New inner drum test bench for dynamic tests of PLT and truck tires

Martin Gießler[1], Frank Gauterin[1], Michael Frey[1], Hans-Joachim Unrau,[1]

[1] Institute of Vehicle System Technology, Karlsruhe Institute of Technology (KIT), Germany

Abstract. At the Institute of Vehicle System Technology at the Karlsruhe Institute of Technology (KIT) a new inner drum test bench had been build up and put into operation in 2022. This test bench allows the analysis of PLT (passenger and light truck) and truck tires under realistic quasi-stationary and dynamic loads on different real track surfaces. The test bench consists of a rotating drum and a load unit based on a servo-hydraulic hexapod unit, which allows almost any setting of the operating conditions of the tire with frequencies of up to 30 Hz. An electric wheel drive unit allows the tire to be loaded with respective drive and braking torques. In addition, the test bench construction principle allows the investigation of chassis systems, which can be attached to the Hexapod and be operated as a quarter vehicle.

Initially, the authors discuss the future demands on the experimental analysis of tires and identify major research fields for the usage of the new test bench. After this introduction, the authors present and describe details of the construction and the main technical specifications of the new test bench. The technical specifications will be compared to requirements resulting from the operation of PLT and truck tires, so that the operation field of the new test bench is more precisely described. Finally, first experimental results will be presented, that demonstrate the functionality of the test bench and give a first impression of future applications of the test bench.

Keywords: Inner drum test bench, tire forces, dynamic response.

1 Introduction

1.1 Institutes automotive test benches for research and development of tires

The new tire test bench presented in this paper expands institute's test possibilities, so that institute's existing test benches are shortly presented. Since 1960 the institute performs research projects with focus on tire characteristic supported by several tire test benches. Within those projects, we gained knowledge about tire performance characteristic under different operating conditions and further developed our test benches. These tire testing and development knowledge influenced the design process of the new inner drum tire test bench. A short description of existing tire related test benches are given within the next text passage and will be compared at the end with the application fields of the new test bench.

The **Flat Track / Outer Drum Test Bench (FPS)** is used for rolling resistance measurements of vehicle tires. This test bench allows measurements on two outer drums and on a continuous flat track with the same wheel suspension and the same measurement system.

The continuous flat track is implemented by a steel band, which is guided around the two drums. The diameters of the drums represent the European and the North American standard (2.0 m and 1.71 m). The wheel suspension containing the measurement system can be adjusted precisely over the two drums and the flat track. A hydrodynamic surface bearing supports the steel band in the area of the tire contact zone.

The measurement system consists of a six component measuring hub, which was purposebuilt for rolling resistance measurements. An auxiliary motor in the wheel suspension is used to eliminate the influence of bearing friction. Furthermore, the aerodynamic losses that result from the wheel rotation can be determined by lifting the test tire from the surface at the desired speed and sustaining the rotation speed of the tire. This proceeding also implies that the measured rolling resistance is free from the influence of the aerodynamic properties of the tire.

Fig. 1 Tire rolling on flat track (steel band)

Fig. 2 Tire rolling on outer drum

Table 1. Technical specification of FPS

Parameter	Value
Drum outer diameter	2 m 1.71 m
Max. speed	300 km/h (drums) 250 km/h (flat track)
Camber angle	-10° … +10°
Slip angle	-5° … +5°
Max. vertical force	10 kN
Max. lateral / longitudinal force	1 kN
Max. aligning torque	300 Nm
Max. driving torque	30 Nm

Recent research performed at this test bench focusses on rolling resistance under realistic operation conditions, [1] and efficient layout of tire and rim dimensions, [2].

At the existing **inner drum test bench (IPS)** the tire is mounted on a special wheel suspension and rolls on the inside of a drum with a diameter of 3.8 m. The advantage of the construction is, that an equal waterfilm can be brought up on the inside of the drum. So it is possible to investigate the influence of the waterfilm depth on the characteristic properties of tires. Furthermore the construction of the drum enables tests on different types of real roadway surfaces. Therefore segments of asphalt or concrete are fixed on the inside of the drum.
Since a cooling system is installed, also measurements on ice and snow surface can be conducted. Therefore the drum can be cooled down to a temperature of -15 °C and snow can be produced onside.
During measurements of longitudinal force a hydraulic motor drives or brakes the wheel. During measurements of lateral force the slip angle is varied continuously. Additionally, tire load and camber angle can be varied continuously.
The forces and moments, which affect the wheel, are measured with a six component measuring hub, which is installed between wheel and bearing and which is rotating with the revolutions of the wheel. Therefore the measurements are not altered by the drive shaft and the disturbing friction of the bearings is eliminated.

Fig. 3. Inner drum tire test bench with tire rolling inside a drum

Table 2. Technical specification of IPS

Parameter	Value
Drum inner diameter	3.8 m
Max. speed	200 km/h (without track) 150 km/h (with track)
Track types	Safety walk, div. concrete, div. asphalt, snow, ice
Slip angle	-20 … +20°
Camber angle	-10° … +20° (with special adapter: +30° … +45°)
Ambient temperature	-15 … +30 °C
Water film depth	0 … 3 mm
Measuring system – max. forces	15 kN (durability tests max. 12 kN)
Max. tire radius / width	450 mm / 310 mm

Recent research performed at the IPS focusing on tire's fine dust emission [3], tire noises [4] and force transmission on wet road, [5].

The steerable **vehicle-in-the-loop (ViL)** test bench can be used for testing vehicles in terms of efficiency, [6]. Therefore, the direct connection between the wheel hub and the load engines for driving/braking torque and for steering (Alignment torque simulator) allows a reproducible simulation of tire influence on vehicle operation during cornering and straight driving. Increased precision is achieved by the application of a drive & brake pedal robot and a steering robot which allows testing without a human driver and reproducible simulation of a manual driving.

In addition, this steerable vehicle test bench utilizes a driving simulation platform combined with a novel radar-target-simulator for the realistic simulation of vehicle's environment during radar-based automated operation. This test set-up allows tests for validation and development of radar-based automated driving functions.

Recent tire related research focusing on consumption relevant loads during cornering, [6] and radar target simulation under consideration of vehicle body movement, [7].

Fig. 4 Total view

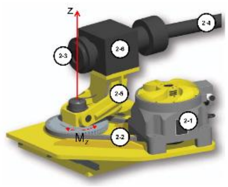

Fig. 5 Aligning torque simulator

Table 3. Technical specification of ViL

Parameter	**Value**
Max. wheel rotation speed	2,000 rpm (200 … 260 km/h)
Max. wheel torque per wheel	2,500 Nm @ 800 rpm (209 kW)
Max. front wheel aligning torque	1000 Nm
Max. wheel load	3,000 kg
Wheel base	1.8 – 4.9 m
Track width	1.2 – 3.9 m

Table 4 compares institutes existing tire related test benches with the new inner drum test bench (GRIPS) in terms of product type, research focus and key performance tests. It highlights the main application fields of the new test bench in comparison to the existing test benches.

Table 4. Main application fields of institutes test benches for tire research and development.

		GRIPS	FPS	IPS	ViL
Test bench type		**Inner drum**	Outer drum and flat track	Inner drum	Powertrain / Vehicle
Products		**PLT and commercial vehicle tires**	PLT Tires	PLT Tires	Vehicles, PLT and van tires
Research focus	Tire: Material, tread design, construction	**++**	++	++	-
	System interaction	**++**	-	+	++

		GRIPS	FPS	IPS	ViL
Key Performance Tests	Efficiency (Rolling Resistance)	**+**	++	+	+
	Safety (Force transmission)	**++**	+	++	+
	Dynamic Response	**++**	-	+	-
	Comfort (chassis interaction)	**++**	-	+	-
	Environmental effects (Noise, emissions)	**0**	-	+	+

1.2 Motivation

Even so that simulation technics speed up the development process of tires, tire test machines are still needed not even to validate development targets (like rolling resistance or noise) but especially to support the further development of the tire with experimental research campaigns. Validation of development targets incl. legal requirements are often performed on standard test benches specialized for this purpose (e.g. rolling resistance measurements on outer drums with highly sensitive measurement unit). The test bench presented in this paper is able to perform different kinds of tests on PLT and truck (commercial) tires, so that the test bench can be categorized as a multi-purpose tire test bench for tire research and development. Major application fields of the presented tire test bench result from the development goals for PLT and truck tires, which are shortly discussed within the next text passage.

Requirements on tires can be classified in the fields of safety, efficiency and economy (including energy consumption, mileage and weight), dynamic response and comfort, [1]. The weighting or prioritization of those requirements are majorly influenced by tire's application. Whereas prioritization of development goals for passenger car tires are influenced on consumer relevant ratings such as EU label or tire tests of automobile associations (**Table 5**), the economic rating plays a major role in development of commercial tires. Economy of commercial vehicle tires depend mainly on the factors achievable mileage on the most traveled roads, efficiency (rolling resistance) within the operation cycles and lastly on purchase costs. Since the differences in rolling resistance might not have a clear, direct measurable influence in overall operation costs of commercial vehicle tires, the fleet operators select often tires with high mileage and high robustness to reduce downtime, [11].

These key tire performances depend on the application field of the certain commercial vehicle. Compared to PLT tires, application field of commercial vehicle tires are more specific but wider spread, so that special requirements result from the dominating use cases (**Fig. 12**) and further classification (**Table 6**). This classification lead to a theoretical number of 240 variants, whereas not all of these variants are requested and therefore tires specialized for this category are not offered. For 5 selected tires, parameters relevant for the layout of the test bench are given within **Table 7**.

Table 5. PLT-Tires: Evaluation criteria of EU label and ADAC tire test, [10].

Test Criteria		EU Tire Label	ADAC Tire Test
Dry Road	Braking ABS		x
	Driving Behavior		x
	Driving Safety		x
Wet Road	Braking ABS	x	x
	Aquaplaning		x
	Handling		x
	Cornering		x
Noise	Inside (Cabine)		x
	Outside	x	x
Consumption	Rolling Resistance	x	
	Full consumption		x
Wear			x

Table 6. Classification of tires for commercial vehicles, based on [11].

Application	Operation segment	Axle-Position	Special Properties
Urban	Goods transport	Steer-Axle	Retread
Regional	People transport	Drive-Axle	Low Rolling Resistance
Long Haul	Construction	Trailer-Axle	Super Single
Construction		All-Position	Sensor integrated
Off-Road			

Table 7. Example of max. vertical load and nominal tire radius for different segments, [11].

Tire	Segment	Max. Load (Single) / kg	Nominal radius / mm
305/70R22.5 L	People transport urban	3550	499
445/65R22.5 M	Construction	5800	575
295/75R22.5 G	Long Haul	2800	507
315/80R22.5 L	Regional / Long Haul	4125	538
445/65R22.5 L	Off-Road	5800	575

2 New Inner Drum Test Bench for dynamic tests on PLT and commercial vehicle tires (GRIPS)

2.1 Overview

The new inner drum tire test bench (**Fig. 6** and **Fig. 7**) consists of a rotating drum with an inner diameter of 4.5 m, wherein the tire can roll either on drum surface or on special track segments (which lower the inner radius to 4.45m). The whole test bench with a weight of 106t is installed at a spring mounted seismic mass of around 242 t. The air spring system of the seismic mass allows change of eigenfrequency due to extra installed air tanks, when critical operation phases are passed (drum speed, hexapod actuation).

The test wheel is mounted on a dynamic, universal suspension realized with a servo-hydraulic hexapod unit, which allows almost any setting of the operating conditions of the tire with frequencies of up to 30 Hz. For optimal control of the hexapod, additional force transducers and acceleration sensors are attached to the six hydraulic linear actuators of the hexapod. Forces and torques transmitted from the tire to the track are measured with a measuring hub between wheel and hexapod.

A special designed drive shaft connects the wheel with the output shaft of the transmission of the wheel drive. Transmission and shaft allow operation of PLT and truck tires with different requirements on loads, speeds and position changes. An electric motor runs the wheel drive and generates drive and braking torques.

This electric wheel motor is coupled electrically with the drum motor, so that power generated during braking phases serves as a power source for the other electric motor. Additional power is taken from electric net especially to accelerate the drum up to test speed. To decelerate the rotating components, the electric motors are running as a generator and feed back power to the net. Generated peak power will be reduced by an integrated braking resistor.

The electric drum motor drives a belt transmission connected to the input shaft of the transmission. Two output shafts of this transmission allow to operate the drum at different speed and load ranges.

The drum is covered by a steel construction to hinder objects to be ejected from the drum (e.g. broken tire or wheel parts). In the inner drum surface different tracks can be installed to test the tire on realistic road surfaces. Those tracks are fixed through screws to the drum. A frontal cover at the upper part of the drum prevents object ejection in axial direction.

The whole test bench is controlled through a test bench software, which includes mainly safety checks, condition monitoring, set up of test sequences and measurement and control of test bench’s actuators. The test bench control unit can be coupled with external programs or simulation models, which sending control values. E.g. this control values can be calculated within a driving dynamic simulation to test the tire within realistic operation sequences. The operator monitors and controls the machine from a desk within an extra room near to the test bench room.

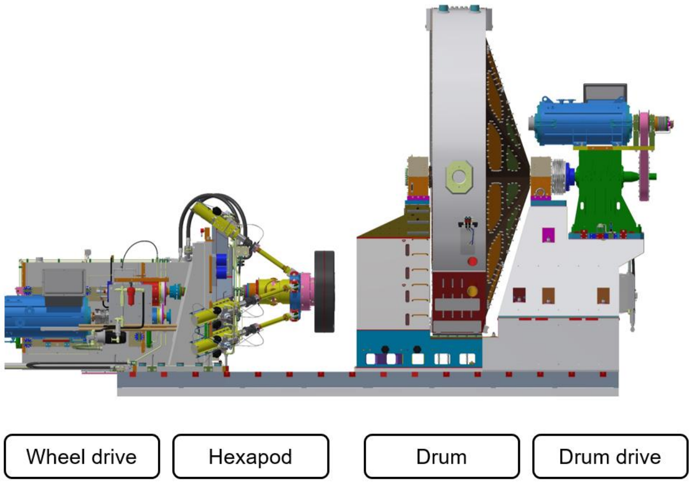

Fig. 6. GRIPS – Side view, Source: Inova GmbH.

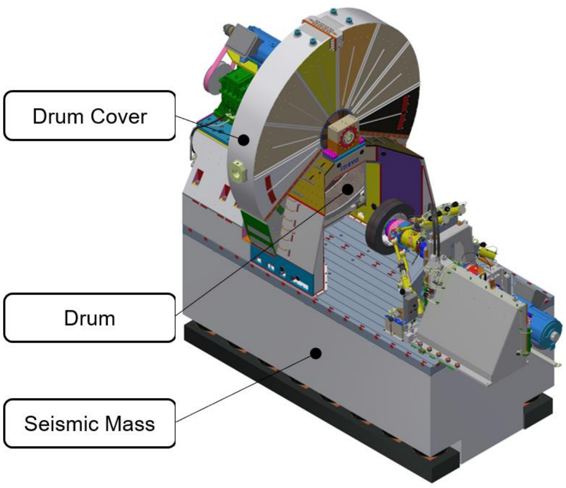

Fig. 7. GRIPS – Total view, Source: Inova GmbH.

2.2 Technical specifications in detail

An overview of the technical specification of the new test bench (**Fig. 8**) is given within **Table 8**. The table already states the usability for dynamic tests on PLT and truck tires. The test tire can have a **dimension** up to 650 mm in diameter and 605 mm in width, so that the test bench is well suited for relevant tires (compare to **Table 7**).

Table 8: New inner drum test bench: Technical specification.

Parameter	Value
Inner diameter of drum	4.5 m
Max. track width	605 mm
Max. drum speed at track level	250 km/h
Max. tire radius	650 mm
Track types	On request
Slip angle	-15 … +15°
Camber angle	-10° … +10°
Max. frequency of change in wheel position	30 Hz
Max. power of electric motors	630 kW
Max. vertical force	60 kN
Max. longitudinal force	26 kN
Max. lateral force	40 kN
Max. torques	M_{x_max} = 25 kNm M_{y_max} = 14 kNm M_{z_max} = 10 kNm

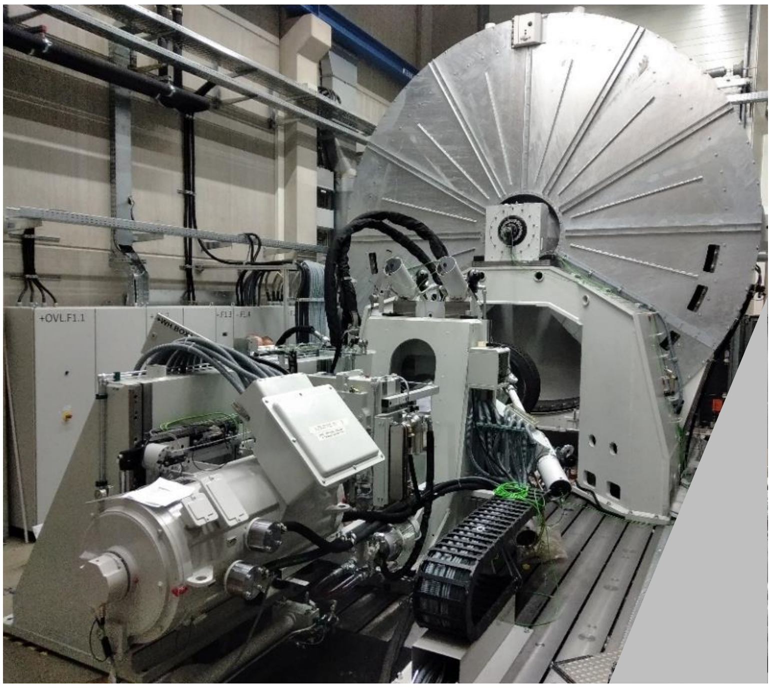

Fig. 8. New inner drum tire test bench GRIPS: Wheel drive and drum with cover.

Depending on the operation mode (transmission ratio incl. respective efficiency rate in max. torque mode) the electric drives can deliver a **longitudinal force** of up to 26 kN for truck tire tests and turn the drum with a max. tangential speed of up to 250 km/h for PLT tire tests, **Fig. 9**.

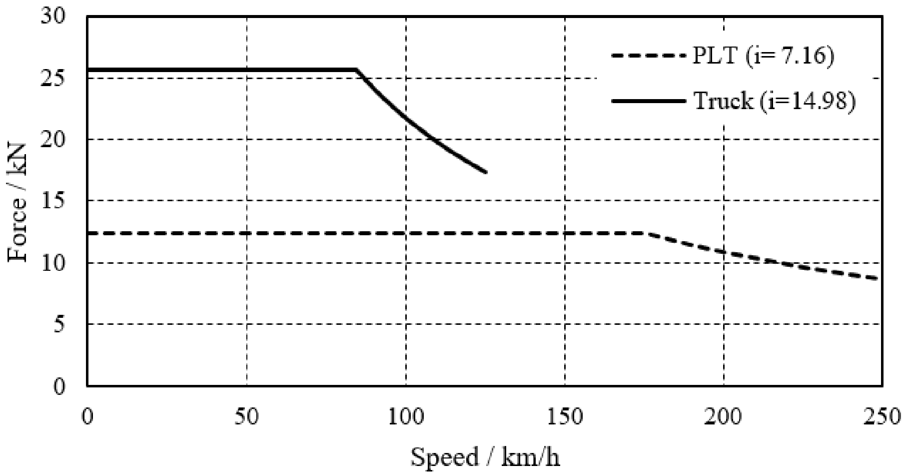

Fig. 9. Maximum longitudinal force delivered by drum drive (efficiency 95.7%) for the two selectable gear ratios.

The **big diameter** of the drum lead to a small curved contact area. E.g. for a tire of size 445/50R22.5 (estimated contact width w = 400 mm), a load index of 161 (F_z = 45.371 N) and an inflation pressure p_i of 8.5 bar, a contact length L of 120 mm can be calculated with following equation:

$$L \approx F_Z/(p_i \cdot w) \tag{1}$$

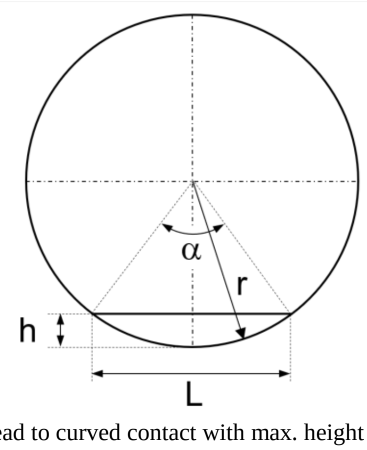

Fig. 10. Contact length L lead to curved contact with max. height of h.

The resulting angle α can be determined with following equation:

$$\alpha = 2 \cdot \arcsin\left(\frac{L}{2 \cdot r}\right) \tag{2}$$

So that the height of the circle segment h can be determined with following equation:

$$h = r \cdot \left(1 - \cos\frac{\alpha}{2}\right) \tag{3}$$

For the given example tire, the height of the circle segment h would be 1 mm, which is nearly neglectable, since it is close to a flat road.

2.3 Selected possible key performance tests

Tire's main function is the **force transmission** between vehicle and road. This safety relevant key performance can be measured on the new test bench within the limits resulting from the max. measurable forces in vertical direction of 60 kN and in lateral direction of 40 kN. Compared to that, the max. generatable torque of drum and wheel drive limit the longitudinal forces to a maximum of 26 kN (**Fig. 9**).

The force transmission characteristic can be determined as the transmitted force coefficient μ (as a ratio of longitudinal or lateral force to vertical force) in dependency of the vertical force, so that an extrapolation of this dependency allow the estimation of transmittable lateral and longitudinal forces at higher (dynamic) vertical forces. One test result on transmittable lateral force coefficient μ_y of a truck tire on a steel track is shown in **Fig. 11**.

Further application of the new tire test bench in terms of force transmission can be the determination of cornering, drive and braking torque stiffness especially for commercial vehicles with electric drives and in urban and long-haul operation with lower acting lateral and longitudinal forces (**Fig. 12**). In addition, parametrization of tire models for quasi-stationary and dynamic force transmission (Pacejka Magic formula, F-Tire) can be performed based on measurements on the new test bench.

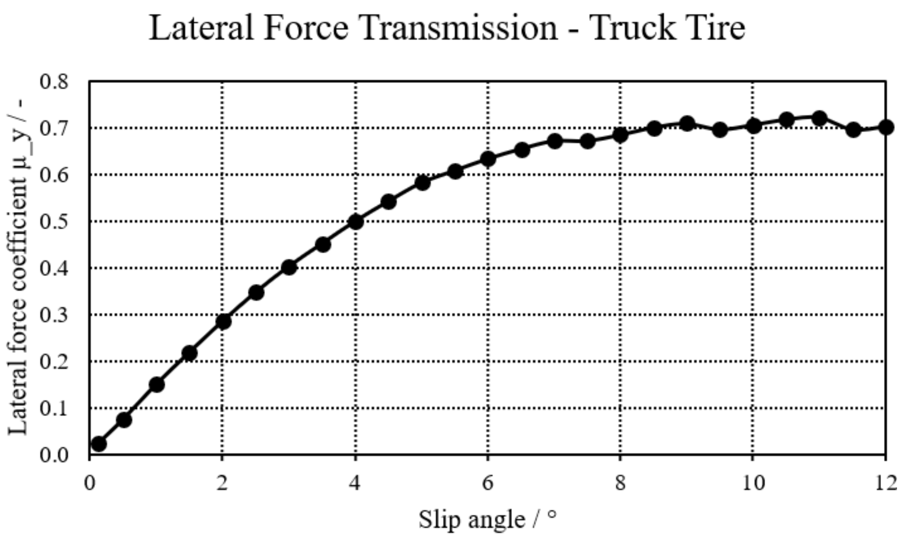

Fig. 11. Lateral force transmission - Truck tire: 445/50 R22.5; p = 8.65 bar; F_z = 45 kN; v = 80 km/h; track: steel.

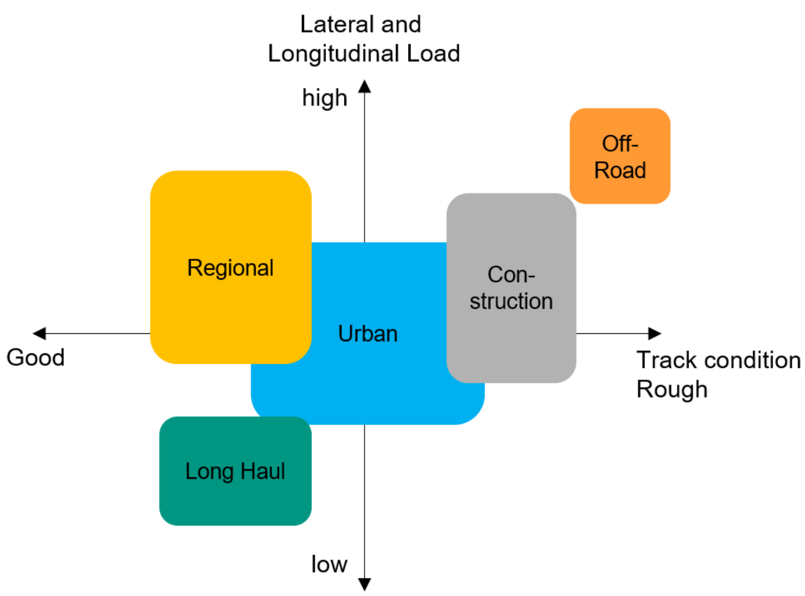

Fig. 12. Tires for commercial vehicle: Application oriented classification with special requirements on transmittable lateral and longitudinal forces and track condition, according to [9].

The efficiency of truck tires is another application field of the new test bench. Efficiency relevant **power loss ΔP** of a tire results from the rolling resistance and from slip losses, when transmitting longitudinal or/and lateral forces. For a braked, free rolling and driven tire the power loss ΔP can be calculated with eq. (4) and the characteristic of resulting curve is presented within **Fig. 13**.

$$\Delta P = [F_R \cdot (1 + s_{wheel}) + F_{xTS} \cdot s_{wheel}] \cdot v_v \tag{4}$$

With F_R – Rolling Resistance Force; F_{xTS} – Longitudinal force, s_{wheel} – Wheel slip, vehicle speed v_V

Rolling resistance of truck tires is compared to PLT tires lower and reaches values of 0.4% of vertical forces (compare [11]). Since the measuring hub measures the braking torque with a maximum relative uncertainty of up to 0.25%, the rolling resistance as an absolute value cannot be determined with this test setup. Still a comparison of different tires at same vertical load in terms of power loss is possible.

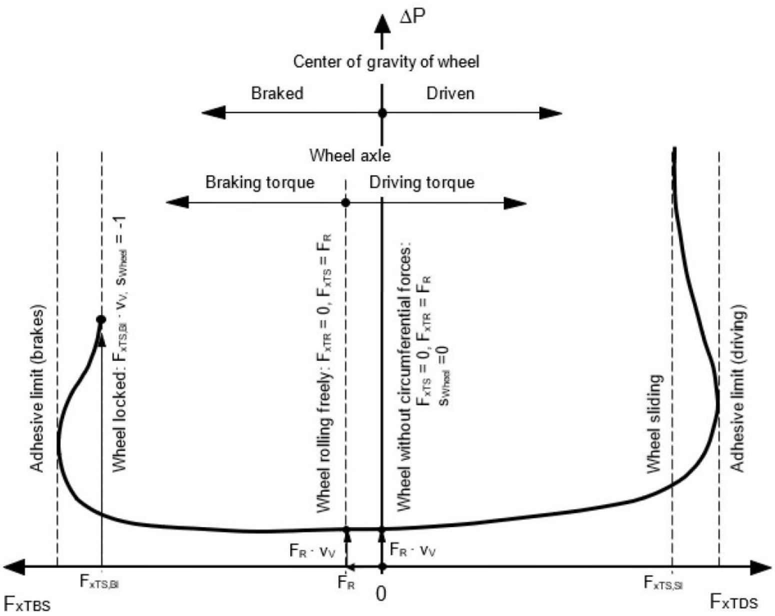

Fig. 13. Power loss ΔP under constant vertical load, plotted against the circumferential force F_{XTS}, which is supported on the road as tractive force and can be measured as reaction force at the measuring wheel hub, translated from [13].

The servo-hydraulic hexapod unit serves as a universal suspension of a quarter vehicle, so that realistic wheel position changes during compression and rebounding can be applied not only under quasi-stationary loads but especially during **dynamic changing wheel load**s (vertical loads or/and lateral loads). The alternation of wheel position can be performed up to 30 Hz in single directions (**Fig. 14**). Within this diagram, the maximum possible amplitude for the four degrees of freedom are printed in dependency of frequency. Under real operation max. amplitude of wheel position changes are far lower, so realistic dynamic tests of truck wheels can be performed with the new test bench.

Within the commissioning of the test bench, first tests of hexapod had been performed and an unloaded wheel had been actuated in z-direction with a max. z amplitude of 175 mm at low frequency, **Fig. 15**. This measurement result show that for an unloaded wheel between 2.5 and 20 Hz higher amplitudes can be achieved compared to the calculated target performance (**Fig. 14**). Between 20 and 30 Hz the measured amplitudes meet the target performance, while amplitude was limited within the range 0 to 10 Hz. The phase shift between set and actual oscillation is small.

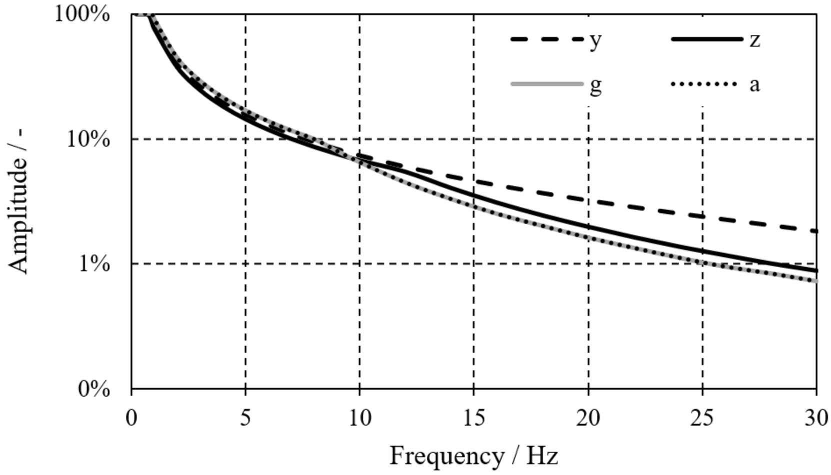

Fig. 14. Calculated target performance for movement of loaded wheel actuated by Hexapod: Maximum amplitude as frequency response for relevant actuation directions - Change of wheel position lateral (y) and vertical (z) and change of wheel camber angle (g) and slip angle (a) (100%: Δy = 115 mm; Δz = 175 mm; Δa = 18°; Δg = 18°); Source of calculated data: Inova GmbH

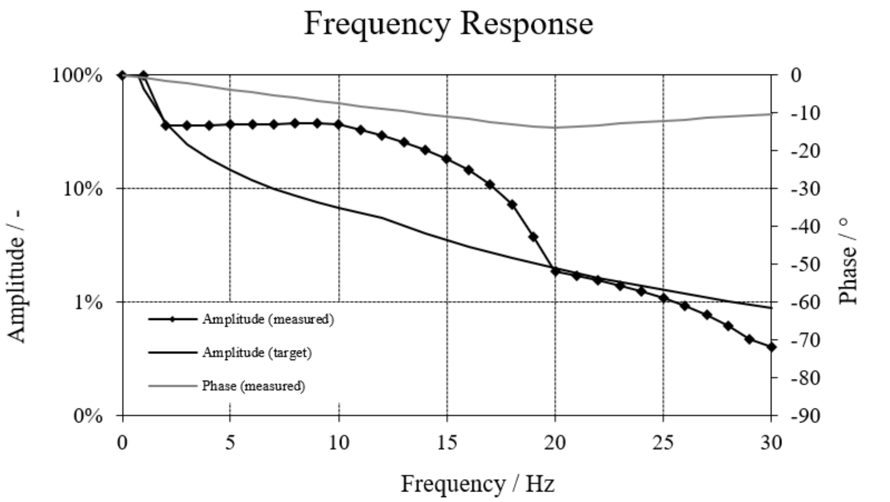

Fig. 15. Measured performance for movement of an unloaded wheel actuated by Hexapod: Maximum amplitude in z direction and phase shift as frequency response (100% amplitude: Δz = 175 mm).

Fig. 16. Truck wheel mounted on the hexapod in front of the inner drum.

3 Summary

Within this paper, we presented and discussed technical details of the new inner drum tire test bench at the Karlsruhe Institute of Technology, Institute of Vehicle System Technology. Besides PLT tires especially truck tires with high wheel loads can be tested on this test bench in terms of safety relevant force transmission and efficiency. Furthermore, the drives of the test bench allow tests at high speed (safety) and under dynamic changing wheel positions to determine comfort or driving dynamic relevant key performance parameters.

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