Impacts on the road and their effects on road construction and road preservation costs

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In order to update and to extend the findings of the AASHO Road Test, a research project was carried out in five stages with the main objective of investigating the effects of constructional design parameters of commercial vehicles on the impacts on the road. As a consequence of these investigations, the various effects caused by the type and contact pressure of the tyres and by the vibration characteristics of the vehicle were added to the static axle load. For calculating the impact on the road caused by a vehicle unit or by a whole vehicle fleet a formula for the influence factor was established. Moreover, the proportional relations between measured instantaneous wheel loads and strains in or on the surface of the pavements indicated that it will normally be sufficient to carry out the measurements on the vehicle and to use these values in a computer simulation model to determine the impacts on the road. The effects of increased impacts on the road on the costs of new construction and preservation of pavements were determined. The results show higher costs of up to 5 percent for new construction projects and of about 20 percent for the preservation of the existing federal trunk road network.

1. General information

For a better understanding of the following chapters it seems advisable to give some general information about the situation in the Federal Republic of Germany before reunification concerning the road network, the expenses for road construction and road preservation, heavy lorry traffic and the weights of commercial vehicles.

With about 500,000 km of roads the Federal Republic of Germany has a very well developed road network. The arteries of this network, the federal trunk roads, carry about half of the mileage travelled on all roads. Bituminous construction is the predominant type of structure of this network. Fig. 1 gives a rough overview of the standardized structures of bituminous pavements.

The various road building authorities spend a lot of money on roads year by year. In 1987, the investments for new construction and preservation of the federal trunk roads amounted to about 4.9 billion DM. As an estimate, about 40 percent of this are spent on pavements (Fig. 2), of which again 70 percent are to be attributed to heavy weight traffic.

Lorry traffic increased enormously in the past, demonstrated by the development of the kilometre-performance of goods transport by road (Fig. 3). It need not be mentioned that long-distance transport is predominantly using the motorways. The reunification of both parts of Germany and the realization of a single internal market in the European Community by 1993 have caused and will cause not only a growing demand for kilometre-performance in goods transport, but additional impacts on the road and the need to adapt the standards to be met by the roads.

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Fig. 2 Investments in federal trunk roads

Fig. 3 Development of lorry traffic

Finaliy, Fig. 4 presents the permissible gross weight of commercial vehicles at different time periods. As can be seen, the weights of two- and three-axle lorries and of four-axle articulated vehicles increased considerably. The establishment of "road-friendly" suspensions proposed with the aim of reducing the impacts on the road were used to increase the weight of some vehicles. Fig. 5 with the permissible axle loads shows that this "bonus" increased the tandem axle load too, besides the high axle load of 11.5 t allowed for the driving axle of the vehicle.
parameters of commercial vehicles on the impacts on the road.

The entire research programme comprised five stages:

In the 1st stage the effects of the type of tyre (single and twin tyre) and the contact pressure on the strain, measured on and within a bituminous pavement, were investigated.

In the 2nd stage an investigation was made as to how the supplementary dynamic loads can be influenced with measures taken on suspensions and dampening.

In the 3rd stage the running tests were continued to quantify the axle load dynamics on a cement concrete pavement as caused by joints and step formations in need of repair.

In the 4th stage supplementary investigations have been made to determine the influence of tandem and triple bogies on the impacts on the road.

The 5th stage was initiated to investigate the effect of axle load, type of tyre and tyre contact pressure on rutting.

As a consequence of these investigations the various effects of vehicle design parameters, e.g. type of tyres, tyre contact pressure, vibration characteristics of the vehicle, were added to the static axle load by using so-called equivalence factors. Thus we obtain an evaluation of the impact on the road with a better correspondence to practical conditions.

For calculating the impacts on the road caused by a vehicle unit or by a whole fleet the formula in Fig. 7 was established.

\[
\sigma = \sum_{i=1}^{N} \left( \eta_1 \eta_2 \eta_3 \eta_4 \eta_5 \right)^{\frac{1}{4}} \left( \frac{P_{\text{stat}}}{\text{stat}} \right)^{\frac{1}{2}}
\]

\[
\sigma = \text{Influence value for the impact on the road}
\]

\[
\eta_1 : \text{Equivalence factor for wheel type}
\]

(Single-tire wheel: \(\eta_1 = 1\)), Twin-tire wheel: \(\eta_1 = 0.9\)

\[
\eta_2 : \text{Equivalence factor for wheel contact pressure}
\]

\[
\eta_3 : \text{Equivalence factor for dynamic wheel load parameters}
\]

(Mean vibration characteristic: \(\eta_3 = 1083\), excellent vibration characteristic: \(\eta_3 = 1032\))

\[
P_{\text{stat}} : \text{Static axle load}
\]

\[
i : \text{ith axle}
\]

\[
N : \text{Number of axles per vehicle}
\]

Fig. 7 Influence factor for the impact on the road

2.2 Impacts on the road caused by wheel loads and the influence of the tyres

In the testing programme the following parameters were being varied:

- axle load
- size of tyres
- internal tyre pressure
- vehicle speed
- vibration excitation by passing a defined transversal sill.

To minimize dynamic wheel loads, a fully air-sprung lorry (6.5 + 13 t) was used and in addition a semi-trailer of an articulated vehicle.

The strains in the surfacing of a bituminous pavement caused by vertical forces were measured with strain gauges and compared with the values of wheel-load measuring devices on the vehicles.

Results

- The impact on the road at constant speed can be approximately determined by a sine-wave load. (This type of load application can therefore continue to be used in laboratory tests). The maximum strain is found at the instant of the vehicle passing without time lag.
- The strain decreases with increasing speed, but above approximately 40 km/h it remains nearly constant. (This can be explained by the material properties of the asphalt which depend on the load duration. This duration decreases with increasing passing speed which causes an increase of the dynamic elasticity modules. The theoretical findings have now been confirmed under practical testing conditions.)
- The maximum equivalent strain (for a biaxial stress condition) it is necessary to determine the equivalent strain, characterized by the longitudinal and transversal direction) under a twin tyre is 45 percent lower than that under a single tyre.
- The maximum equivalent strain increased by approximately 7 percent for the single tyre as well as for the twin tyres. The strain can be lowered by a bigger tyre size, due to an increased width and an increased distance
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of the wheel rims.
- The measurements of the wheel load on the vehicle indicated in all cases proportional relations between instantaneous wheel loads and strains in the surfacing.
- Taking some theoretical works into account, a twin-tyred wheel should only receive a bonus of 10 per cent which corresponds to the equivalence factor \( r = 0.9 \) in Fig. 7.
- In the case of the equivalence factor \( r = \frac{C_r}{C_s} \), Fig. 8 was derived from the results demonstrated before.

2.3 Quantification of the dynamic wheel load

Two road sections having a different roughness have been selected to study the effect of the dynamic wheel load variations on the impact on the roads. These roads were tested with two buses of the same model but with different spring and dampening characteristics, and with an articulated vehicle.

Measurements on the road were only performed on one road. At the surface, a length of 26 m was equipped with strain gauges, length 6 cm, located at intervals of 33 cm and partly 2.0 m.

The intention was to detect the half-wave of the axle natural frequency of 10 Hz and the body natural frequency of 1 to 2 Hz, which together essentially correspond to the dynamic wheel loads.

Results
- An important result was that for different runs with the same vehicle the maximum strain values for all testing speeds have always been recorded at the same point of the road (Fig. 9).
- The good correlation of the measurements of dynamic wheel loads on the vehicle and the strain measurements on the pavement was confirmed once again.

The vehicle with the softer body suspension combined with hardness dampening compared with the standard bus loads to a reduction of the dynamic load peaks. The shock factors are reduced by approximately 10 per cent from a range of between 1.4 and 1.55 to a range of between 1.3 and 1.4 under the same condition. The average effective wheel load, however, can only be reduced by about 3 per cent.

2.4 Impacts of dynamic loads on cement concrete pavements

Three vehicles were used for the measurements: a lorry equipped with a parabolic spring suspension and hydraulic vibration absorbers, a bus adjusted for "road-friendliness", and an articulated vehicle. The impact on the road was measured by strain gauges on the surface of the pavement.

Results
- The measurements confirmed the results of the relationship between the vibration characteristics and the strain on the road on the one hand and the good agreement between this measured strain and the instantaneous wheel load measured on the vehicle on the other hand.
- In future research work it will normally be sufficient to limit the measurement to those on the vehicle, instead of measuring the pavement strain on or within the surfacing, and to use these values in a computer simulation model to determine the impacts on the road. For this reason, there seems to be no need for follow-up investigations to the AASHO Road Test on roads only for the purpose of determining the influence of vehicle parameters on the behaviour of pavements.

2.5 Influence of vehicle suspension and dampening systems on the impact on the road

The vertical additional dynamic loads of fully loaded vehicles with single, twin and triple axle were determined on some test sections of a test area with constant test conditions and on a motorway.

Results
- Single axle

(a) On "good" roads, the mean shock factors of the peak values were below 1.3, on "average" roads about 1.4, and on "bad" roads about 1.7.
(b) In the case of axles equipped with leaf springs, the predominant vibrations due to the tyres were around 2 Hz because of frictional dampening.

(c) A modern lorry axle with parabolic springs in combination with hydraulic shock absorbers does not generate additional dynamic forces which are any higher in practice than an axle with air springs and dampening.

- Twin axle
(a) The highest recorded shock factors were between 1.3 and 1.45 on "good" roads and up to almost 2.0 on "bad" roads.
(b) The highest values always involved a lorry balance-arm unit with pull rods and can be attributed to unabsorbed pitching motion in the connection of the axles.
(c) Harder body-mounted springs and tyres always resulted in higher additional forces.
(d) The additional dynamic wheel loads can be drastically reduced with these systems by installing a shock absorber.

- Triple axle
(a) The highest recorded shock factors were between 1.2 and 1.5 on "good" roads and up to over 2.0 on "bad" roads.
(b) The latter value was recorded primarily in conjunction with a new axle-unit with elevated axle-equalization path and can also be attributed to unabsorbed vibrations in the axle connection.
(c) Installing shock absorbers did not significantly reduce the dynamic loads, but this aim is achieved by pneumatic suspension.
(d) The magnitude of the peak values and the effective value of the total wheel load differed by a factor of 3 or slightly more on all test sections. This confirms the approximately normal distribution of the roughness of a road.
(e) In all cases, the distribution of forces exerted on the road could be clearly attributed to the driving speed. Since all heavy commercial vehicles have approximately the same natural frequencies and travel at about the same speed on the trunk roads in particular, this means that the peak values of the additional dynamic wheel loads always occur on relatively limited sections of highway.

Related to the maintenance and rehabilitation needs of a road engineer, damage caused by those peak loads is also limited to relatively small areas of a road. Thus, the improvements of the vibration characteristics of a vehicle need not be evaluated on the basis of the question of how they can reduce the peak values but how they reduce the effective values. Only the latter represent the statistical characteristics of the road roughness and the average behaviour of a pavement and should, therefore, be used as the evaluation criterion for vehicle and road engineering.

As the correlations given in Fig. 10 show, the parameters which influence the effective dynamic load are, besides the vibration characteristics of the vehicle, its driving speed and the unevenness of the road. As was explained before, the impact on the road is related to the natural frequency of the wheels (8 to 15 Hz). Since the driving speed of commercial vehicles covers a range of up to 100 km/h, the corresponding range of wave lengths is between 0.5 and about 3 m, as Fig. 11 shows. Unevenness with wave lengths beyond this range influences other requirements on a road surface (driving safety, driving comfort, load protection) more than the impact on the road.

2.6 The effect of axle load and tyre characteristics on the rutting of asphalt pavements

Within the framework of the above-mentioned research programme the influence of wheel loads and inflation pressures on the development of rutting was examined on an experimental and theoretical basis. The tests were carried out at a test facility which enables the simulation of load and temperature conditions on real surfacings with defined supporting layers.

Fig. 12 shows the results of the experimental and theoretical examinations. They confirm the well-known relationship between deformation processes and the square root of the load repetitions. As you can recognize, type of tyre, wheel or axle load and the internal tyre pressure substantially influence the development of rutting on asphalt pavements.
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Sine - shaped unevenness function, depending on
the time and the distance

\[ T = \text{Period of vibration} \]
\[ L = \text{Wave length} \]
\[ w = \text{Circular frequency} \]
\[ n = \text{Number of load passes} \]
\[ \text{Material-related coefficient} \]
\[ b = -0.05 + 0.0023 \cdot Q \]
where: \( Q = \text{Wheel load (kN)} \)
\[ \text{Internal tire pressure (bar)} \]
\[ \text{Number of lane divisions} \]
\[ \text{Width of the relevant lane} \]
\[ \text{Gradient of the road} \]
\[ \text{Influence on the road} \]

**Fig. 11** Correlation between wave length of unevenness, driving speed and frequency-ranges of heavy vehicles

**Fig. 12** Correlation between axle load, tyre type and tyre pressure and rut depth

3. Adaptation of the road network to the increasing impacts on the roads

In the past, the pavements of federal highways had been adapted to the development of maximum axle loads and gross weights in a sufficient manner, especially during the last two decades when the limit values remained nearly constant. But now we are forced to adapt the structural design guidelines to the increased impacts on the roads.

The Federal Highway Research Institute estimated the additional impacts on the roads taking into account the "influence values for the impact on the road" of the individual types of vehicle and their mileage performed on the various road categories.

The results of this estimate are shown in Fig. 13. The impact on the pavements caused by the total vehicle fleet expected in future (without or only with partly realized "road-friendliness") will rise to about 45 to 50 per cent of the value caused by the vehicle fleet with 10 t driving-axle load for which the pavements are designed. Therefore, we added a factor \( f_{SV} \) of 1.5 to the relevant load figure (Fig. 14).

**Fig. 13** Additional impacts on the road caused by various vehicle fleets

\[ VB = DTV(SV) \cdot f_p \cdot f_{t1} \cdot f_2 \cdot f_3 \cdot f_{SV} \]

**Fig. 14** Relevant traffic load figure for the classification of pavements
The difficulties arising in connection with the higher impacts on the roads are naturally far less applicable to the building of new roads than to the adaptation of the existing road network. We are not only obliged to strengthen the pavements. We will do this by standardizing so-called strengthening classes corresponding to the condition of the road. But we also have to improve the stability of the asphalt mixtures because we expect a growing development of ruts due to traffic by heavy vehicles.

4. Cost aspects

When determining the effects of the increased impacts on the roads on the costs, one must distinguish between the additional costs related to
- the construction of new pavements,
- the preservation of existing pavements.

Taking into account the additional impact factor \( f_a \) in the formula for calculating the relevant traffic load figure, this will roughly lead to a 4 cm thicker base course in new road construction, which can easily be assessed in terms of money (about 7 DM/m²).

Related to the preservation of roads the frequency distributions of axle load classes can be transformed to standard axle load applications with the aid of the formula for the influence factor of the impact on the road \( f_a \). With the simplifying assumption that the preservation intervals \( \Delta t \) change in relation to the number of equivalent standard axle applications, the preservation costs can be determined as a function of \( \Delta t \) on the basis of a so-called "flexible preservation strategy model". The required input data are

- road stock data and their future changes
- investment time series
- preservation intervals (rehabilitation, reconstruction)
- type of preservation measures
- unit costs of these measures.

A study carried out recently (Fig. 15) showed a tremendous increase in funds required for the preservation of the federal trunk roads due to the increase of axle loads and of traffic volumes, both for pavements and for bridges.

A more comprehensive study including not only the additional costs for the individual road authorities but also costs (and benefits) for the road user, conducted by the Battelle Institute, showed that any increase in permissible axle load would result in an overall benefit, that means a benefit-cost ratio above 1.0 (Fig. 16). But as we can see, an increase in gross weights, without increases in permissible driving-axle load or even when we reduce it, would be the most profitable solution for the national economy.