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A portable wheel tester for tyre-road friction and rolling resistance determination

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Abstract. The paper describes theory of operation, design and construction as well as results from primarily experiments with a portable wheel tester that has been developed by the authors as a device for on-site determination of tyre-road braking/driving friction and rolling resistance. The paper includes schematics, drawings, descriptions as well as graphical results form early tests with the presented device. It is expected that the tester can be useful in road accident reconstruction applications as well as in vehicle dynamics research.

1. Introduction

Knowledge of the wheel-surface forces is essential for vehicle dynamics studies, vehicle design, accident reconstruction, road construction and maintenance. The μ parameter, a non-dimensional longitudinal surface reaction on a driving wheel, is a basic factor describing vehicle handling dynamics and, consequently, road safety. Braking distance, forward acceleration and lateral dynamics measures are directly dependent upon the μ parameter. Similarly, the f_{RR}, coefficient of rolling resistance plays a significant role in vehicle dynamics analysis as a measure that describes energy consumption by a rolling wheel. Both the parameters, μ and f_{RR} can be determined experimentally with the use of several devices.

Methods and devices for wheel-surface forces determination include the following [2 – 7]:

- devices for sideway force coefficient determination, in which a test wheel is inclined and rolls freely, without slip, for example SCRIM Tester, $\alpha=20$deg, s=34%, Mu-Meter, $\alpha=7.5$deg, $s = 13\%$;
- devices for fixed-slip, longitudinal wheel force determination, the test wheel is straight positioned and the slip percentage is set up for a given value, for example: Griptester, $s=14\%$, DWW Trailer, $s=86\%$, Skiddometer BV-11, $s=18\%$, Norsemeter, $s=20\%$;
- devices for variable-slip measurements of wheel-road friction, examples: Norsemeter, $s=5$–95 %, Petra, $s=0$–100 %;
- devices for locked wheel measurements, $s=100$ %, LPCP Adhera, Skiddometer BV-8, Stuttgarter Reibungstester, ASTM E-274, Skid Resistance Tester SRT-3 [13].

Besides the over-mentioned methods and devices there are numerous laboratory or field test stands, as for example multi sensor measuring head for three-dimensional wheel-surface forces determination, drum testers or the so called dynamometric trailer for wheel force determination in road or off-road condition. One method utilizes an instrumented vehicle with a rotating wheel force transducer that

enables three-dimensional wheel force measurements. The measuring device, rotating wheel dynamometer was built with strain gage force transducers and utilizes a RF, non-contact data transfer. The device was used in multiple off-road tests.

Figure 1. STR-3 trailer-type wheel tester.

Another type of measuring equipment for surface friction determination are portable friction measuring devices, which are used mainly by road construction or maintenance engineers. They include:

- British Pendulum Number device, which enables to determine the BPN factor by simple drop test of a rubber–coated test skidder, supported on a bearing;
- Dynamic Friction Tester with a rotating skidder to determine friction at a speed between 5 and 90km/h;
- VTI Grip Tester, a device in a form of a portable wheel trailer, operated by a walking technician, enables to determine surface friction at 25% wheel slip (see figure 2);
- Drag-Sled Tester, handy operated, enables to determine surface friction in a simple pull or push test, they utilize either external dynamometers or built-in electronic force measuring instruments (TORTUS 3).

Figure 2. VTI Grip Tester.

The aim of this study was to develop a portable wheel tester that will be easy in operation and allow to determine both braking friction and rolling resistance coefficients. Our goal was also to develop a RF non-contact microprocessor based device for data acquisition and transfer to any available portable device (a smartphone or tablet computer). Finally, we also have developed a custom

specialized software which supports the field measurements and helps in determining μ and f_{RR} values online.

2. Design of the portable wheel tester

2.1. Mechanical design of the tester
The tester is a three-wheeled portable device designed for easy and quick operation over a variety of surfaces, road (asphalt, bitumen, Belgian pavement, etc.) and off-road (grass, soft soil of smooth surface). In the design, two strain gage type transducers have been used to measure horizontal force acting on the axis of a test wheel. The front test wheel together with two rear wheels are of 150mm diameter, they have pneumatic tyres with air valves in order to maintain inflation pressure. The main frame of the tester supports rear wheels, which rolls freely and a suspension of the test wheel. The suspension (shown in figure 3) integrates the test wheel and its axis, brake disc bearings and their housings, which are mounted to the strain gage transducers. The suspension functions so that any action (a force or a torque moment) on the test wheel in horizontal plane is reduced to pure longitudinal forces acting 50/50% on the two transducers. The bearings that support the test wheel axis are rocker type to compensate any nonlinearities that could be the result of assembly as well as the measuring action.
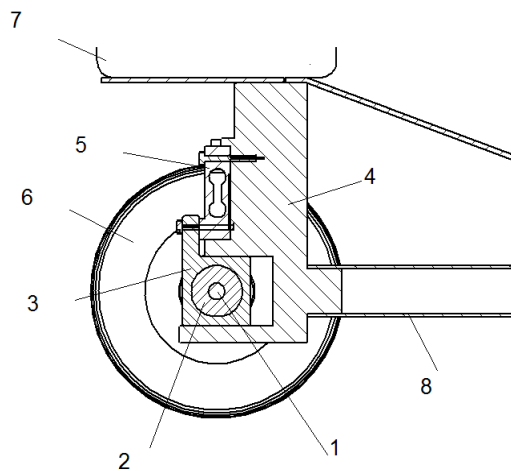

Figure 3. A schematic of the test wheel suspension in the portable wheel tester. 1 – wheel axis, 2 – ball bearing, 3 – bearing housing, 4 – suspension frame, 5 – strain gage sensor, 6 – test wheel, 7 – ballast.

2.1.1. Tyre size effect
In order to reconstruct wheel-surface interactions, an effect of tyre size (width, diameter) has to be considered. Regarding the contact pressure as a parameter describing the wheel-surface interactions and disregarding the tread effects, contact area and contact pressure for the test wheel under various loads has been determined at a normal inflation pressure. Wheel load – contact pressure pairs have been taken to construct a relationship which is a nomogram to calculate an additional weight that has to be added to load the test wheel for a given tyre. The net weight on the test wheel (without additional ballast) is 3kg. Sport weight-lifting round weights have been used and this solution enables to apply the additional load in steps: 5, 10, 15, 20, 25, 30 and 35kg. Ballast heavier than 50kg can damage the mechanical structure of the tester and may have significant effects on load cells readings. The relationship has shown included in figure 4. Based on this simple model, it is possible to determine additional weight for a given tyre for which we want to determine the μ or f_{RR} value. As an example,

for a tyre that generate contact pressure 100 kPa an additional weight of 30kg is needed to reconstruct tyre – surface interactions and determine the values of μ and f_{RR}.
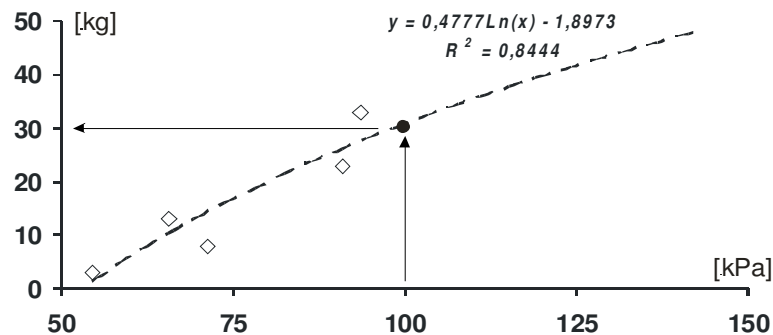

Figure 4. Wheel load – contact pressure relationship for the test wheel for determining the additional ballast weight.

2.2. Microprocessor device for measurements control and data acquisition

The measuring system of the tester has been built with a scale wheel, supported on two load cells, which give readings of both horizontal and vertical forces acting on the wheel. Based on the measured data, rolling and braking friction can be determined. The portable wheel tester wirelessly transfers measured data—horizontal force acting on the test wheel—to a mobile device (a phone or a tablet), and custom data analysis software determines friction coefficients just after the measurements. A RF wireless data transfer system utilizes the Bluetooth IIs technology and it is integrated with a microprocessor control device into a small, battery operated system (shown in figure 5). One can perform measurements wirelessly, with no physical contact with the device. All those features facilitate the operation of the tester and moreover, such a design idea is related to the philosophy of the internet of things.
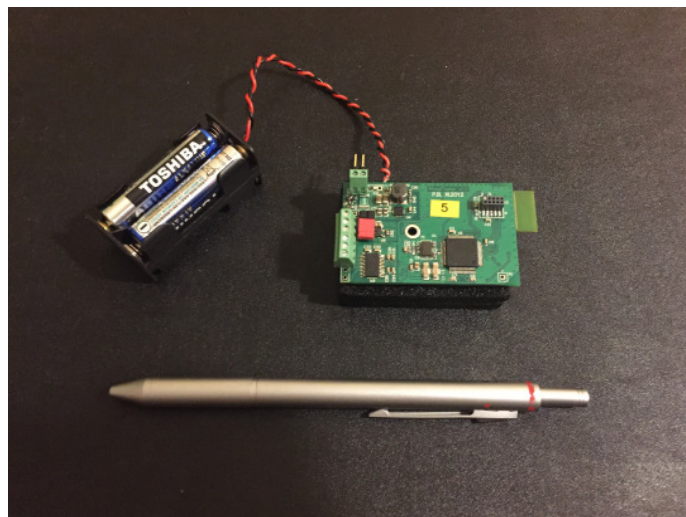

Figure 5. A microprocessor-based electronic control unit for acquisition and wireless transfer of measured data.

2.3. Data analysis software

The software uses an algorithm that allows the choice of a range of *My* data for averaging and determining the f_{RR}. This is performed by selecting the starting and ending point of the chosen range.

The algorithm also provides a smart tool for searching for *My* data required for braking friction μ_B determination. The final results, the f_{RR} and μ_B are readily presented on the screen. Figure 6 shows sample readings from the tester with the software activated for surface friction determination.
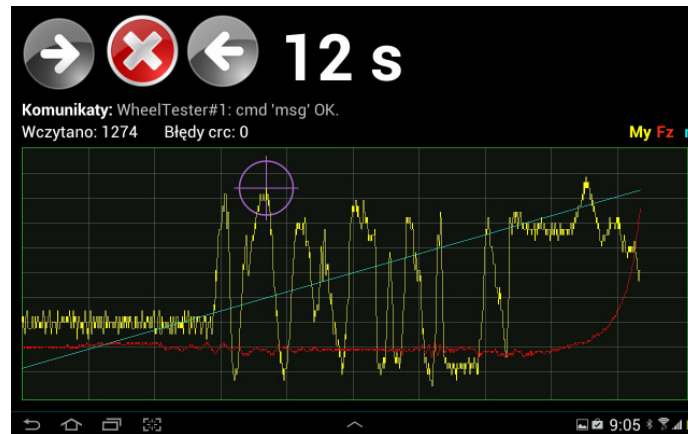

Figure 6. Sample readings from the tester as visualized by the software, together with markings for determining the μ and f_{RR} values online

2.4. *Operating the tester*

The wheel tester operation is very simple. An operator pushes the arm to move the tester forward at a low speed, as seen in figure 7. The push arm is mounted to the main frame of the tester and is movable in the vertical plane in order to fit the level of the grips with the height of the technician for ease operation. During rolling resistance readings, the test wheel rolls freely; for braking friction measurements, a hand-operated brake is activated to block the test wheel. An engineer, standing nearby in the range of the RF device can see the readings online. Using a touch screen of a portable device with installed data analysis software and active Bluetooth RF transceiver, the engineer chooses a portion of data obtained during a free rolling test for determination of f_{RR} value and the result appears on the screen. There is a possibility of recording the complete data set. For a braking friction test, the two persons have to correlate their procedures. First, the operator of the tester begins to push the tester with a typical forward speed. At a moment known for the analysis engineer, the operator brakes the test wheel and continues to push the tester for 2-3 seconds. The engineer can read the data online and has to choose a peak value of the longitudinal force on the touch screen. The software performs calculations and the result appears on the screen.

Figure 7. Operating the wheel tester

2.5. Early tests and calibration of the tester

The device has been examined in several test runs, performed on three different surfaces: bitumen, Belgian pavement and grass. Figure 8 includes raw data in form of time courses of horizontal force measured by the tester. This data has been captured onto the memory stick card and this function of the tester is useful in any research oriented measurements. Simply, while not determining the actual values of f_{RR} and μ_B , one may obtain the complete data an use it for further analysis.
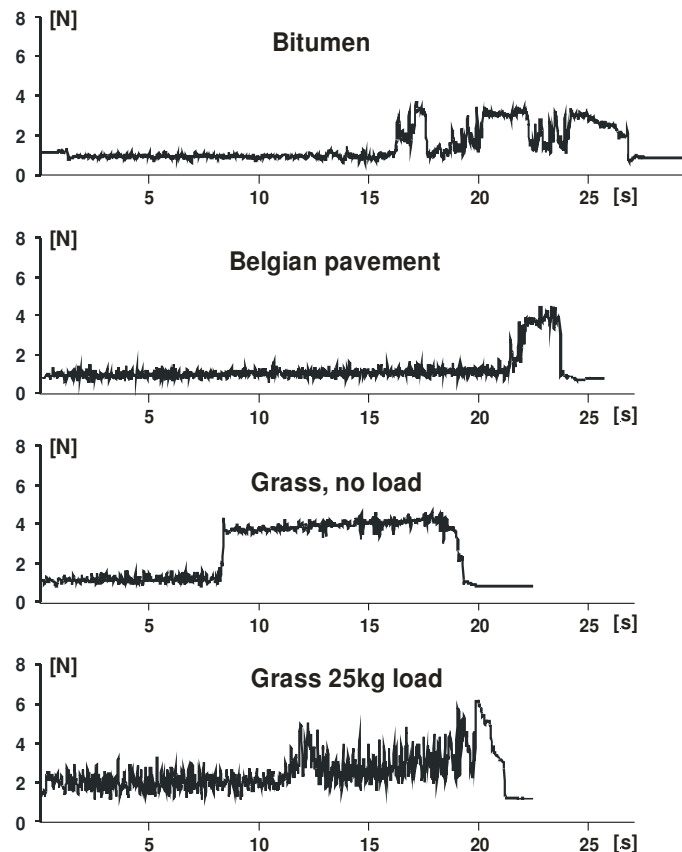

Figure 8. Time courses of the horizontal force obtained for three different surfaces: bitumen, Belgian pavement, grass – no load on the tester, grass – 25kg load (top to bottom)

3. Applications of the tester

Generally, the portable wheel tester can be useful as a supporting device in on-road and off-road vehicle dynamics studies, where knowing an actual value of μ and f_{RR} is important. Applications include vehicle braking and acceleration tests, tyre testing, lateral dynamics and vehicle handling dynamics experiments, etc. Those applications are typical for academia and research institutions and there the ability of determination and recording of raw data (horizontal forces versus time) will be of interest. Another subject, where such a device can be of help is road accident reconstruction. There a quick yet precise determination of actual values of μ is crucial for the procedures. The tester can be transported even in a compact passenger car, so bringing the device to the accident place will not be a problem. The data analysis software can be used in such application as a toll that provides with immediate results. Besides the on-road application, the presented device can be used in terrain conditions to determine μ and f_{RR} coefficients which corresponds to wheel-soil interactions. The general concept and mechanical design of the tester enable to determine braking/driving friction as well as rolling resistance on soft, deformable tractive surfaces such as arable soils, grass, snow, etc. The tester has already been used as a evaluation tool in a method for testing grassy runway surfaces.

For a given grassy airfield, determining of actual μ and f_{RR} values is important to make decision on performing take-offs or landing on this runway, especially after rain, when the grass and surface is wet. The tester has proved its functionality. However, after the tests on a grassy surface it was concluded that for off-road applications the mechanical design of the tester have to be changed. Modification have to be made to the wheel brake, as the prototype disc brake may collide with uneven, rough surface of grass blades during test runs. This drawback can be easily eliminated by the use of a rim brake.

4. Conclusion
We have designed and developed a prototype of a portable wheel tester for determining the μ and f_{RR} values in field experiments. The tester utilizes strain gage type sensor technology together with RF and microprocessor based electronic for data acquisition. There is a possibility to determine wheel friction and rolling resistance online and a specialized custom software has been developed to support this functionality. Application of the tester include vehicle dynamics testing, both on- and off-road, road accident reconstruction and testing and evaluation of grassy runway surface. At the current stage of the project, the tester can reconstruct wheel-surface conditions for tyres inflated to approx. 120kPa. For higher inflation pressures, it is needed to modify the mechanical design of the device. Further development of the tester will also include modification of the brake system for off-road conditions.

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