of this paper sponsored by Committee on Flexible Pavement Design.