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 surfacing 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.
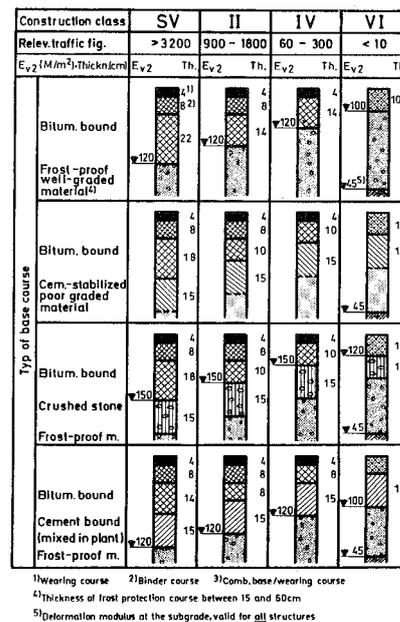

Fig. 1 Standardized structures of bituminous pavements

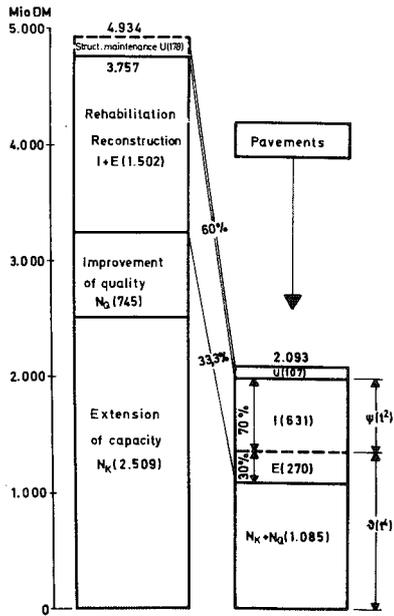*Heavy vehicles and roads: technology, safety and policy.* Thomas Telford, London, 1992.
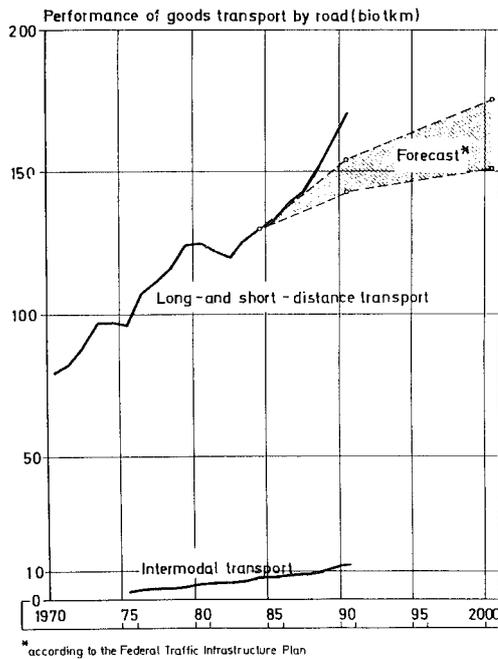
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Fig. 2 Investments in federal trunk roads

Fig. 3 Development of lorry traffic

Finally, 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.

Gross weight (t)		Before	After	Limits	
			19.7.1986	1.8.1990	Tendency
Lorry	2 axles	16,0	17,0	18,0 *	
	3 axles	22,0	24,0	26,0 *	
	4 axles	30,0	32,0	32,0 *	
Trailer	2 axles	16,0	18,0	18,0	20,0 **
	3 axles	22,0	24,0	24,0	
Road train LZ	(2+1)	26,0	27,0	28,0	
	(2+2)	32,0	35,0	36,0	
	(2+3),(3+2)	38,0	40,0	40,0	
Articulated vehicle SZ	(2+1)	26,0	27,0	28,0 *	
	(2+2)	36,0	35,0	38,0 *	
	(2+3) (3+2)	38,0	40,0	40,0	(44,0)
SZ with container (intermodal transport)		44,0	44,0	44,0	

x) Driving axle(s) with twin tires and airsprings or comparable springs
xx) Semi trailer

Fig. 4 Permissible gross weight of commercial vehicles

Axle loads (t)		Before	After	Limits	
			19.7.1986	1.8.1990	Tendency
Lorry, tractor					
Single axle		10,0	11,0	11,5 *	
Double axle		16,0	18,0	19,0 *	
Trailer					
Single axle		10,0	10,0	10,0	(11,0)
Double axle	(space d < 1,0 m)	10,0	11,0	11,0	
	(1,0 ≤ d < 1,3 m)	16,0	16,0	16,0	
	(1,3 ≤ d < 1,8 m)	16,0	18,0	18,0	
	(d ≥ 1,8 m)	16,0	20,0	20,0	(22,0)
Triple axle	(d ≤ 1,4 m)	22,0(24,0)	21,0	21,0	
	(1,3 < d ≤ 1,4 m)	22,0(24,0)	24,0	24,0	(26,0)

x) Driving axle(s) with twin tires and airsprings or comparable springs

Fig. 5 Permissible axle load of commercial vehicles

2. Impacts on the road

2.1 Introduction

A vehicle causes an impact on the road in the contact zone between the vehicle and the roadway, e.g. in the tyre contact areas. As demonstrated in Fig. 6, vertical, longitudinal and lateral forces can be effective here, which are influenced by the different components of the "circle-of-interaction vehicle/roadway/driver". In the following only vertical forces composed of the static and the dynamic axle load are considered. Here a differentiation has to be made between the impacts of the traffic load on the structural behaviour of the pavement and on the formation of ruts at the surface of bituminous pavements.

In order to update and to extend the findings of the AASHO Road Test a research project, jointly financed by the Association of the German Automobile Industry (VDA), the Federal Minister of Transport and the motor vehicle manufacturers Daimler-Benz and MAN was being undertaken with the main objective of investigating the effects of constructional design

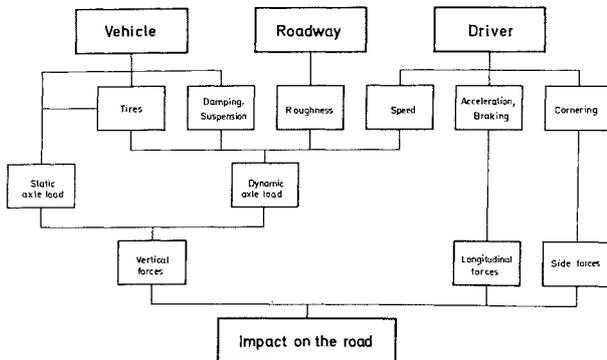parameters of commercial vehicles on the im-
pacts on the road.

Fig. 6 Circle-of-interaction vehicle/roadway/
driver

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 con-
tinued 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 η . Thus we ob-
tain an evaluation of the impact on the road
with a better correspondence to practical con-
ditions.
For calculating the impacts on the road caused
by a vehicle unit or by a whole fleet the for-
mula in Fig. 7 was established.

$$\vartheta = \sum_{i=1}^{N} (\eta_I \cdot \eta_{II} \cdot \eta_{III} \cdot P_{stat})_i^4$$

ϑ = Influence value for the impact on the road

η_I : Equivalence factor for wheel type
(Single-tire wheel: $\eta_I = 1$), Twin-tire wheel: $\eta_I = 0,9$

η_{II} : Equivalence factor for wheel contact pressure

η_{III} : Equivalence factor for dynamic wheel load parameters
(mean vibration characteristic: $\eta_{III} = 1,083$,
exellent vibration characteristic: $\eta_{III} = 1,032$)

P_{stat} : Static axle load

i : i^{th} axle

N : 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 para-
meters 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 mea-
sured 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 con-
  ditions.)
- 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

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 η_{I} = 0.9 in Fig. 7.
- In the case of the equivalence factor η_{II}, Fig. 8 was derived from the results demonstrated before.
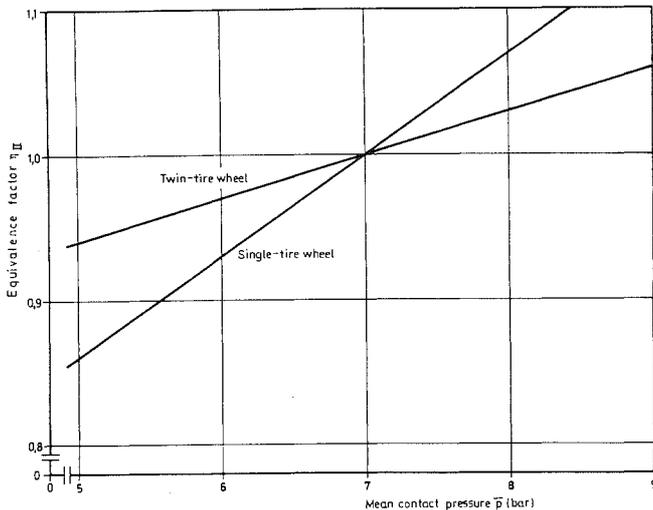

Fig. 8 Equivalence factor for wheel contact pressure

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 harder dampening compared with the standard bus leads 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.
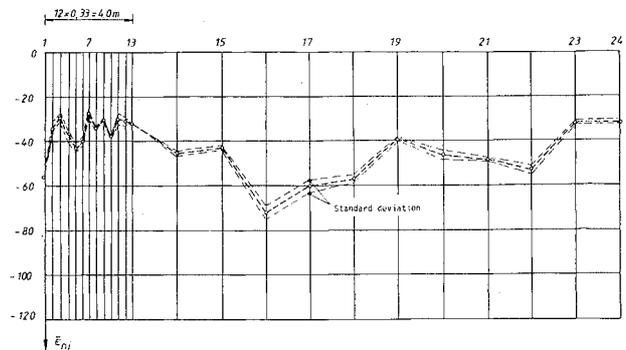

Fig. 9 Measured surface strain on the pavement

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.
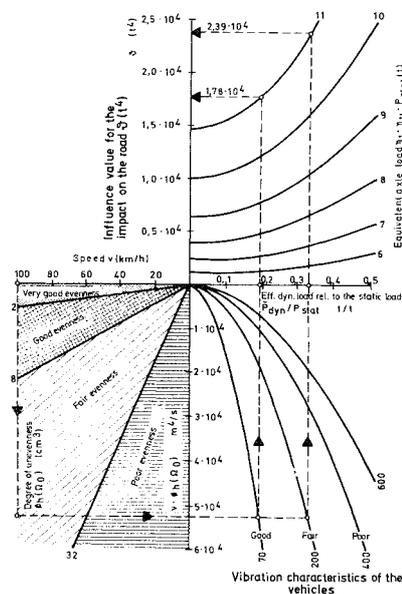

Fig. 10 Correlation between the various influences on the impact on the road

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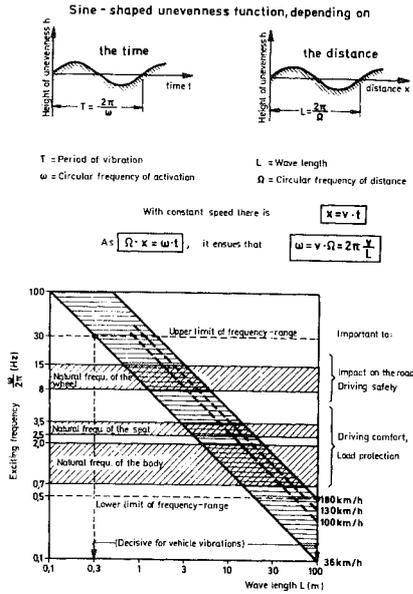
Fig. 11 Correlation between wave length of
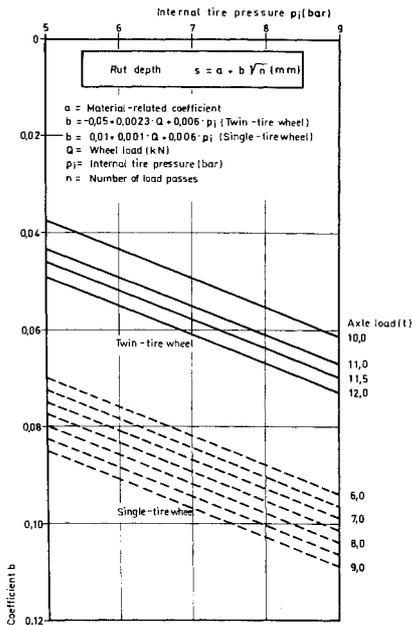unevenness, driving speed and fre-
quency-ranges of heavy vehicles

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 esti-
mated 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 pave-
ments are designed. Therefore, we added a
factor f_{sv} of 1.5 to the relevant load figure
(Fig. 14).

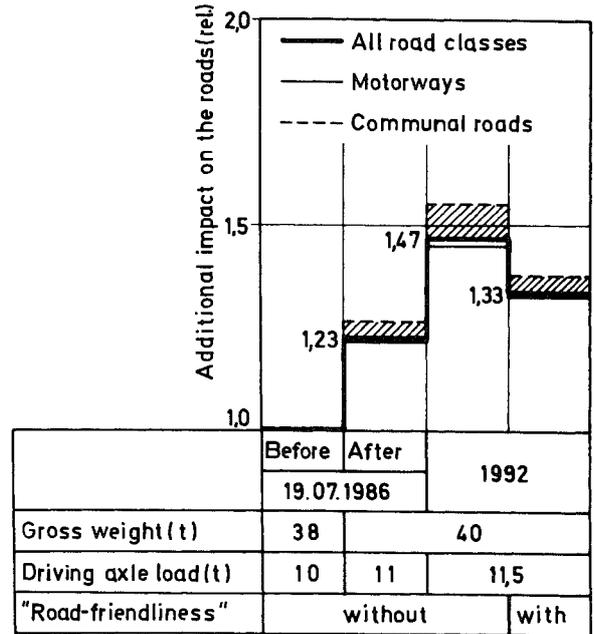|	Before	After	1992
	19.07.1986		
Gross weight (t)	38	40	
Driving axle load (t)	10	11	11,5
"Road-friendliness"	without		with

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

$$VB = DTV^{(SV)} \cdot f_p \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_{SV}$$

VB   = Relevant traffic load figure

$DTV^{(SV)}$ = Average daily traffic of heavy weight vehicles
in a cross-section at the open-to-traffic time

f_p = Factor for the evolution of $DTV^{(SV)}$

f_1 = Factor for the number of lanes in the cross-section

f_2 = Factor for the width of the relevant lane

f_3 = Factor for the gradient of the road

f_{SV} = Factor for the additional impact on the roads

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 road 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_{sv} 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 $\mathcal{N}$. With the simplifying assumption
that the preservation intervals Δt change in
relation to the number of equivalent standard
axle applications, the preservation costs can
be determined as a function of Δt 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 per-
missible 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 in-
crease in gross weights, without increases in
permissible driving-axle load or even when we
reduce it, would be the most profitable solu-
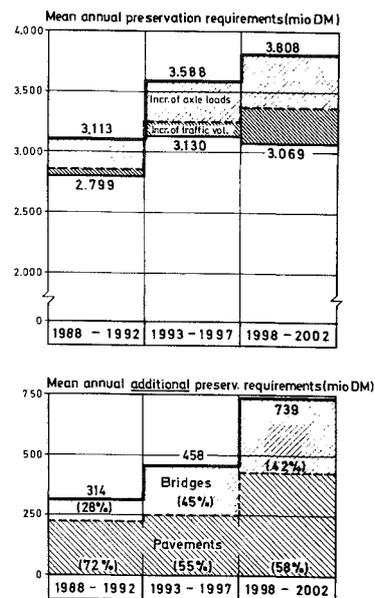tion for the national economy.

Fig. 15 Development of the preservation
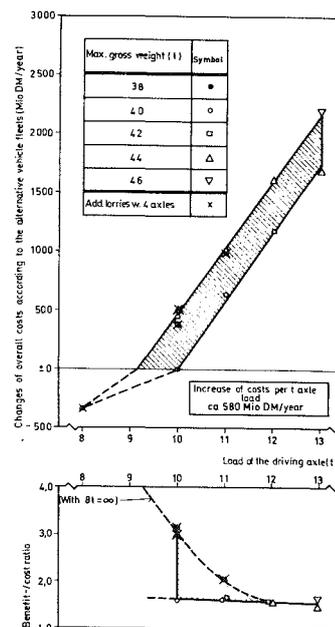requirements for federal trunk roads

Fig. 16 Overall costs according to alternative
vehicle fleets