Methods for experimental investigations on tyre-road-grip at arbitrary roads

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Abstract – Having a look at safety to traffic and the prevention of accidents it can be observed that technical improvementc in active safety of vehicles have let to various positive effects in this area. Among other components the tyre-road-contact takes a key role in the development of active safety technologies. All forces in accelerating, breaking and vehicle guidance have to be transmitted through the tyre-road contact area by friction forces. A common way to characterize a friction process is to identify the coefficient of friction μ between two touching materials. Even though there are several approaches to experimentially characterise road surfaces, no standard method exists. In this paper an overview of existing test methods is given. Furthermore the preliminary design of a newly developed portable test device with its possibility to investigate the tyre-road-friction of arbitrary roads or even places of accidents is shown.

NOTATION

g	Constant of gravitation	A	Area	α	Slip angle
h	Height	E_d	Dissipated energy	μ	Coefficient of friction
l	Length	F_G	Gravitation force	μ_{Lo}	Longitudinal coefficient of friction
m	mass	F_H	Horizontal force	μ_{La}	Lateral coefficient of friction
p	Contact pressure	F_N	Normal force	δ	Temperature
s	Sliding length	F_R	Friction force	ω	Angular velocity
v	Velocity	R	Radius		
v_s	Sliding velocity	S	Slip ratio		
v_p	Peripheral velocity	T	Torque		
v_v	Vehicle velocity				
w	Width				

INTRODUCTION

The tyre-road contact takes a key role in providing a safe vehicle guidance and has a large impact on safety to traffic. The tyre-road contact is the only connection of the moving vehicle to the road. All forces causing the dynamics of vehicle movements like accelerating, breaking and vehicle guidance are transmitted through this contact area. The accruement of these forces is caused by the physical phenomenon of friction. The phenomenon of friction appears in many technical applications. While in some applications the effect of low friction forces between two contact partners is required, for example in rotational and axial bearings, hydraulic and pneumatic seals etc., other applications claim for high friction forces like the tire-road contact of vehicles. The friction process can be characterized by identifying the coefficient of friction μ between two materials in the contact area. The dependence of the coefficient of friction μ on various parameters, non-linear constitutive equations as well as the complexity of its investigation cause a huge request for research on this subject. Even though there are several approaches to experimentially characterise road surfaces with a focus on the friction behavior of tyres no standard method exists. The range of existing test rigs varies from small manually operating devices to very complex vehicle based systems. One point for all these test devices is the ability to measure in a parameter range defined by the contact pressure and sliding velocity in the contact area of a breaking tyre. While the small and portable devices have problems to reach such a suitable wide parameter range, the use of the vehicle based systems goes hand in hand with very high technical and financial effort as well as limited portability. To fill the gap between existing test methods the Institute of Dynamics and Vibration Research and the Continental AG are working on the development of a new innovative high-performance portable test rig by applying knowledge from lab and tyre vehicle testing This new portable test device with its possibility to investigate the tyre-road-friction at arbitrary roads or even at places of accidents can be seen as a further step to a higher level of safety to traffic.

BASICS OF FRICTION MEASUREMENT

Efforts to bring more safety to traffic are often focusing on the tyre-road contact and especially on the friction processes taking place in the contact area. All forces generated in this area have their origin in the occurrence of friction phenomena. These phenomena are not fully understood yet. In General the coefficient of friction μ is defined as the ratio of the resulting friction force F_{F} and the acting normal force F_{N}

$$\mu = \frac{F_{\mathrm{F}}}{F_{\mathrm{N}}}. \tag{1}$$

Additionally the rubber friction is influenced by many non-linear dependencies of various parameters like sliding velocity v_{s}, contact pressure p, temperature δ etc. This causes a great need of studies in this field to get a better understanding of friction phenomena. To tap the full potential of these mechanism there are great endeavors to gain insights into friction processes. In addition to numerous theoretical researches a large number of experimental investigations are carried out on this subject. [1]

Experimental investigations can be separated into indoor testing under laboratory conditions and outdoor testing. Laboratory investigations have the goal to vary only one parameter while keeping all other parameters as constant as possible. This allows precise parameter studies which could lead to a better basic understanding. Another benefit of laboratory investigations is the possibility to verify analytical calculations on the one hand and to provide input parameters to model-based simulations on the other hand. Outdoor testings are facing realistic testing conditions concerning the texture and condition of the road, environmental and weather influences etc. Particularly for accident research realistic testing conditions are of great interest. In what follows, the description of test methods is limited to outdoor testings.

Outdoor-testing can be categorized into two different groups. More precisely it consists of the longitudinal friction principle and the lateral friction principle. The longitudinal friction principle can be considered similar to a straight line braking maneuver. A freely rolling tyre (radius R) has a peripheral velocity v_{p} that is proportional to angular velocity ω. When a braking torque is applied to the rolling tyre its peripheral velocity v_{p} decreases as well as the vehicle velocity v_{v}. If the applied torque exceed a certain limit and the peripheral velocity v_{p} of the tyre decreases faster than the vehicle velocity v_{v}, slip can occur in the contact area. The slip ratio S is defined by

$$S = \frac{v_{\mathrm{s}}}{v_{\mathrm{v}}} = \frac{v_{\mathrm{v}} - v_{\mathrm{P}}}{v_{\mathrm{v}}} = \frac{v_{\mathrm{v}} - \omega \cdot R}{v_{\mathrm{v}}}; \tag{2}$$

where

$$v_{\mathrm{s}} = v_{\mathrm{v}} - v_{\mathrm{p}}. \tag{3}$$

Note that for a braking tyre $0 \leq S \leq 1$ a special case can be regarded when $S = 1$. In this case the tyre is locked and the sliding velocity v_{s} of the tyre-tread-blocks in the contact zone is equal to the vehicle velocity v_{v}, i.e. $v_{\mathrm{s}} = v_{\mathrm{v}}$. The friction coefficient μ_{Lo} for longitudinal friction shows a strong dependence on the slip ratio S. A typical friction-slip curve $\mu_{\mathrm{Lo}} = \mu_{\mathrm{Lo}}(S)$ is shown in figure 1. It can be seen that friction increases as the slip ratio increases until it reaches a maximum value. Then friction is decreasing as the slip ratio increases further until a slip ratio $S = 1$ is reached, which stands for the locked wheel state. Using ABS braking systems sliding velocities of the tread blocks can be expected in a range between 0 and 3 m/s.

In addition to the longitudinal friction principle the lateral friction principle represents the second category of outdoor testings. This principle is related to the cornering of a vehicle. In a lateral motion a difference between the moving direction of the vehicle and the wheel rotation-plane can occur. The angular difference between both directions is described by the slip angle α, shown in figure 2. Forcing the rotating wheel to move straight on causes lateral friction forces. The lateral friction coefficient μ_{La} varies with the slip α angle in a similar way as the longitudinal friction coefficient μ_{Lo} does with the slip ratio S.

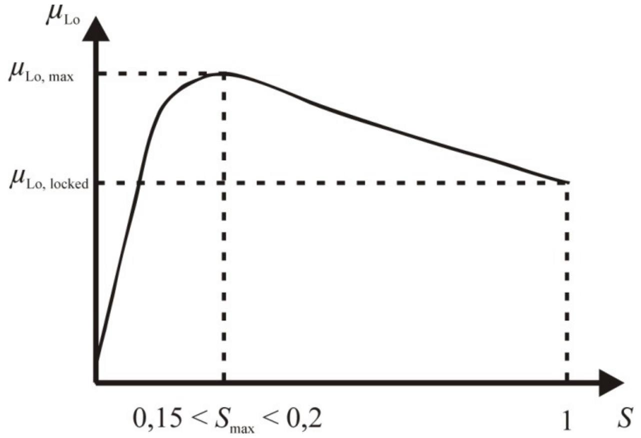

Figure 1. Illustration of longitudinal friction coefficient-slip ratio curve cf. [2]

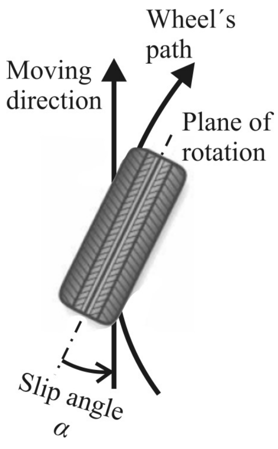

Figure 2. Illustration of slip angle cf. [2]

ANALYSIS OF EXISTING TEST METHODS

There is a large number of test devices available based either on the longitudinal or transverse friction principle. Most devices are using a test tyre which causes a need for very high forces that have to be applied. These devices are usually mounted on vehicles or trailers and can only be applied on wet surfaces. In figure 3 some examples are shown. It is obvious that these designs go hand in hand with very high technical and financial effort as well as limited portability.
A special case is represented by devices using the longitudinal friction principle at a slip ratio $S = 1$. In this case there is no need to use a whole tyre as a test object. More precisely it is sufficient to use a rubber sample representing the tyre tread blocks in the sliding contact area. Figure 4 shows two devices of this category, the “Skid resistance pendulum” and the “Abrollgleiter” [3]. While the vehicle based devices are equiped with extensive measurement technology to determine the friction coefficient directly, the portable devices do identify the difference energy ΔE_d due to dissipation in the applied friction process. This energy ΔE_d can be translates into a certain value that should represent the friction coefficient. Both portable devices presented here are converting an initial energy into kinetic energy. In case of the “Skid resistance pendulum” the reached angle after leaving the contact zone determines the friction coefficient. In case of the “Abrollgleiter” the length s needed to dissipate the whole kinetic energy of the device is measured. Both systems have no electrical measurement value acquisition. For this reason there is no possibility of monitoring the occurred friction process over time.
In addition the devices have to be adjusted very carefully to ensure that they are operating correctly. This leads to high demands on the operator to detect failed measurements and avoid them.

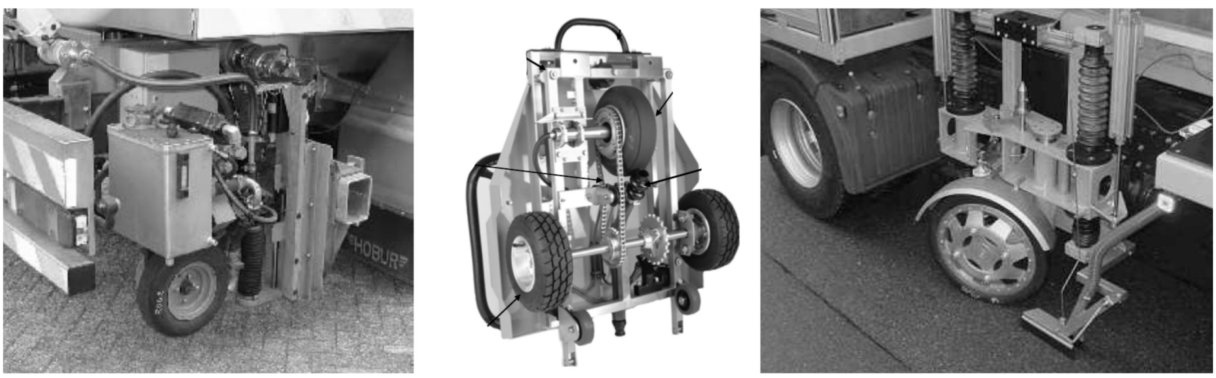

Figure 3. Examples for vehicle based devices (ROAR NL [4], Griptester [5], SKM [6])

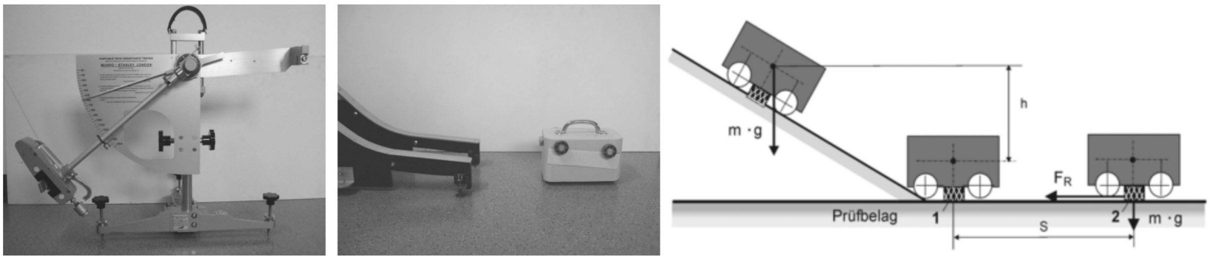

Figure 4. Examples for portable devices [3]

Figure 5 shows a classification of the existing test methods. At this point it can be concluded that the small and portable devices have problems to reach a suitable wide parameter range and to avoid errors in measurements. As mentioned before the use of vehicle based systems goes hand in hand with very high technical and financial effort as well as limited portability. To make further steps in this friction testing technology the Institute of Dynamics and Vibration Research and the Continental AG are working on the development of a new portable test rig. The new test rig should fill the gap between existing test methods. More precisely it should enable parameter studies in a suitable wide parameter range and measurements for the classification of a road grip level on public roads, test tracks and even at the places of accidents.

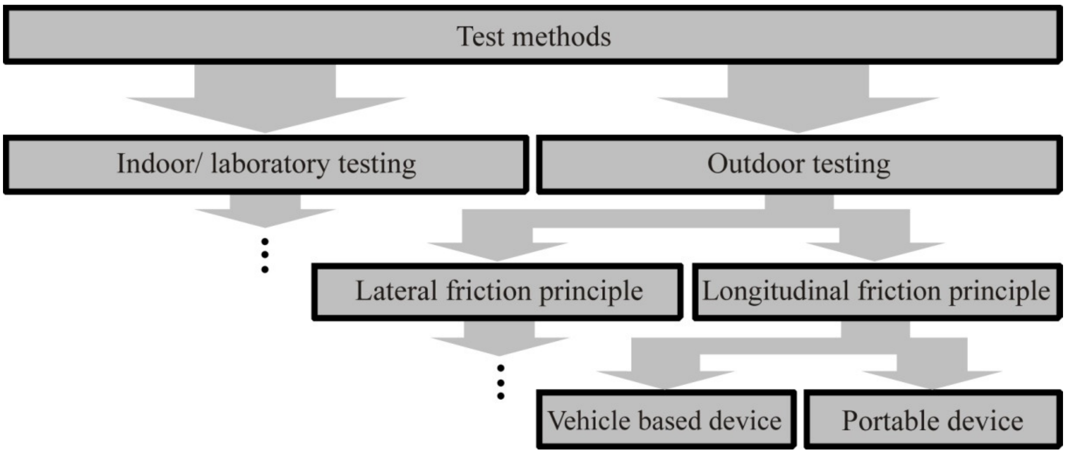

Figure 5. Classification of test methods

CONCEPT AND SAMPLE GEOMETRY OF THE NEW TEST RIG

From the previous analysis the following requirements can be deduced. To achieve an improvement to the state of the art it is considered necessary to develop a test rig that is operating in an appropriate parameter range concerning contact pressure and sliding velocity. This parameter range should be equal to the parameter range a braking tyre is exposed to under real conditions. Further a direct measurement principle for the coefficient of friction is useful for the possibility of avoiding or at least detecting errors measurements. The design of the test rig should enable an easy handling and require a minimum adjustment effort. The dimensions of the test rig should allow the transport in a van. The collected main requirements are listed in Table 1.

Table1. List of test rig requirements

Transport dimensions	1.5 m x 0.5 m x0.5 m
Maximum weight	30-40 kg
Measuring length	ca. 1 m
Nominal contact pressure	2- 3.5 bar
Sliding velocity	0-3 m/s

To meet the identified requirements a test method with a linear moving rubber sample is chosen. This decision is mainly driven by very good experiences with the “High Speed Linear Test Rig” (HiLiTe) of the Institute of Dynamics and Vibration Research [7]. The standard rubber sample geometry used for the HiLiTe has the dimension 80 mm x 20 mm x 8 mm (width w x length l x height h) which causes a request for high operating forces. Smaller rubber samples would lead to a reduction of the required forces. The occurring normal forces F_N and friction forces F_F in dependence of the sample area A are estimated by calculation. For this calculation the contact pressure is set to p = 3.5 bar and the coefficient of friction to μ = 1.2. Then the friction force F_F in dependence of the contact area A is defined by the following equation. Some results are listed in table 2.

$$F_F(A) = \mu \cdot F_N(A) = \mu \cdot p \cdot A = \mu \cdot p \cdot w \cdot l. \tag{4}$$

Table 2: Estimated Forces for const. friction coefficient μ = 1.2 in dependence of the contact area A

Size (w x l) [mm]	Contact area A [mm^2]	Normal force F_N [N]	Friction force F_F [N]	
80x20	1600	840	672	Ref.
40x20	800	280	336	
30x30	900	315	378	

DESCRIPTION OF THE NEW TEST RIG

The calculation shows that downsizing the rubber sample leads to a reduction of the required forces. Another result is that sample sizes A > 1000 mm^2 cause normal forces F_N that are higher than the gravitation force F_G of the test rig itself under the assumption of a total weight of 40 kg. In a further step it has to be investigated if the necessary downsizing leads to different friction coefficients. For this reason measurement of the friction coefficient were carried out on the exiting test rig HiLiTe. The parameters for pressure and sliding velocity are varied in the range defined by the requirements of the new test rig. The tests were performed for three different rubber compounds and the 80 mm x 20 mm sample geometry is defined as reference. The characteristic diagrams in figure 6 show the results of the chosen 30 mm x 30 mm geometry compared to the reference geometry. It can be seen that both diagrams for each compound show the same characteristic and the measured values show only small deviations.

The definition of the rubber sample size leads to further requirements regarding to the drive of the test rig. For the design of the test rig a linear servo motor unit was chosen. The unit consist of a linear guidance system and has a stroke of 910 mm. The maximum force of 580 N is sufficient to generate the requested friction forces F_F and provides enough force buffer for accelerating the driving unit. The driving unit consists of the sliding stator of the linear motor, 3D strain gauge force sensor and the sample mount. The linear motor unit is mounted on vertical linear bearings at each side. Hence it has a degree of freedom (DOF) in vertical direction. The normal force F_N on the rubber sample is applied by the weight of the linear motor and can be increased by the use of an additional weight. By using different weights the normal force can be adjusted in order to achieve the required contact pressures p of 2 bar, 2.5 bar, 3 bar and 3.5 bar. The free body diagram, shown in figure 7; illustrates the working principle of the test rig.

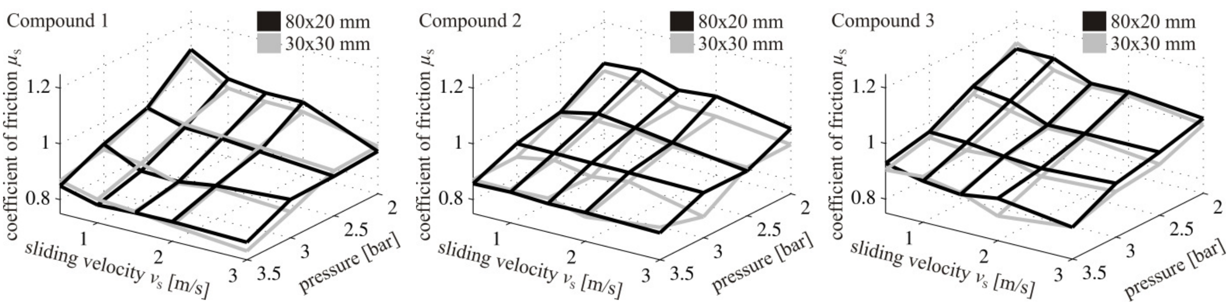

Figure 6. Characteristic diagrams of the friction coefficient μ

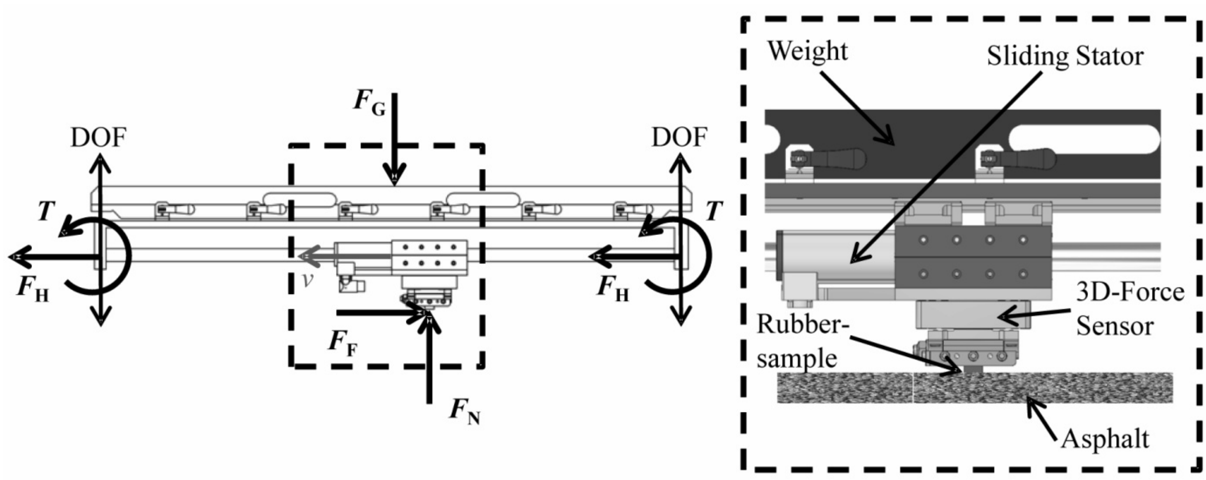

Figure 7. Free body diagram of the test rig concept

The design of the sample mount enables a very quick changing of the samples. The rubber samples are vulcanized on 90 mm x 90 mm steel plates which can be fixed in a clamping arrangement. In addition the sample mount has a rotating DOF along the driving direction (figure 8). This gives the opportunity of compensating a certain misalignment of the test rig on the street or a possible twist of the road.

The coupling of the linear motor unit to the inertial environment is ensured by an aluminum framework. To achieve the smallest possible total weight of the test rig the frame is designed with a focus on light weight. As a result the frame has much less mass than the linear motor unit and its additional weight. This leads to the fact that the occurring friction force F_F in the contact area of the rubber sample can be higher than the horizontal force F_H applied by the frame. In this case the frame would start moving. To avoid this problem without increasing the total weight of the test rig running boards are installed for the user to stand on them. The additional weight of the user ensures a fixed coupling to the ground [8]. For approaching different positions within the travelling path of the linear motor a lifting device is installed. The rubber sample can be changed by turning the test rig on its side. It is possible to turn the test rig on both sides so the user never has to stand with his back in the direction of traffic. For transporting the running boards can be lifted and the installed handles and rolls ensure an easy handling.

Further all components of the test rig are resistant to corrosion and are water proofed. This enables investigation under wet and snowy conditions.

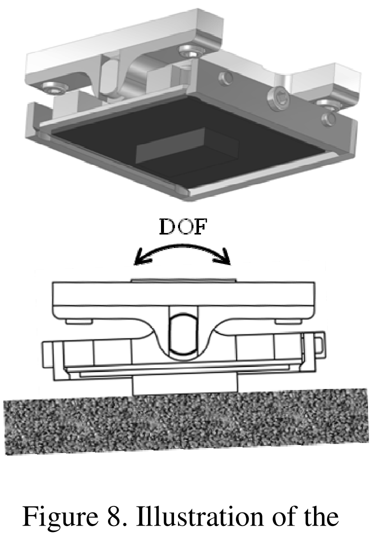

Figure 8. Illustration of the sample mount

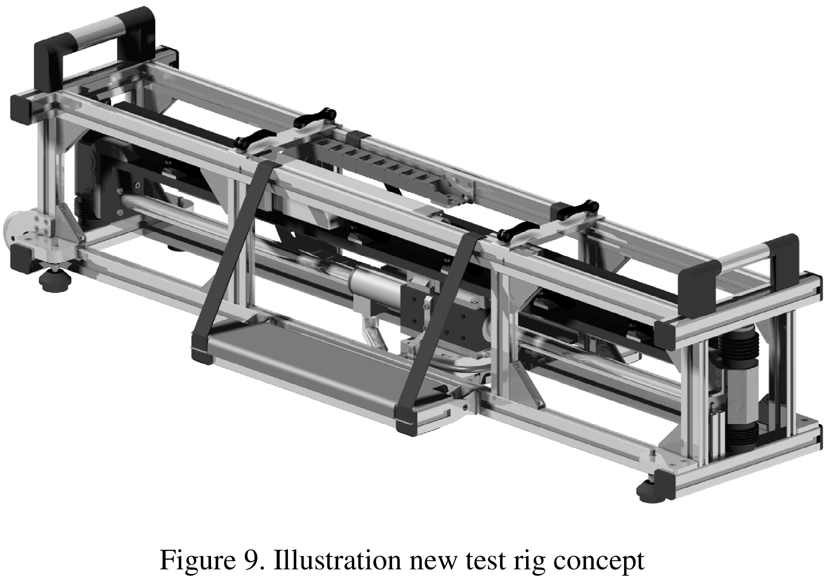

Figure 9. Illustration new test rig concept

CONCLUSION

A short overview of existing test methods for characterizing the friction behavior of road surfaces is given. It shows a wide range of existing test methods and devices. Nevertheless there is a certain gap between the very complex vehicle based devices and the smaller portable devices. To overcome this gap and to cover the need for further investigation methods a new test rig was designed. Preliminary investigations show that the new design full fills the requirements for friction coefficient measurements. As a result a test rig prototype was built (figure 10). The test rig enables investigation on rubber friction at arbitrary roads, test tracks and even places of accidents. It operates in a sliding velocity range of up to 3 m/s and applies a contact pressure between 2 bar and 3.5 bar. Due to its design the test rig is very easy to handle. One vertical and one rotational DOF make almost any adjustment unnecessary. In combination with the featured measurement system the risk of faulty operation and errors in measurements is reduced to a minimum. First results will be shown in [9].

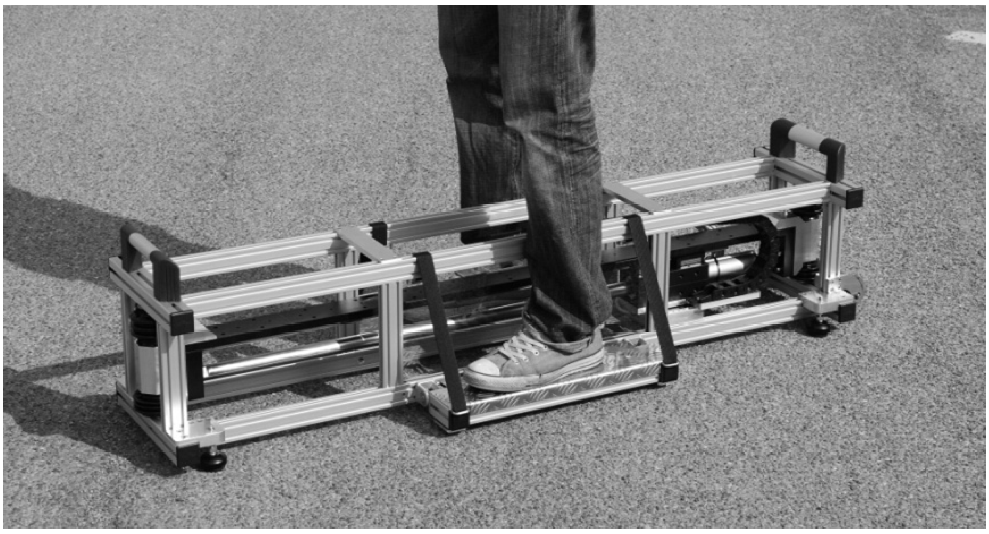

Figure 10. Prototype of the new test rig design

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