The Trailer Coupling - a Neglected Sub-System?

by H.G. Naundorf and K.P. Weibel, BMW AG/Munich, Fed. Rep. of Germany

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1. Introduction

The automobile was invented in 1886. Although originally conceived as a solo machine, our predecessors rapidly hit upon the idea of using it to tow another vehicle. What they needed was a coupling device between the pulling car and the towed vehicle. A lot of devices were invented.
But of greatest interest was the patent letter of the Westfalia Company Nr. 613435 of the year 1934. It described a ball-head trailer coupling which is still used today. The first car which was assembled with this ball-head trailer coupling was a Dixie 6/24. This Dixie was built by the Eisenach Motor Company, the later BMW plant, fig. 1.

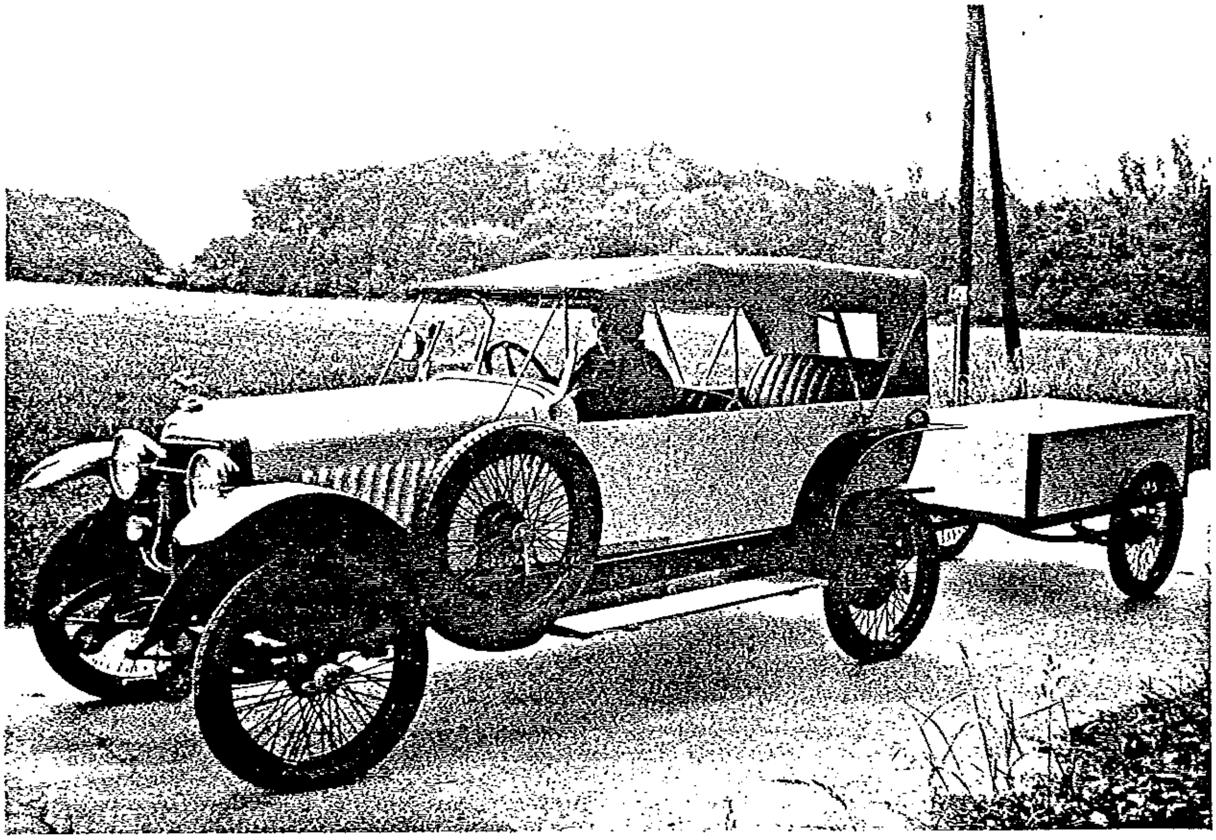


Fig. 1: Dixie 6/24, pulling a trailer

Today, the use of automobiles to pull trailers is a more topical matter than ever before. The high degree of mobility, afforded by the automobile, is playing an increasing part in our modern leisure-oriented society. Fig. 2 shows a car and trailer outfit with a keel-yacht of impressive overall dimensions, sufficient to dwarf even such a large car as the BMW 7′ series.

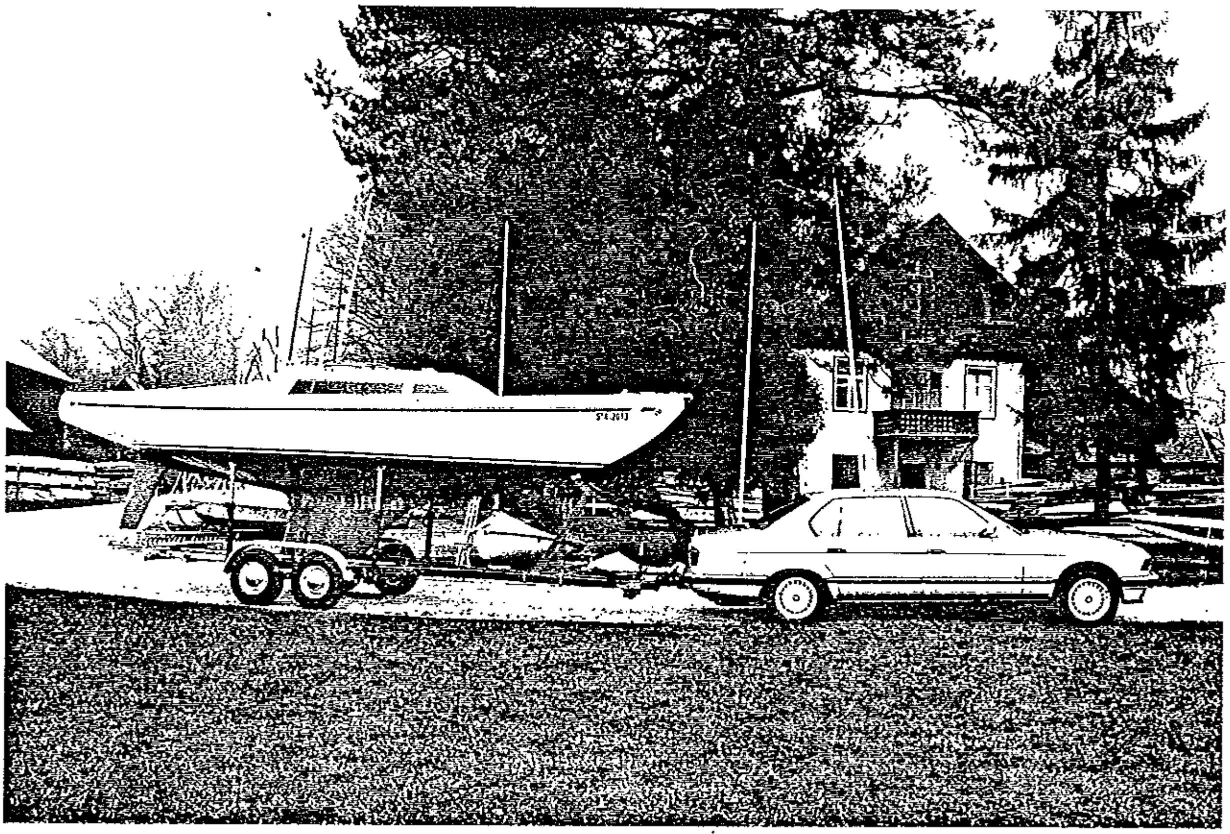
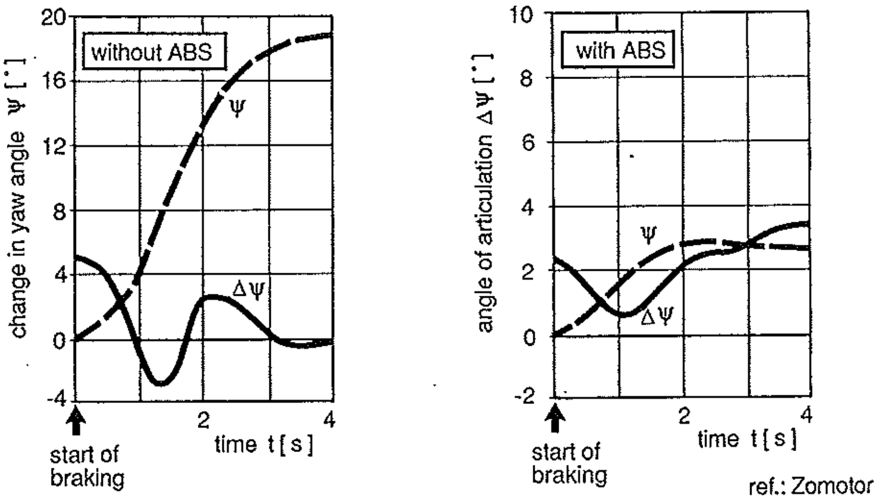


Fig. 2: BMW 7′ with a trailer, carrying a keel-yacht

The demands, imposed by trailer towing, lead to dynamic driving problems and problems of operating strength in connection with the innocent-looking, almost invisible trailer coupling, and the thin sheet metal of the unitary construction car body. Both which are extremely difficult for the layman to conceive.
This paper is intended to describe the varied and extensive development work which has to be invested in even this seemingly "harmless" vehicle component.

2. Dynamic driving considerations

Towing a trailer has drastic effects on the vehicle response, of which the driver of a solo vehicle is accustomed: performance, hill-climbing ability, dynamic stability and braking all vary from the normal standards, particularly in extreme situations. However, many of the technical devices and systems which have been introduced to render the solo vehicle safer, such as the power steering, anti-lock braking system, anti-slip control, self-levelling suspension and automatic transmission, also improve the behaviour of the car and trailer combination. Fig. 3 exemplifies this. [1]



ref.: Zomotor

Fig. 3:

Influence of ABS to car/trailer driving stability

Measurements were conducted around a bend of 100 m radius at a speed of 80 km/h. Without ABS the trailer combination skids straight out of the bend, with ABS the trailer outfit remains tractable. Further investigation with ABS on the trailer (SCS of Lucas Girling Company) shows interesting improvements. [2]

The system components attached to the towing vehicle, the coupling, towbar and trailer suspension, were for a long time treated with neglect by those responsible for development work, but recently the manufacturers of these sub-systems have studied them more closely, both from a purely theoretical point of view in the interests of science and with regard to the properties of the overall system, as it concerns the automobile manufacturer.

Improvements to towing vehicles were referred to above. Those relating to the trailers themselves primarily involve chassis and suspension measures: independent suspension for tandem-axle trailers, tyres of larger dimensions, improved dampers and brakes. Careful tuning of suspensions in conjunction with various towing vehicles has also led to automobile manufacturers recommending specific types of trailer for use with their vehicles.

Manufacturers of towing attachments have introduced couplings with detachable ball heads and devices to increase the stability of the complete outfit.

Instability (or snaking) is incurred as a result of disturbances acting on the car and trailer combination, for example lane changes, load-reversal reactions and gusts of wind from the side. When assessing the dynamic stability, reference is made to the attenuation (or decay) of movements representing changes in the angle of articulation between towing vehicle and trailer (fig. 4).

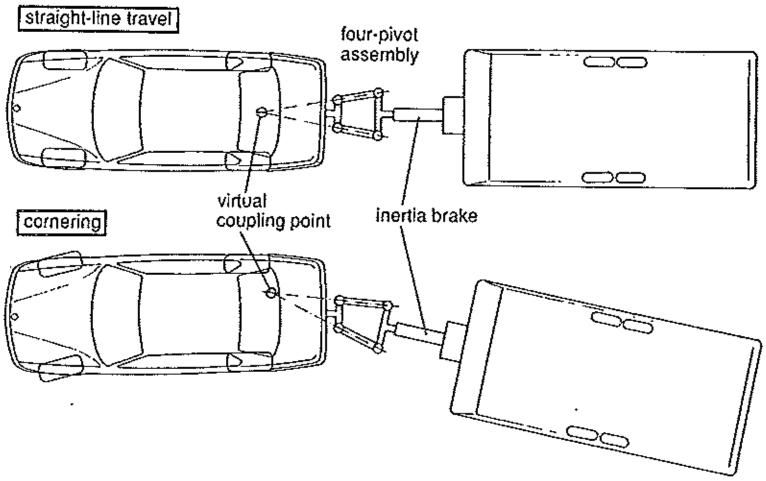


Fig. 4:

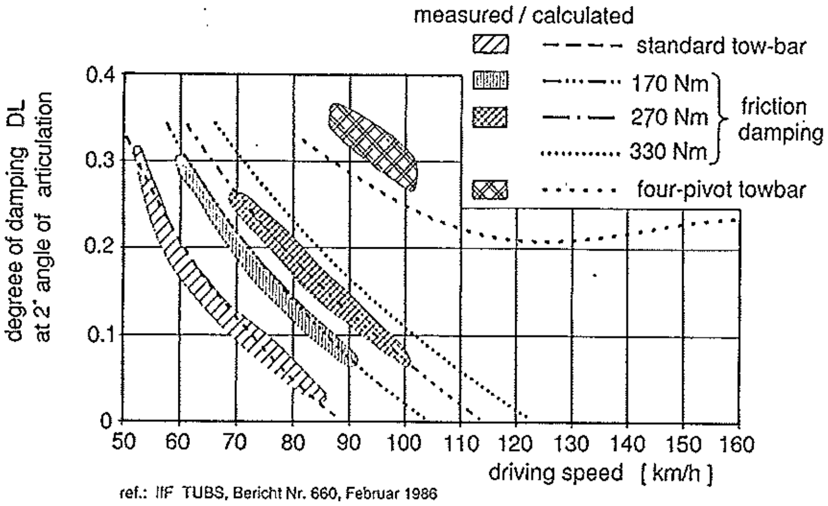
Four-pivot trailer coupling

The damping process decreases as road speed goes up. The critical driving speed v_{crit} is that at which no further damping of articulation movement takes place. Most car and trailer combinations revert to this condition at a road speed of between 90 and 120 km/h, but in some cases the critical driving speed has proved to be even lower. The graph shows the results of several outfits: measured values (scattered zones) and calculated values (single curves).

Influence of damping is obtained by using a friction damper or by taking a trailer coupling with virtual towbar extension, fig. 5.

Indeed if this type of coupling is adopted, it becomes impossible to determine any finite critical speed.

The 4-pivot coupling with virtual tow-bar extension has not become series production, because of the disadvantage of the complication mounting the trailer to the pulling vehicle.



ref.: IIF TUBS, Bericht Nr. 660, Februar 1986

Fig. 5:

Influence of damping to the critical driving speed

3. Customer use, basis for evaluation

The previous section made reference to measurable physical (dynamic driving) principles. However, company-philosophical considerations also play a part when one comes to examine the manner in which customers drive their car and trailer combinations, and when considering the associated strength assessment principles.

This was borne out at the start of body strength testing in the BMW operating strength laboratory back in 1972, on cars exposed to trailer towing loads and using real-time roadgoing programs. The test program measured and run in this case led to massive body damage with a very short time, the consequence of a large number of extreme situations having accumulated, e.g. repeated starting on a 20 % gradient, starting with the driver's foot slipping off the clutch pedal, pulling boats out of the water on river banks and driving on very poor road surfaces, like gravel-roads.

It was therefore decided to introduce a relative element to this extreme test situation philosophy by conducting a customer survey. BMW's Service Division asked customers who applied for an increase in their cars' permitted trailer loads to complete a questionnaire which then served as a basis for selecting a test program equivalent to the most demanding customer usage requirements.

A statistical limit value of H95 was selected for data evaluation, with extreme values suppressed. (For example, two of the customers who completed the questionnaire stated that they towed a trailer for approximately 50,000 kilometres per year. On checking with these customers, they were found to be caravan manufacturers' sales representatives!) The results are shown in fig. 6.

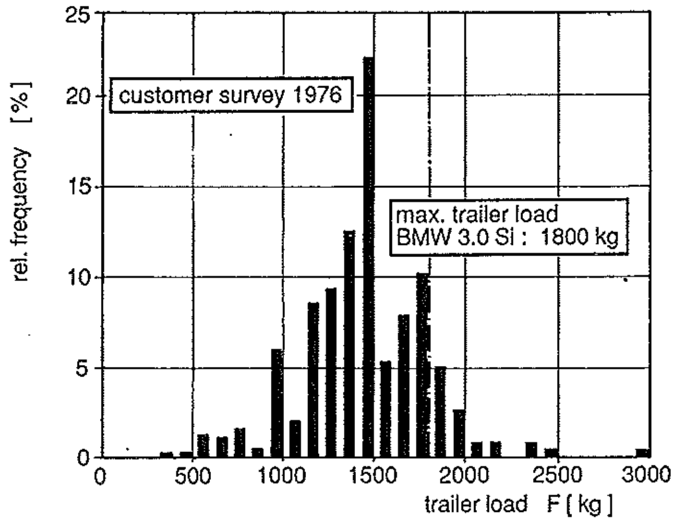


Fig. 6:

Towed loads of the BMW model range

It will be seen that towed loads ranged from 300 to 3,000 kg, in other words, in isolated cases the permitted trailer load of even the largest towing vehicle (2,070 kg) was considerably exceeded. The mean value was approx. 1,450 kg.

Fig. 7 shows the annual distances covered while towing a trailer. The average was approx. 3,500 km, comprising some 1,800 km on highways, 1,000 km on ordinary main roads, 600 km on country roads and 100 km on untarred roads.

Fig. 8 indicates practical use distribution. 48 % of the trailer were caravans, followed by 22 % horseboxes and smaller proportions of boat, car-carrying and general-purposes trailers.

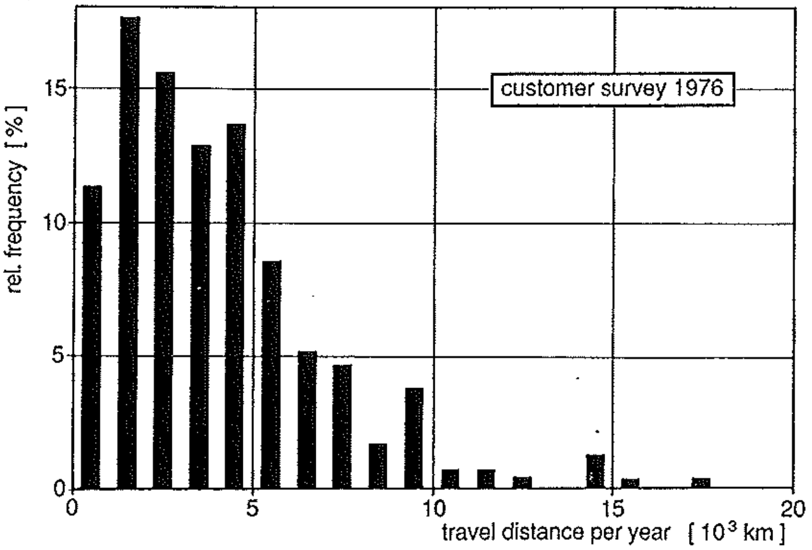


Fig. 7:

Distances covered when towing a trailer

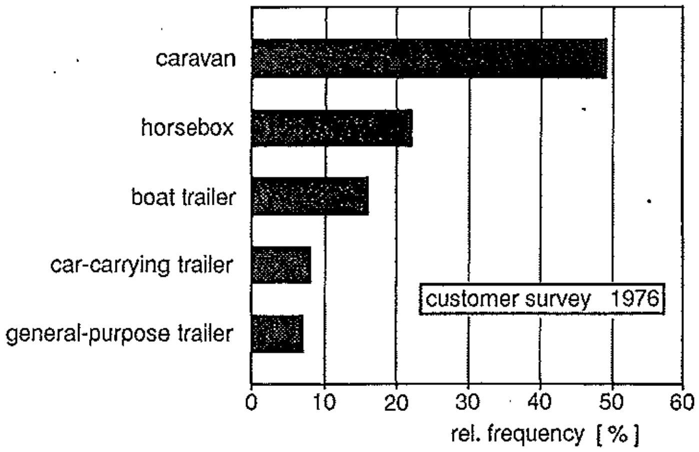


Fig. 8:

Trailer utilization

Other items of interest from the survey results are:

- 83 % of all trailers had tandem axles
- 33 % had installed a damper or similar device to prevent snaking and jack-knifing
- 47 % normally towed their trailer on long journeys only
- 65 % claimed to drive "briskly"
- under 20 % claimed to drive in a "sporting" or "hard" manner

4. Measuring technology

The measurement process is part of overall development activity, and the availability of suitable measuring equipment is an essential factor in operating strength testing.
This situation is clearly indicated in fig. 9, in which the work sequence through data aquisition, signal processing and operating strength testing can be followed.

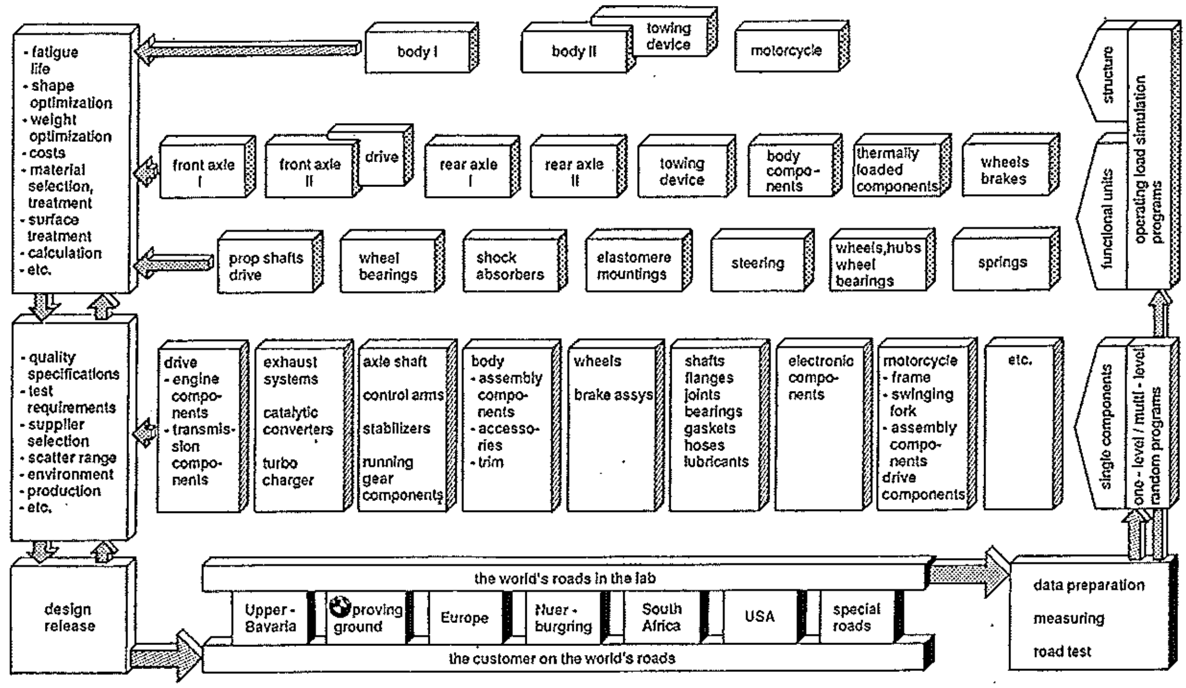


Fig. 9: Map of the BMW's test rig family (operating strength)

Since the technologies involved are well known (PCM tape recording, counting methods and frequency analysis by computer), there would seem to be no necessity to describe details of data recording and the further stages in signal processing, however, certain unusual details none the less deserve mention.

The measuring device initially adopted used discrete force sensors for the three spatial axes, see fig. 10.

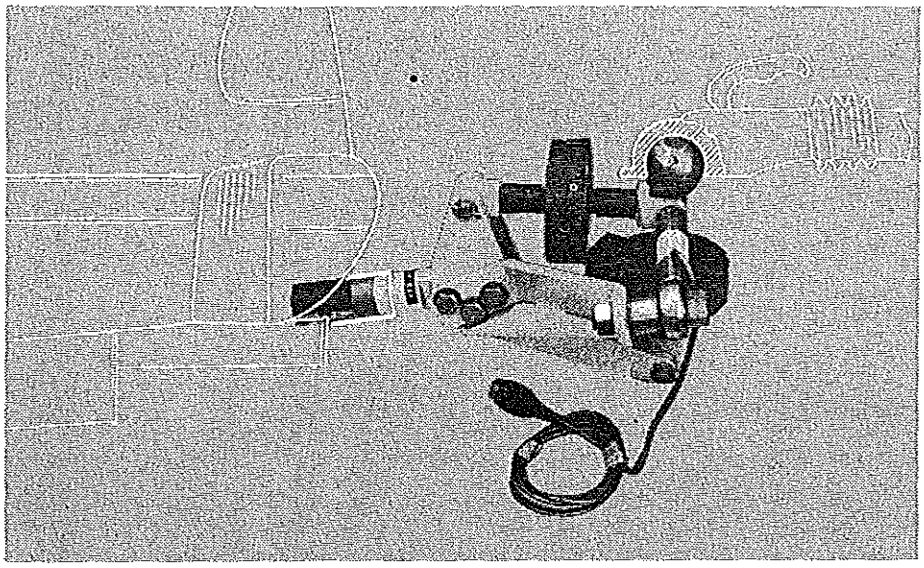


Fig. 10:

Load cell for towing forces (1st generation).

Problems arose when it came to accommodating the relatively bulky load cell in the cut-away ball-ended rod. Direct mounting of the strain gauge on the ball-ended rod was rejected on account of a lack of response sensitivity and the inability to compensate in full for the mutual influences of longitudinal, lateral and vertical forces.

Further simplification became possible with the advent of the three-dimensional compact load cell manufactured by the Kistler company, using a piezo-electric measuring system.

New problems arose when the trailer coupling with virtual towbar extension was examined. The desired effect is obtained by a four-pivot linkage located behind the ball head. In view of the presence of these additional pivots, the ability of the towbar socket to move on the ball had to be inhibited. This naturally led to moments being generated in addition to the lateral forces at the ball head, which then had to be recorded by a suitable device. Their significance in terms of operating strength had to be established and the necessary design measures taken to withstand them.

Initially, two of the above-mentioned three-dimensional force sensors were employed for this purpose, however, the risk of damage to the sensors in that configuration was high. Accordingly, four such sensors, making 12 channels in all (fig. 11) were adapted although this was not necessary to obtain a full pattern of the loads occurring.

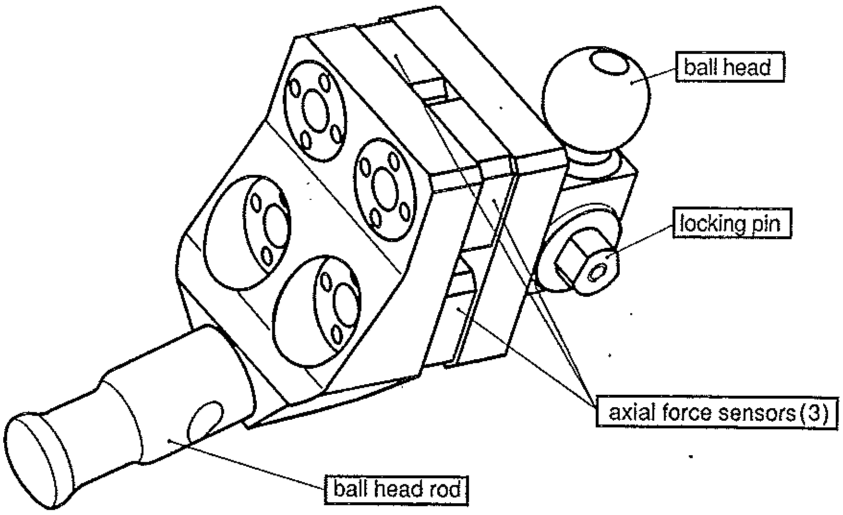


Fig. 11:

Load cell for towing forces and moments

This change also meant considerably greater complexity in the measured signal processing equipment and the controlling of the servo-hydraulic test actuators. The 12 measurement signals were used to generate three translational desired-value signals in the various axis, and a moment around the vertical axis of the ball towing head (which was locked out of action as previously described). Linear mathematics linked the individual measurement channels, as derived from the geometric relationship to the desired test rig. Actuating signals were generated elegantly by means of an analog computer. This (currently somewhat neglected) instrument, among those at the engineer's disposal has an advantage compared with digital computers, which require a knowledge of program language and a corresponding degree of programming work if they are to perform such tasks, of permitting direct transfer of the mathematical relationship to the plug board. The result of this process is shown in fig. 12.

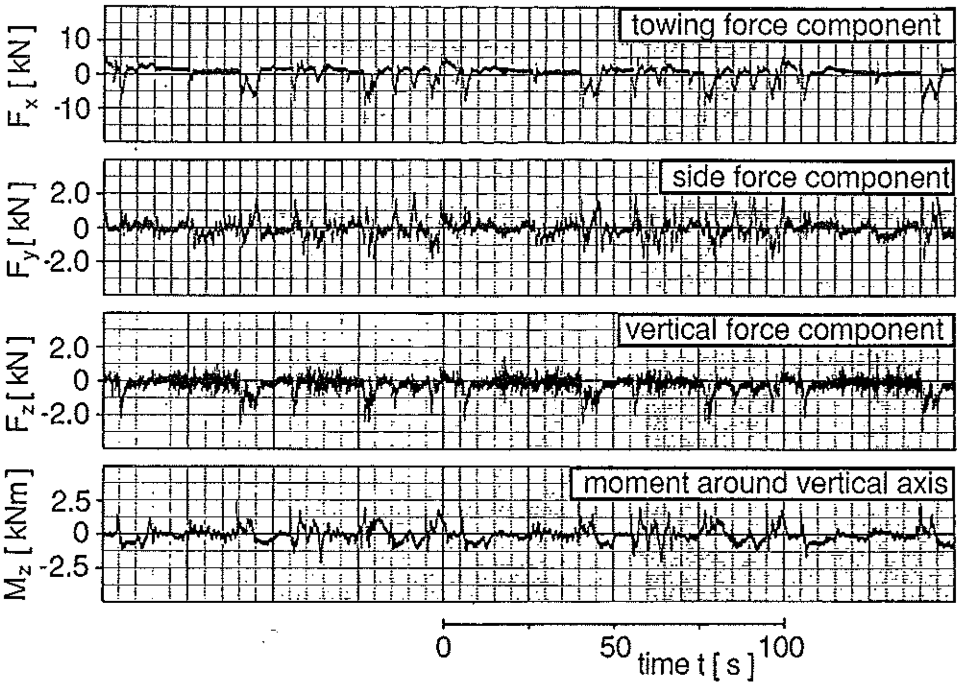


Fig. 12: Towing with four-pivot assembly/Ball head loads

5. Test rig technology

5.1 Body testing with particular reference to trailer towing

At this point, reference should once again be made to fig. 10, in which the "world's roads are transferred to the laboratory". This process commences with the recording of relevant data from the BMW proving ground, German roads and those in other European countries, the USA and South Africa, as well as special-purpose roads such as the Nuerburg Ring racetrack. After processing, this data is used as described in more detail above to actuate operating strength test rigs. The equipment comprises of anything from a test rig for almost complete vehicle to complex test rigs for part-structures, e.g. front and rear suspension assemblies, and also constant amplitude fatigue tests on individual components. The circle is completed by way of the design and production departments, and the customers who in due course drive the vehicles on the very roads which have formed the test program inputs [3].

Fig. 13 shows a four-component body test rig for simulating situations in which the operating strength of towing forces is the factor. It is capable of applying vertical towbar load, tractive load, lateral load and bodyshell torsion. However, the disadvantage of this form of body testing conducted separately from solo vehicle operation is that the full extent of the applied loads are incomplete as a result of more than one load occurring simultaneously. Time is lost on account of the additional complexity of mounting the body on a separate test rig and an additional prototype bodyshell has to be made available.

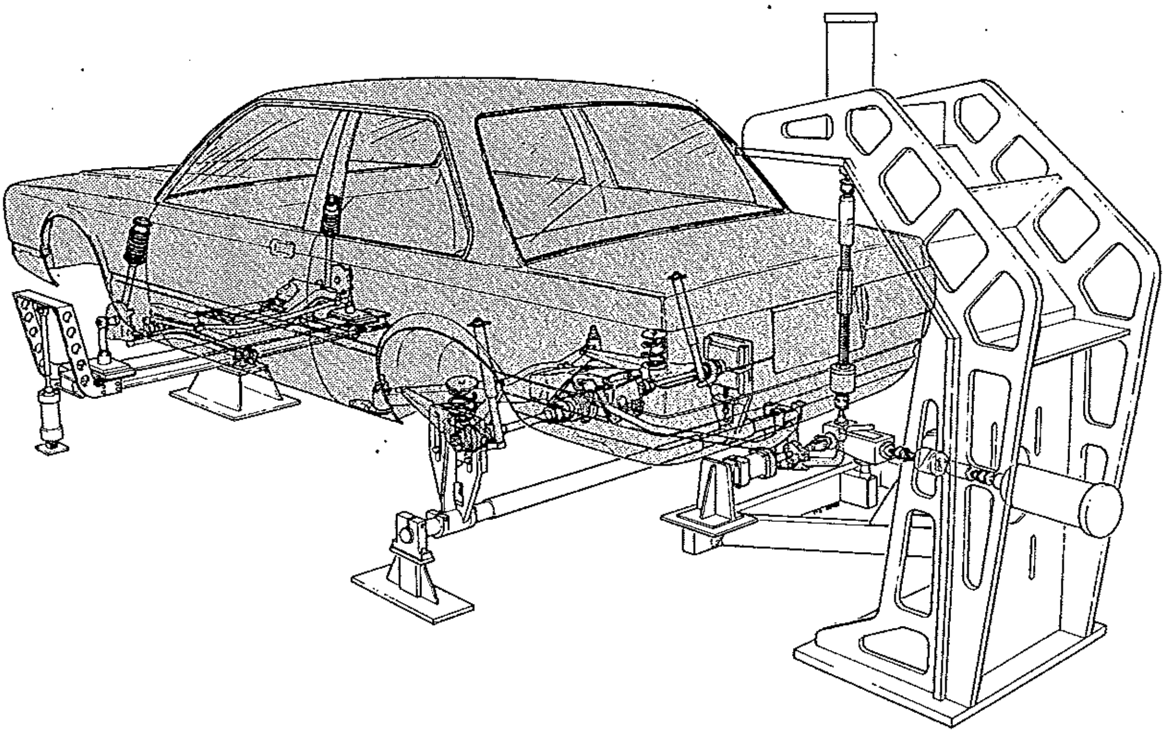


Fig. 13: 4-component body test-rig to generate trailer coupling loads

In order to eliminate these shortcomings, the qualities of the trailer coupling test rig were combined with one of the existing multi-axis body test rigs for operating load simulation. The principal advantage of the resulting multi-axis test rig lies in its degrees of freedom.

Vertical and pitching movements are not subject to restriction. When combined with trailer loads, the forces acting on the body by way of the vehicle's suspension and damping system are coupled with the external loads occurring at the wheel. This 16-channel combined body/trailer coupling test rig is partly shown in fig. 14.

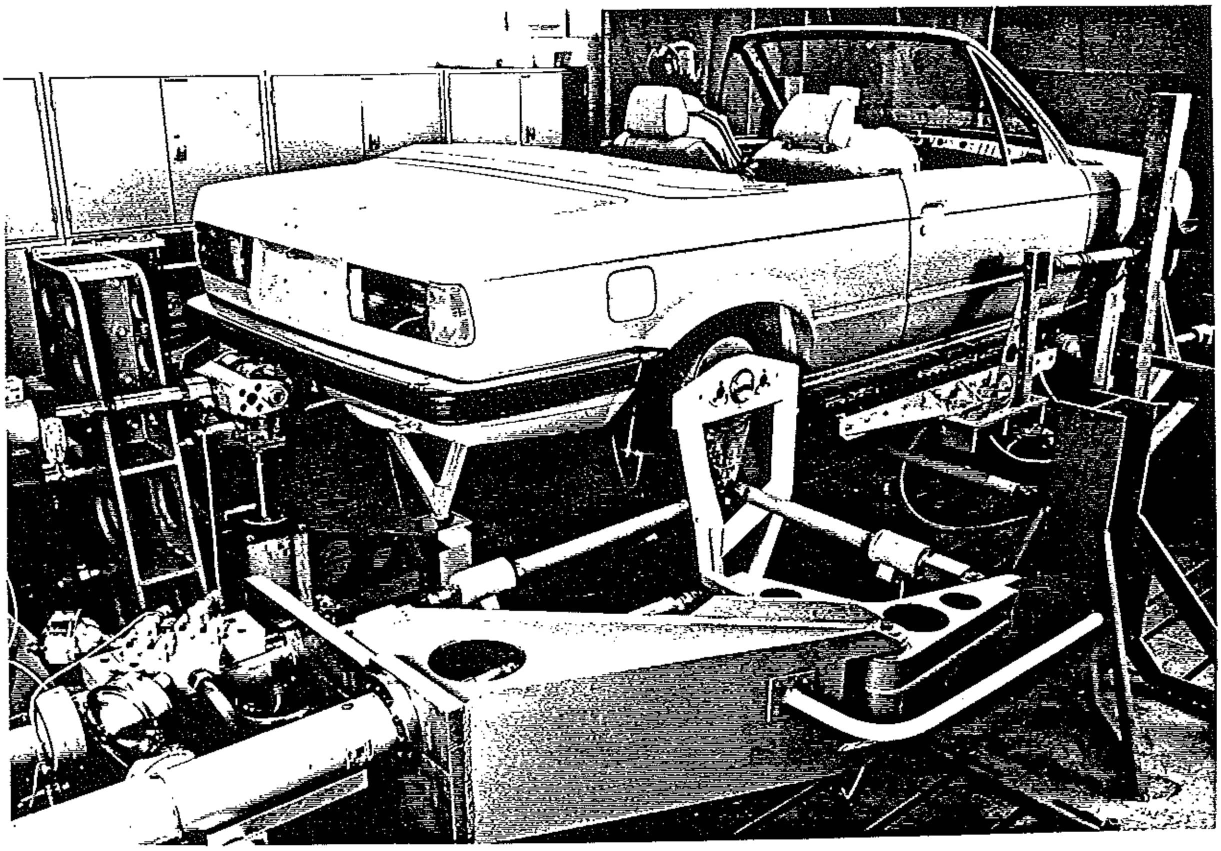


Fig. 14: 16-channel combined body/trailer coupling test-rig

In other words the measured trailer coupling loads have to be superimposed on body movements resulting from the towing vehicle's reactions to road surface irregularities and driving manoeuvres. This cannot be achieved by normal feedback control of the servo hydraulic actuators, since the above-mentioned interlink is severely non-linear (body and wheel eigenfrequencies).

Modern high-speed computers capable of processing large volumes of data now make it possible, by using inverse transmission functions, to vary the desired-value signals for the individual chanels in such a way that the load sequence measured on the road is restored at the body monitoring points. Fig. 15 shows the operating principle of the computing program supplied by the Schenck company, which is named "Iterative Transfer Function Compensation" for short "ITFC".

Fig. 16 illustrates the results of this process. The desired signal for the tractive load factor of a vehicle with trailer when starting (speedy drive-off process) is compared with the drive signal as modified by ITFC. The considerable discrepancy between the modified test rig drive signal and the original desired signal from vehicle operating measurements in terms of amplitude and phase location can clearly be seen.

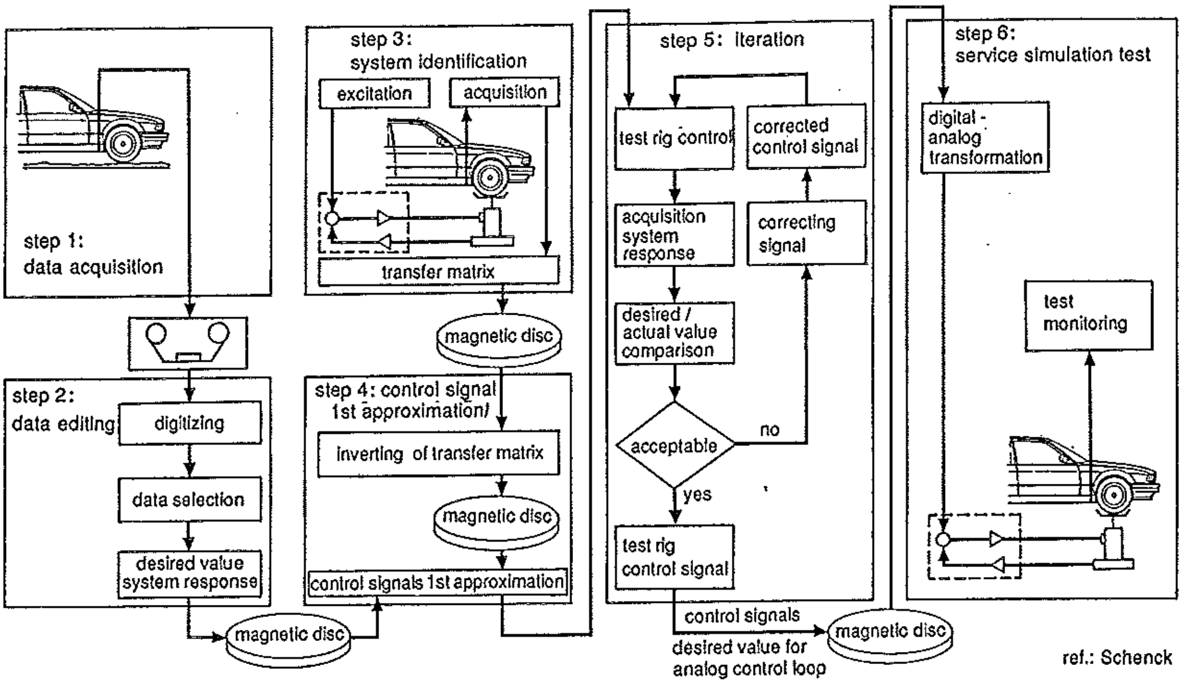


Fig. 15: Job steps of the ITFC control system

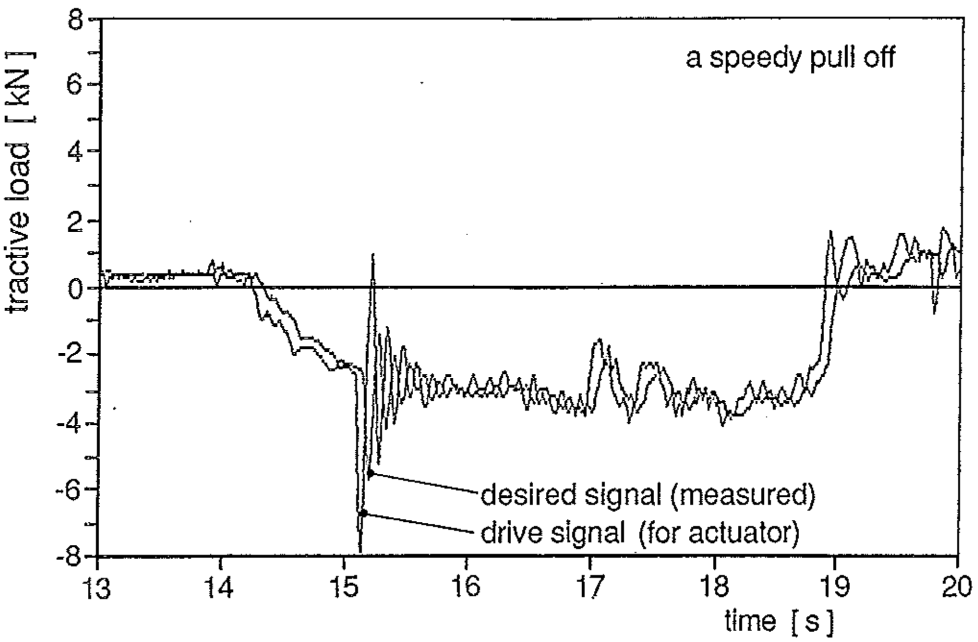


Fig. 16: Measured desired signal vs. modified drive signal

Fig. 17 shows the difference between the input/output signals of the servohydraulic actuator. The control error for the trailer load factor is additionally shown. A satisfactory level of quality has been obtained. This generated signal is necessary, so that on specific monitoring points on the body identical stress pattern occur during simulation on the test rig during driving on the road.

With regard to the mechanical aspects of the test rig, it was necessary to construct a suitable adapter for the ball head of the trailer coupling. This had to be mounted without play, yet be quickly released and transmit the three trailer forces centrally into the ball. Freedom from play was achieved by using a ball with a hard chromium-plated surface of considerably larger diameter than the ball head of the towing attachment and suitable clamping it.

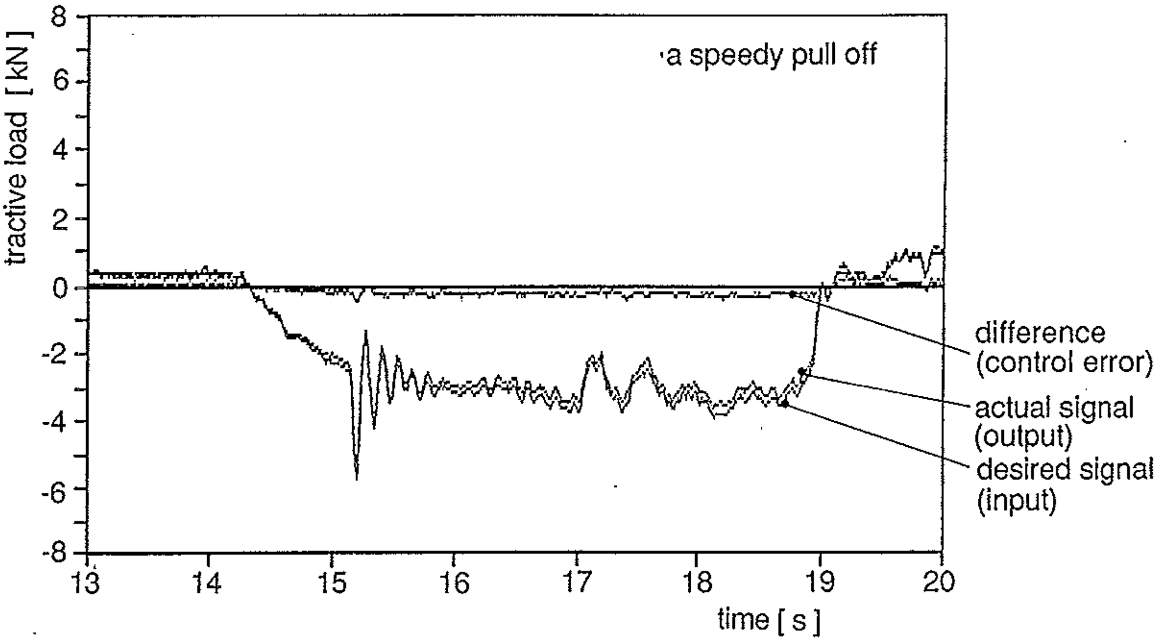


Fig. 17: Comparison of desired and actual signals

This ball was located in a precision housing. The considerable increase in the friction radius, the greater contact area and the provision for lubrication and subsequent adjustment enabled wear to be kept to a minimum or compensated for. This adapter is shown in fig. 18.

An example will serve to illustrate the progress which has been made in the development of trailer couplings. Fig. 19 shows trailer couplings for the BMW 7' series, with the earlier version at the top and the current one below. The former design with its two substitute cross-tubes has been superseded by a coupling with a single cross-tube. This saves approx. 10 kg in weight (equivalent to approx. 30 %), is cheaper and occupies less space. This last-mentioned factor is of particular importance. Every automo-

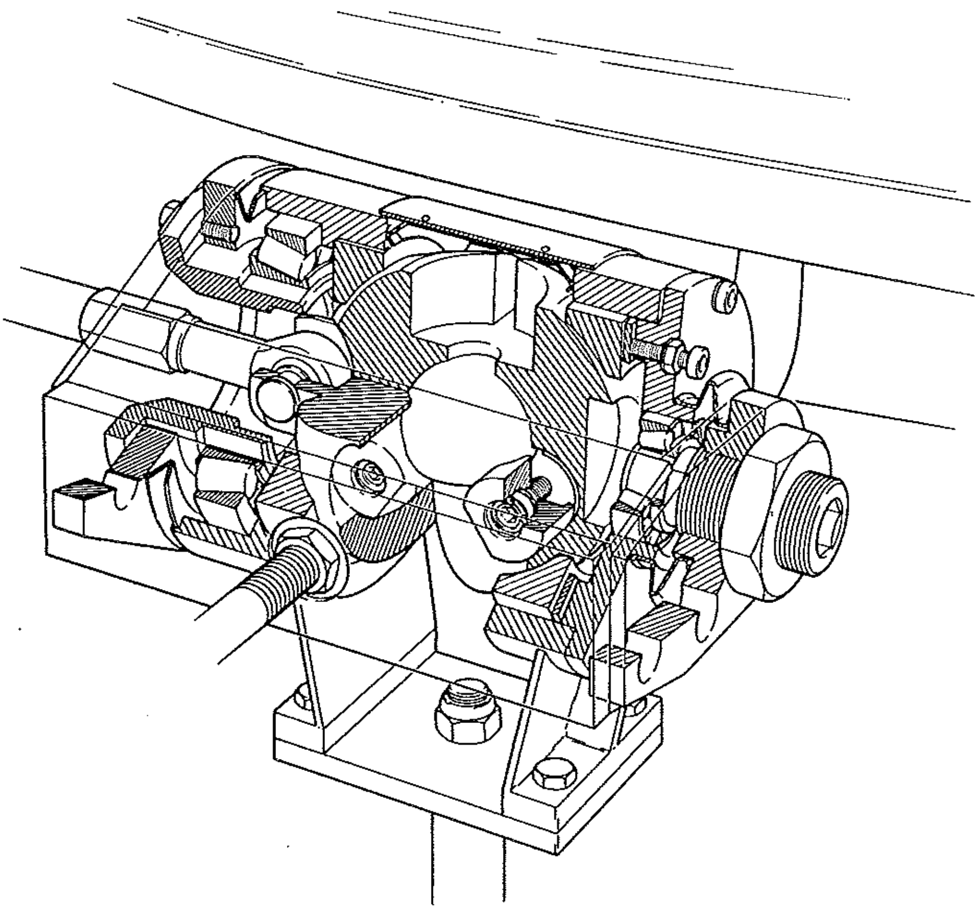


Fig. 18:

Adapter for advanced tow bar testing

bile designer is aware of the problems which arise when attempting to integrate seat bases, propeller shafts, exhaust systems, spare wheel, fuel pumps etc. into a smooth body floor pan.

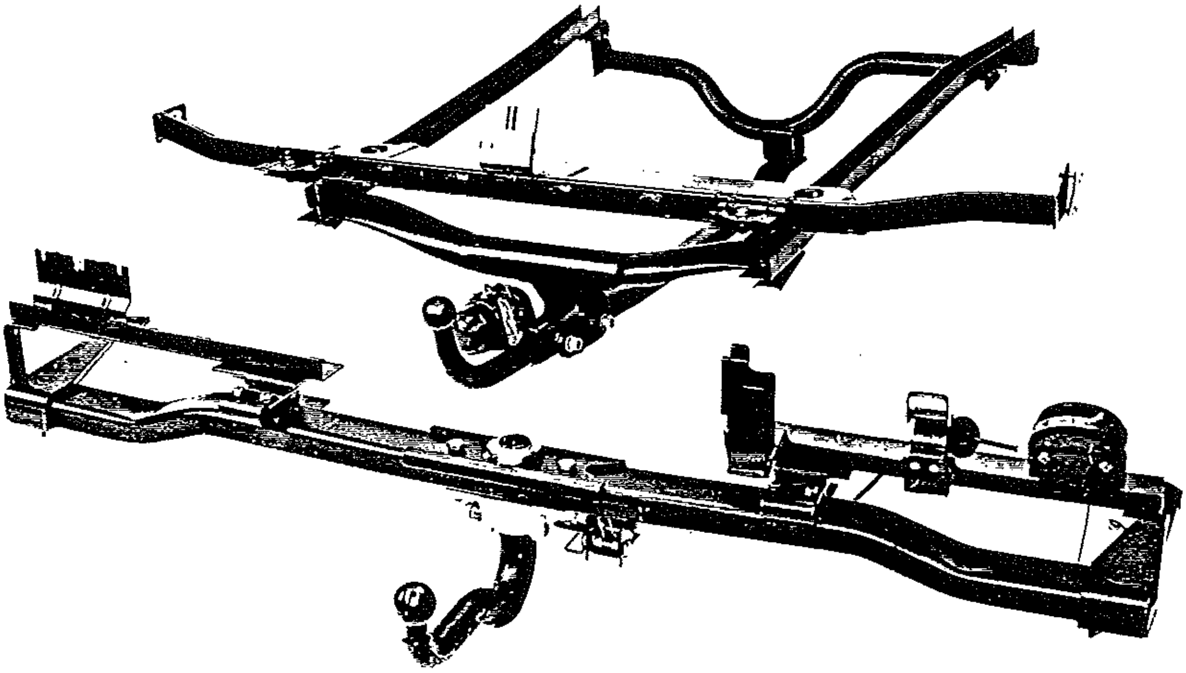


Fig. 19: Trailer couplings former and new BMW 7-series

Before the version shown here was finalised, a great deal of intensive detail development work was needed. Whereas forces were previously introduced to the bodyshell at widely distributed points, they are now concentrated on the rearmost section of the body. Additionally the forces which have to be withstood as a result of the moment round the lateral axis generated by dynamic vertical loads, previously negligible in magnitude, have now risen steeply. Adequate operating strength was achieved by means of an eight-point mounting, by varying the stiffness ratings of the mounting elements and by using a modified body cross-member. The additional bodyshell weight which had to be provided in this area amounted to 1.3 kg.

5.2 Simplified testing

Trailer couplings are normally purchased from suppliers. Products from up to three suppliers are approved for use on BMW cars. For reasons of cost and the need for secrecy (where testing would be carried out on the supplier's premises), and also in view of the need for statistical quality assessment, testing of each of these products on prototype bodies is impossible. To aid the supplier's development work, therefore, and to assure quality control at the car manufacturer, a simple substitute test as close as possible to actual operating practice is needed.
The German Technical Inspection Authority (TÜV) calls for a constant amplitude test in all cases when a general operating permit is applied for, using the resultant load from a trailer coupling mounted to a normally extremely rigid mount. The International Standard Organisation (ISO) has drawn up a similar test with different load assumptions. BMW's own extensive research programme has led to further advancements in test standards even when compared to the ISO-test, and corresponding results are demanded from suppliers as evidence of strength, and from BMW's own quality assurance department (fig. 20).

The following result serves to illustrate the interaction of the test rig configuration referred to above. During the operating simulation test run on the 16-chanel body test rig, a bracket on the trailer coupling fractured. Various versions were investigated by means of constant amplitude tests, their degree of scatter was established, and the most suitable version for use on production vehicles was selected. This version also proved be less costly to produce, since the length of the weld seams was reduced. The results are shown in fig. 21.

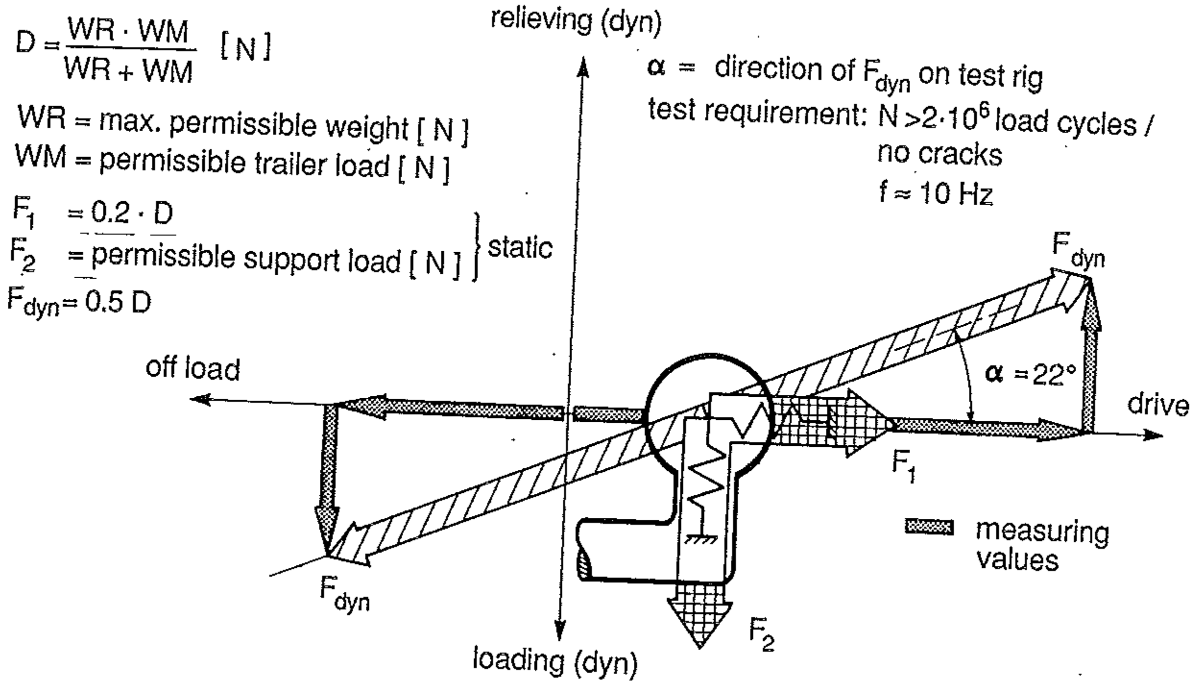


Fig. 20: Substitute test for towing devices

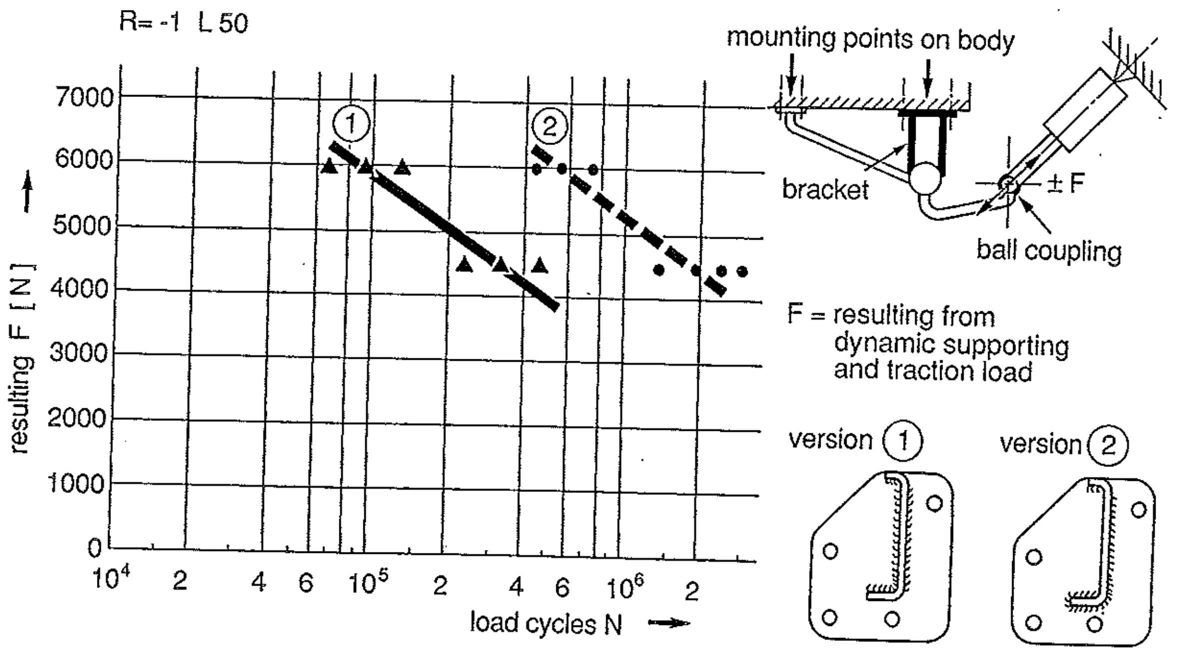


Fig. 21: S/N curves. Trailer coupling/welded seam

6. Calculations

The increasing use of FEM to calculate the effects of design modifications before the first samples are produced, is best illustrated by the following example: the coupling for the 7′ series, already referred to above, is mounted to the rear end of the body by 8 splicing plates (fig. 22).
It represents a statically indeterminate system combining various degrees of rigidity, with the result that the force flow and stress pattern are almost impossible to predict. Accordingly, there is a risk that local variations in rigidity, at or around the areas at which the device is attached to the body, could result in the transfer of the indefinitly high forces through the splicing plates, which in turn could lead to overloading and crack formation.

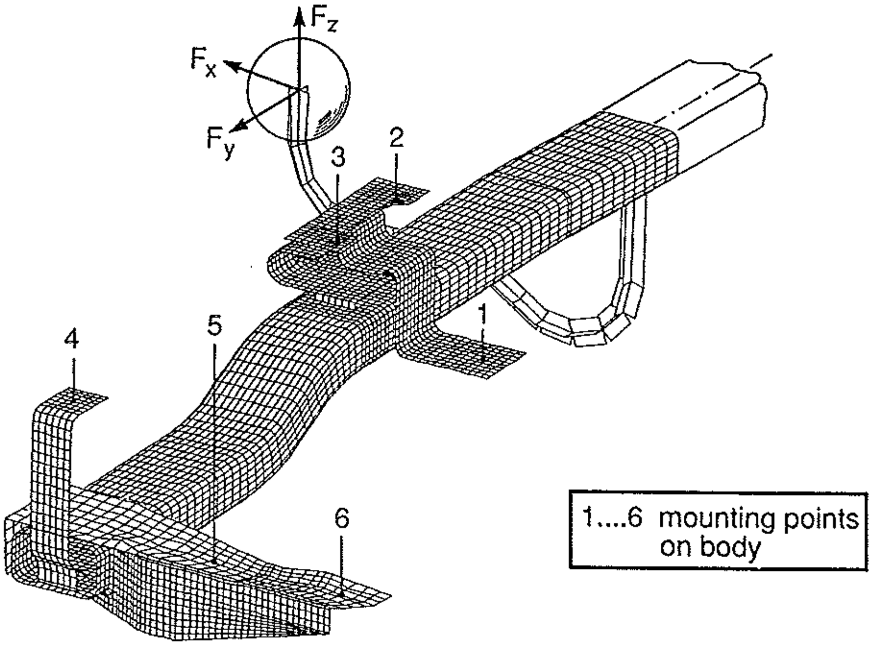


Fig. 22:

FE-Model
trailer
coupling
BMW 7′

This situation calls for the device to be suitably modified.
In the case in question, 13 alternative versions were computed and two of them selected for further examination (fig. 23).

In this way a shortcoming above the mentioned simplified test-method for the trailer coupling on a rigid frame (separated from the body) was also discouvered. Different forces and stresses occured at the mounting points, when using the rigid frame instead of the body. That may lead to incorrect fatigue life evaluation of the component being tested.

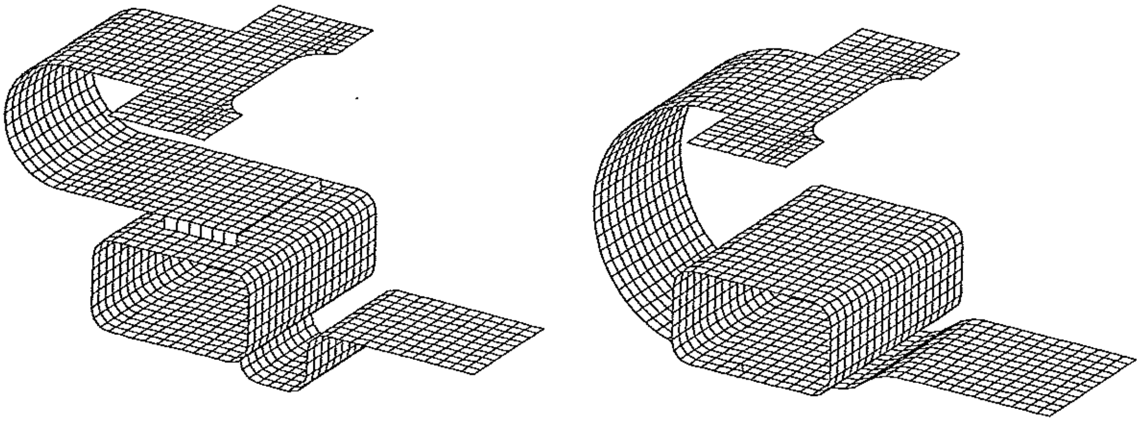


Fig. 23: FE-Model of two versions of attachment plates

7. Future prospects

As society changes, and people enjoy more leisure and experience the urge to make use of the opportunities available to them in a dynamic manner, the automobile is bound to change as well. Formerly a vehicle was the solution of pure transportation problems in a more or less luxurious or sporting manner, to an increasing extent it will become a direct element in the use of leisure time. The ability to attach a trailer, either for business transportation purposes or in the form of a caravan, boat trailer or horsebox, will be insufficient in itself. The car of the future may provide a variable solution to transportation tasks by permitting its owner to transform it, by simple means from a conventional saloon or sedan into a convertible, a station wagon or pick-up or even a semi-trailer tractor to tow a mobile home. Their would seem to be unlimited opportunity for imaginative scope here.

Nevertheless, even history has future. Fig. 24 shows such an outfit, dating from 1898: it is a motor tricycle to which a highly original and luxurious passenger carrying trailer has been attached. As the picture shows, the outfit is still operational today.

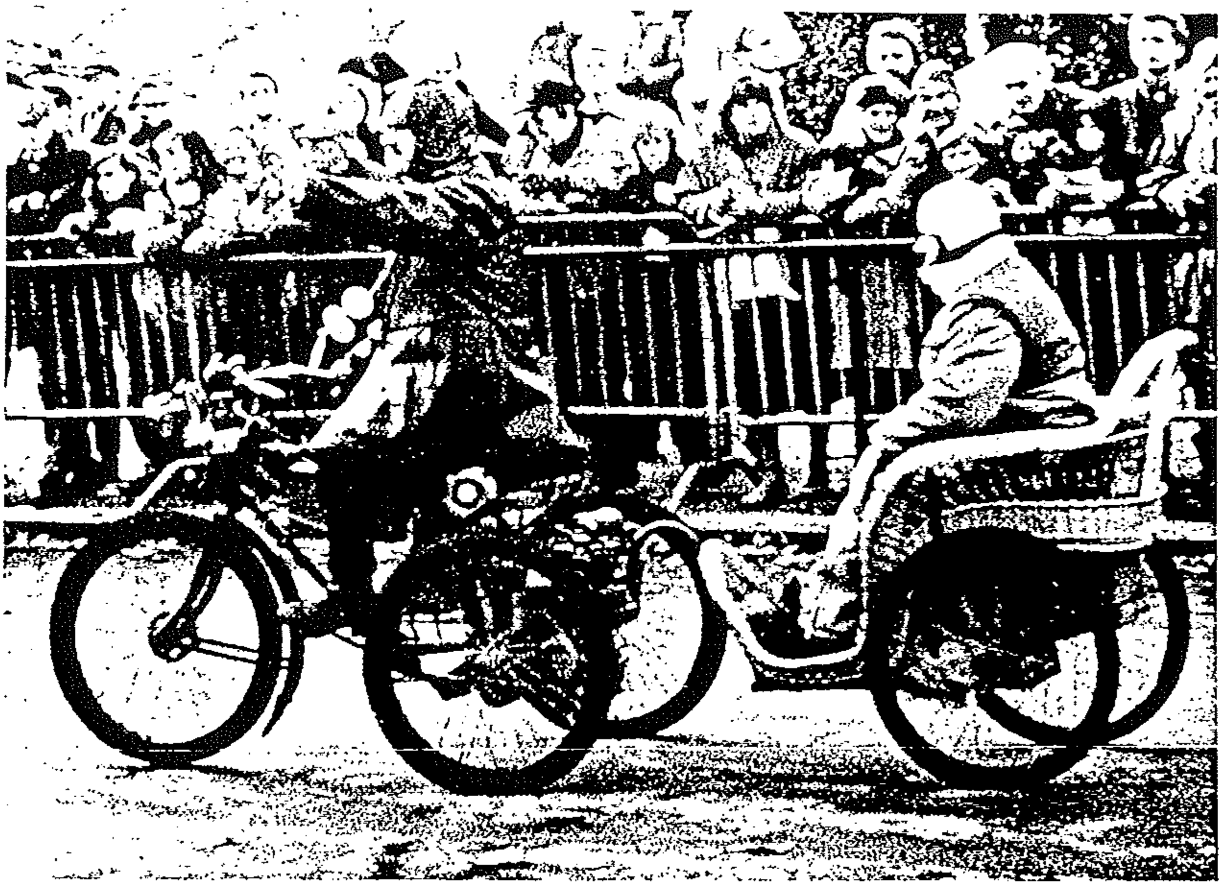


Fig. 24: Motor tricycle built in 1898, London-Brighton Run 1986

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