Investigating the relative movements of wheel-hub seals on heavy trucks and trailers

by Jürgen Neugebauer, Kim Bloxsom and Jim Diehr

The performance of wheel bearings on heavy goods vehicles is significantly dependent on the oil bath seals located in the bearings between the wheel-hub and axle spindle. In order to be able to test this type of seal under simulated operating conditions, the seal movements under driving conditions were measured in five degrees of freedom using a specially developed displacement transducer system consisting of 16 noncontact inductive displacement transducers of type Tr 8. During the road tests, vehicle parameters were varied and different maneuvers carried out. Assessment criteria were produced for the effects of different parameters. It was found that the greatest effects were produced by the vehicle loading and the wheel-bearing adjustment. The experimental reproduction of the load characteristics recorded in the road test took place in a specially developed servohydraulic simulator. There was a good correlation between the results from laboratory tests and those from the road tests.

Introducti

Oil bath seals in heavy truck and trailer wheel-end applications are vital components when it comes to longevity and economic performance of bearing units. The function of the seal in simple terms is to seal bearing lubricant into the hub cavity while preventing the ingress of dirt and airborne contaminants. The objective of this investigative development is to validate their performance characteristics through simulation tests conducted under real conditions. **Figure 1** shows a hub unit with the installed seal.

Previously, it was normal procedure to simulate just the rotational movement between the wheel-hub and the axle spindle in sealing tests in test-rigs. Other movements between the wheel-hub and the spindle, which also occur under actual operating conditions in all degrees of freedom, were ignored for the tests.

Successful simulation of the actual operating conditions requires knowledge of the movements affecting the seal in actual vehicle operation. In order to measure these movements, a transducer system is required that is able to measure the relative movements between the wheel-hub and the axle spindle in all degrees of freedom and convert them into electrical signals.

The movements to be measured at the seal depend on how the hub unit has been adjusted with regard to play. The five degrees of freedom of movement are linear movement in the direction of travel (longitudinal), along the axle (lateral), the vertical direction and then rotational movements about the vertical and longitudinal axes (wobble). Apart from the adjustment of the hub unit, the movements are also affected by tire inflation pressure and driving parameters which include cornering, braking, load changes and extreme vertical shock.

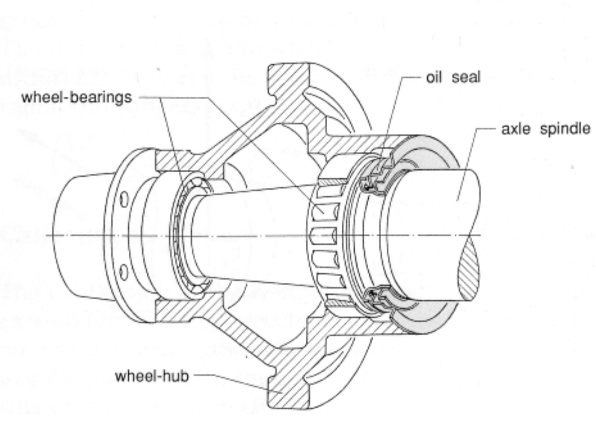

Fig. 1: Internal view of a wheel-hub unit with oil bath seal.

An important requirement for the simulation tests of movements taking place under actual conditions is the application of servohydraulic test equipment [1]. This test equipment has a closed loop control circuit consisting of the servocontroller, servovalve, actuator and feedback transducer, e.g. displacement or force transducer. The computer is used to generate the command signals from the required road data.

Measurement and analysis of seal movements under actual operating conditions

General

The object of tests carried out under actual service conditions is the measurement of the relative movement between the inner and outer sealing rings. These relative motions are essentially equivalent to the motion of the hub with respect to the spindle at that location of the seal. This simplification was made with a view to the simulation in the test-rig. The transducer which was developed enabled the measurement of hub deformation, i.e. the deviation of the hub from a circular shape.

Development of a transducer for seal motion in five degrees of freedom

A definition of the coordinate system used for the seal motion is shown in **Fig. 2**. The rotating and stationary segments of the seal are allowed to move with respect to one another depending on the bearing adjustment. The lateral play in the bearing D_Y also causes radial play due to the tapered shape of the axle spindle. The degree of the radial play is dependent on the slope of the tapered part. The radial play has a vertical component D_Z and a longitudinal component D_X. Both need to be measured separately. The lateral and the radial degrees of freedom of movement lead to angular motions W_Z and W_X about the vertical and longitudinal axes respectively. Apart from these five degrees of freedom of movement the outer ring rotates relative to the inner ring with a speed dependent on the driving speed.

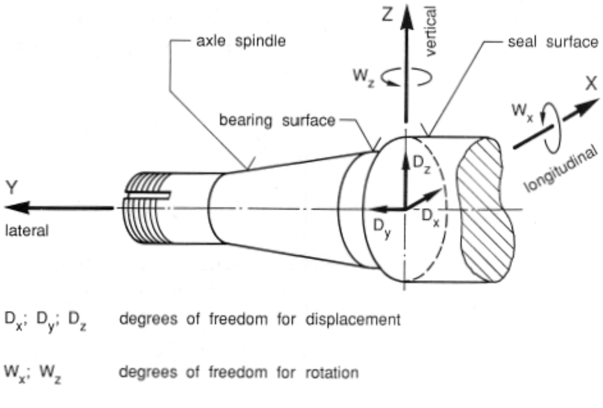

Fig. 2: Definition of coordinates and degrees of freedom.

Due to the unavoidable spread in the bearing adjustment, the ranges of measurement for the five degrees of freedom were defined as follows. Based on previous experience, the ranges for the three linear motions D_X, D_Y and D_Z were selected to be ± 1 mm (0.04 in). The two angular motions W_X about the longitudinal axis and W_Z about the vertical axis were not expected to exceed ± 1°. The measurement problem consisted of measuring changes in displacement in five degrees of freedom. The transducer system which was designed to measure these displacement changes utilized a special arrangement of non-contacting displacement transducers of the type Tr 8 [2]. These transducers work on an inductive principle and are operated with a 5 kHz carrier frequency. They are used in pairs, each pair being wired as an inductive half-bridge. **Figure 3** shows the basic measurement principle of this transducer in which the measurement object is situated between the two transducer heads. Displacement of the measurement object in the direction of the transducer axes causes an increase in the distance to one transducer head and a reduction of the distance to the other one. This causes changes of inductance in the transducer coils leading to an unbalance in the bridge circuit. This bridge unbalance produces the measurement signal. The sensitivity and the measurement range depend on the width of the air gap between the transducer heads and the measurement object. The characteristics of these Tr 8 Non-Contacting Inductive Transducers are not linear, but exhibit excellent reproducibility. By arranging them in pairs as shown in **Fig. 3**, the linearity deviation of the two transducers is almost completely compensated.

Fig. 4 shows a sketch of the arrangement of the transducer system around the measurement object. In order to measure the displacements in all five degrees of free-

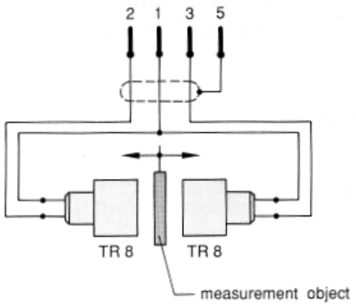

Fig. 3: Basic measurement arrangement using the Tr 8 Inductive Non-contacting Displacement Transducer.

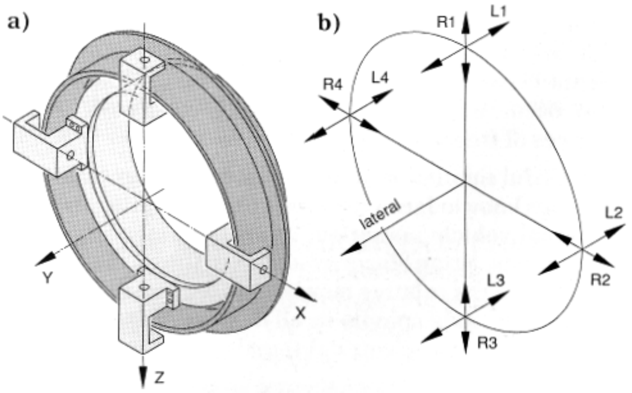

Fig. 4: Arrangement of the transducer system on the measurement object:
a) eight transducer pairs on the stationary ring,
b) measurement directions for the eight transducer pairs.

dom, at least five measurement configurations are required. Quantities such as lateral displacement and both angular motions cannot however be measured directly at one measuring point and they must be calculated from measurements made at different locations.

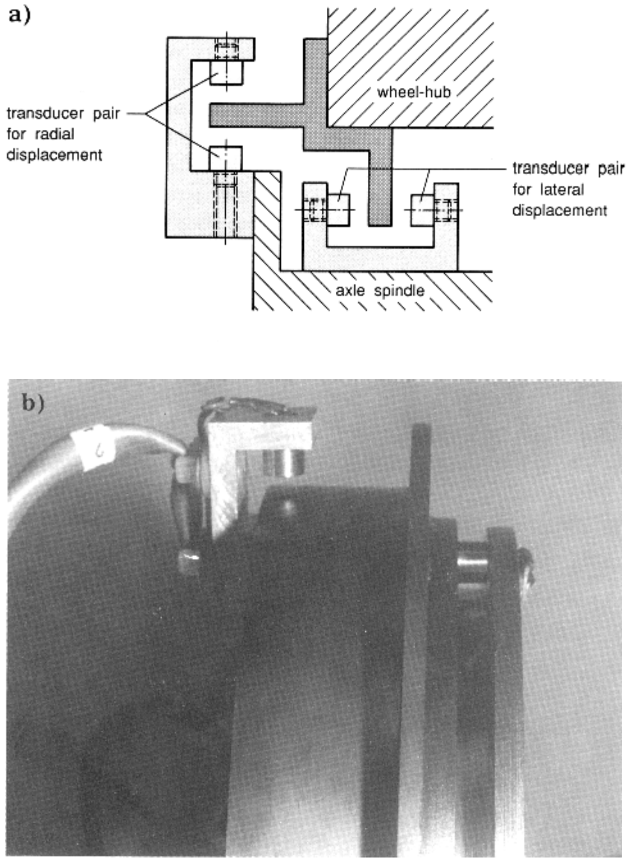

Fig. 5: Measurement of the radial and lateral displacements with Tr 8 Inductive Non-contacting Displacement Transducers arranged in pairs over a measuring ring mounted on the wheel-hub,
a) schematic diagram,
b) photograph of the arrangement.

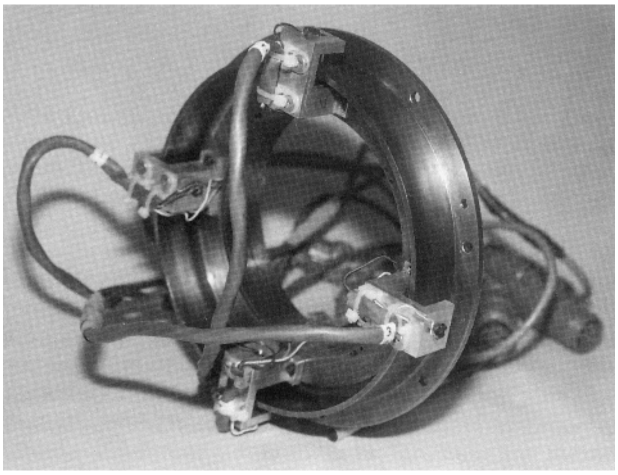

Fig. 6: Photograph of the complete transducer system.

This means that eight transducer pairs are needed on the inner ring as shown in **Fig. 4a**. The four transducer pairs labeled with R measure the radial displacements. Another four transducers, labeled L, measure the lateral motions and also the angular motions. **Figure 4b** shows that the eight pairs of transducers are evenly distributed on the circumference of the inner ring. This ring is rigidly joined to the axle spindle. **Figure 5a** shows two pairs of transducers, one for radial and one for lateral measurements, in a schematic diagram of the axle spindle. The wheel-hub is fitted with a ring having a rim and flange which act as measurement objects for the pairs of transducers. A photograph of the transducer arrangement is reproduced in **Fig. 5b** which shows two pairs of transducers, one for the lateral and one for the radial displacement.

Figure 6 shows an overall view of the transducer system. Since the non-linear transducer signals were linearized by a special electronic circuit, the quantities with the following designations could be determined from the measurements:

Longitudinal linear movement	$D_x = (R2+R4)/2$
Lateral linear movement	$D_y = (L1+L2+L3+L4)/4$
Vertical linear movement (radial)	$D_z = (R1+R3)/2$
Angular movement about the X axis	$W_x = \arctan(L1\text{-}L3)/D$
Angular movement about the Z axis	$W_z = \arctan(L2\text{-}L4)/D$

In these equations **R1...R4** signify the signals from the pairs of transducers **R1...R4** for the radial displacements and **L1...L4** are the signals from transducers **L1...L4**. With these five equations the dynamic movements of both sealing rings relative to one another in all five degrees of freedom can be found from the measurements. The deformation of the wheel-hub is given by half the difference between the signals from oppositely located radial transducers.

Calibration

The calibration of the complete transducer system was carried out on a high precision machine tool which produced the linear motions in the x, y and z directions. The angular motions are then produced during the processing of the measurement signals using the above equations. During the calibration all signals were measured as individual signals.

In order to be able to take into account the residual non-linearities caused by the inductive transducers and the geometrical shape, all non-linear characteristics were stored in the digital Schenck Servocontroller 5900. Its software can describe and linearize non-linear characteristics of, for example, non-contacting displacement transducers with up to 64 points. The signals measured later during road tests were digitized with this unit and converted to the corresponding relative displacements using the stored calibration characteristic.

Test parameters

The objective of the test program was the acquisition of road data under the most varied conditions. This included the influence of different vehicle parameters and road conditions. **Figure 7** is a photograph of the transducer system installed on the axle. In addition an acceleration transducer was included for reference measurements.

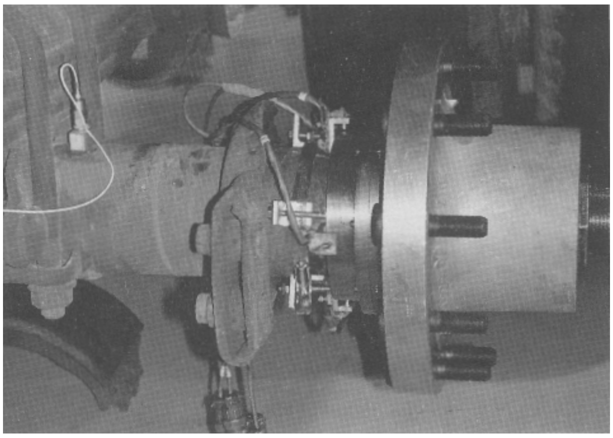

Fig. 7: Measurement arrangement on the vehicle wheel bearing for the road tests.

During the servicing of heavy goods vehicles the correct adjustment of the wheel bearing is very important for the service life of the seals. In the tests two commonly used bearing adjustments were tested and a third provided information on the behavior of the seal under conditions of "loose" adjustment. All settings of bearing adjustment were carried out in the lubricated condition and with the wheel-bearing rotating. The following bearing settings were investigated: no play, slight play in the bearing (1/4 turn release on the setting) and a large amount of bearing play (with the setting nut released by 1/2 turn).

Fig. 8: Test vehicle with a payload capacity of 36 t for the determination of the relative movements in the seal under operational conditions.

Since it is the dynamic load transfer into the tires which actually causes the seal movement, two further parameters were varied, i.e. the tire pressure and the vehicle load. Changes in the tire pressure influenced the deformation and stiffness of the tire, producing changes in the intensity of the dynamic load [3 and 4]. The tire pressure was varied between 4.5 and 6.5 bar (66 to 95 psi). Changes in the vehicle load not only changed the dynamic load factors, which typically reduce with increasing load, but they also increase the static wheel load. It can therefore be expected that the movement at the seal increases. Consequently, measurements were made with both an empty and a fully laden vehicle. The effects of special maneuvers were also examined, e.g. extreme cornering in both directions, an off-road track, a Burma strip, simulated pot holes, railroad crossings and extreme braking conditions. The vehicle used for the tests was the truck shown in **Fig. 8** which has a maximum payload of 36 t (80,000 lb).

Analysis of the values measured in the road tests

The data obtained from the road tests had to be analyzed and prepared so that it would be suitable for a realistic simulation of the seal movements in the laboratory. Time-compression considerations were important in order to obtain the most efficient procedure possible for the testing of the seals [5]. The effects of the bearing adjustment, vehicle payload, tire pressure, vehicle maneuvers and the road conditions on the seal movements were to be investigated.

All the acquired measurements were digitized and evaluated using statistical methods and computer-aided frequency analysis. The results show the main factors influencing the seal movement. From the large number of results obtained from the road tests only a few examples are given here.

Figure 9 shows some measurements obtained from the road test as they were later used for the loading program in the verification tests. **Figure 9a** shows the lateral movement D_Y measured for the three different bearing adjustments. With increasingly tighter bearing adjustment the amount of motion reduces. **Figure 9b** illustrates the displacement/time curves found in all five degrees of freedom. **Figure 9c** gives the legends to the individual road tests, the curves of which are shown in a) and b).

At present there are no known generally applicable methods for the assessment of the damaging effects of the motion sequences on the service life of seals. The objective of the laboratory tests is the assessment of the parameters with regard to their contribution to seal damage. The results of the test clearly show that the intensity of the motions increases significantly with increasing play in the bearing. It can therefore be stated that any deviation in the bearing adjustment from the optimum degree of play has an unfavorable effect on the service life. If the adjustment for a loose bearing is compared with the adjustment for zero play, then it is found that with a fully laden vehicle a four-fold increase in the intensity of movement occurs. This figure rises to 6.2 for

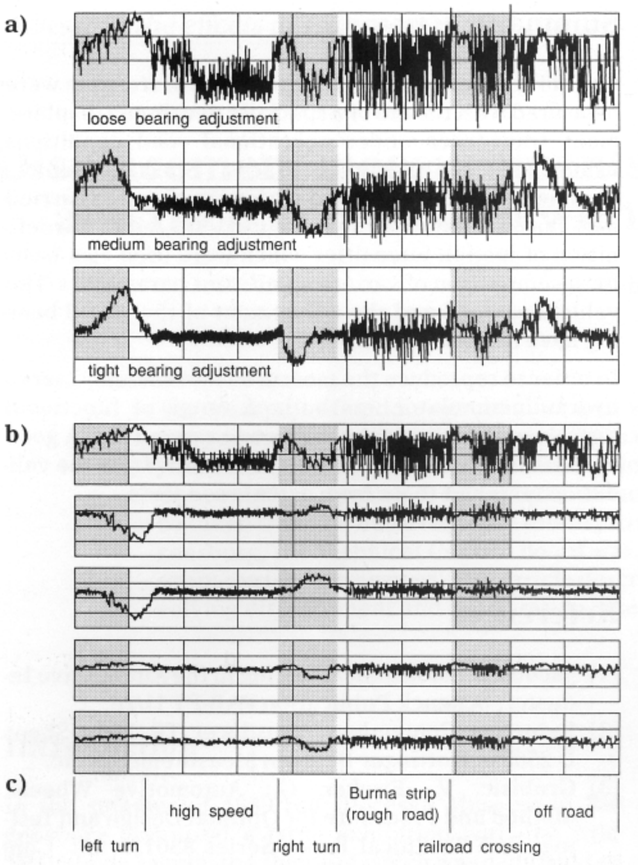

Fig. 9: Examples of measurement results:
a) lateral seal movement D_Y for three settings of wheel adjustment on the bearing,
b) curves of displacement in the five degrees of freedom as functions of time,
c) type of maneuver.

an empty vehicle. The effect of tire pressure is less accentuated. Ort average the amount of movement is about 5 % higher with low tire pressure.

Tests with operational loads

Development of the test equipment

With known testing techniques the seal motions could not be simulated in all the degrees of freedom in real time. Typically, durability tests have previously been conducted on machines with a rotating head which simulates the hub.

In order to be able to implement in the laboratory the real-time motions in the defined degrees of freedom and as measured in the road test, a servohydraulic motion simulator with five degrees of freedom was designed. **Figure 10** is a diagrammatic representation of this test equipment. A triangular frame holds the simulated axle spindle. Each of the three corners of this frame is joined to a servohydraulic cylinder. These cylinders transfer the lateral displacements and the wobble movements through flexible force transfer rods (flex rods) into the fixture and then onto the spindle. The transfer rods are flexible enough not to impair the freedom of movement of the frame. The advantage of this flex-rod system is that it avoids play and friction which have a negative effect on the real-time simulation.

Two other servohydraulic cylinders are coupled to the triangular frame in the vertical and longitudinal directions to produce the radial movement. The vertical cylinder is rigidly joined to a cross-beam in order to provide reaction to the torque generated by the friction of the seal under rotation.

The drum simulating the wheel-hub is filled with the required quantity of oil which is maintained at the desired temperature with a heater. The simulator control system consists of five channels of Schenck Pegasus 5900 Digital Servocontrollers. The data from the road tests was edited and stored on a central laboratory computer System of the type Schenck Pegasus L-Cat. All cylinders are displacement controlled. The road data which was measured with the motion transducer system to five degrees of freedom was converted from the transducer geometry to the test-rig geometry using a mathematical model for lateral actuator command signals. Both radial cylinders could be driven directly from the transducer data.

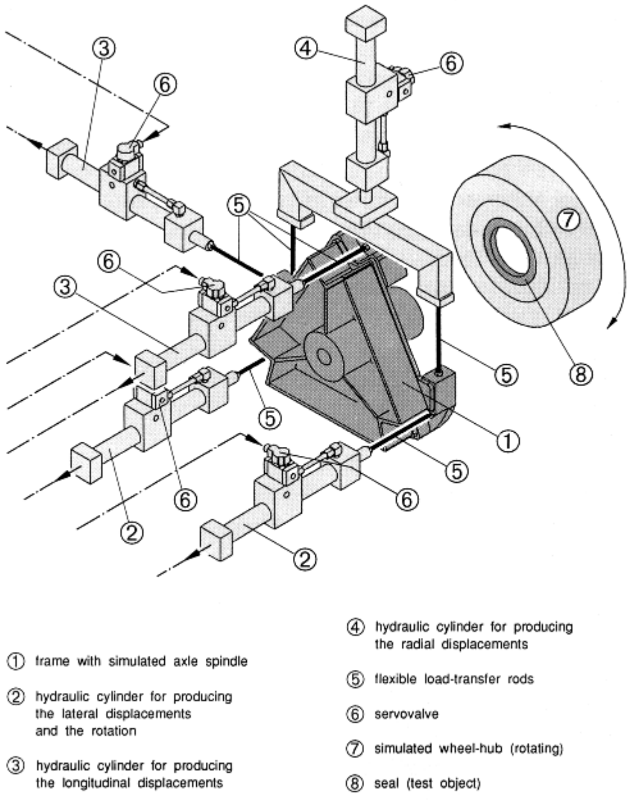

Fig. 10: Design principle of the servohydraulic test equipment for the laboratory simulation of operational loads on truck and trailer wheel-hub seals, showing the arrangement of the hydraulic cylinders and the simulated axle spindle.

Test program

Various seal designs were tested with the amounts of leakage monitored through the use of a proprietary rotating bore leakage collection device. This technique enables the seals and design features to be classified according to the amounts of leakage as well as wear.

The effects of bearing adjustment on a particular seal design could also be determined. In this manner, conclusions could be drawn from the laboratory tests relating them to real service conditions. A direct correlation now exists between the test device, the behavior of the test object and the actual service conditions.

A series of tests under different boundary conditions was conducted. First of all, all sections of the signal as shown in Fig. 9 (loose bearing adjustment) were tracked. A four-hour holding period occurred every 20 hours in order to include any creep processes in the seal material. With a speed of 570 rpm and an oil temperature of 80 °C (176 °F) the results produced after 150 hours of testing were not sufficiently different to make assessment feasible. It was therefore concluded that only the largest amounts of movement, such as occur on the Burma strip, had to be simulated if significant results were to be expected within an acceptable period of time.

By superimposing a static offset on the dynamic signal and by concentrating on the Burma strip, differences in the characteristics of ten seals were found. The experience obtained in practice was qualitatively equivalent to the results in the validation testing. Following this, a new design of seal was investigated and it was found that it stood up to the harsh treatment in the validation test.

Conclusion

The test simulation of seal movements actually occurring in operating conditions represents a significant step in seal testing techniques. With the development of the required test equipment such as the transducer system and the computer controlled simulator, the seal tests were able to simulate actual operating conditions much more accurately. Further investigations will be made concerning real-time movements under adapted environmental conditions, e.g. the effects of winter road-salt and dust.

Summary

The movements of seals in five degrees of freedom were measured with the aid of a specially developed displacement transducer under operational road conditions using selected driving surfaces. Specific vehicle parameters were varied and various maneuvers carried out. The evaluation of the measurements led to the definition of motion intensities which were used as a basis for a comparison of various significant parameters. The vehicle payload and the adjustment of the wheel bearing have the most effect.

In order to reproduce the measured movements, a servo hydraulic simulator was built. A range of functional tests on seals of various designs was carried out. A good correlation was found between the results from the validation tests and those from actual road tests.

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