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SYSTEM FOR INVESTIGATION OF FRICTION PROPERTIES OF THE ROAD SURFACE

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Abstract. Friction properties of the road surface have a great influence on the safety of automobile motion. These properties are characterized by the tyre-to-road adhesion coefficient, which is measured during the routine and acceptance investigations of roads. In the paper, the method of measurement of this coefficient is presented. For investigation of the tyre-to-road adhesion coefficient the special measurement system was developed. The main part of the system is dynamometer trailer, which makes it possible to measure the friction force between tyre and road surface. The adhesion coefficient as a quotient of the friction force and vertical load is a result of measurements. Additionally the system enables to determine the graph of the adhesion coefficient as a function of wheel slip ratio. In the paper a description of the measurement system and a principle of its operation are presented. Exemplary results of tyre-to-road adhesion coefficients measured on different roads are also presented. The results show many differences between these coefficients in dependence of road upper layer technology, degree of its wear, weather conditions, sliding velocity and others. The system originally designed for investigation of friction parameters of road surfaces can have much wider applications, for example in tyre investigations, for automotive experts, in the work of judgment witnesses and others.

Keywords: tyre-to-road adhesion, skid resistance tester, traffic safety, accident reconstruction.

1. Introduction

Friction properties of the road surface have a great influence on the safety of automobile motion, because the tyre-road contact is the only way in which the tangent forces between automobile and road can be transmitted. The friction properties of the road surface are characterized by the tyre-to-road adhesion coefficient which is calculated as a quotient of the friction force and vertical load. The value of this coefficient depends on two interacting elements, i.e. tyre and road surface. Therefore, investigations of the phenomena which occur in the contact area between vehicle tyre and road surface (Gabriel *et al.* 2010; Liu 2008; Persson 2002, 2007) are the field of interest both for automotive engineers and civil engineers. Although, in both cases advantageous is obtaining high value of adhesion parameter. The approach to this matter is different in automotive engineering and in civil engineering.

From the point of view of vehicle dynamics not only maximum value of the adhesion parameter is important, but also its dependence on the longitudinal slip of the wheel. Knowledge of these characteristics is especially important for operation of active safety systems utilising wheel slip regulation e.g. anti-lock brake system (ABS), electronic stability program (ESP), traction control system (TCS), which is presented in many papers (Amodeo *et al.* 2010; Lee, Żak 2002; Lee, Tomizuka 2003; Li *et al.* 2006; Matuško *et al.* 2008; Mirzaeinejad, Mirzaei 2010; Singh, Taheri 2015) or other active safety systems (Milanés *et al.* 2012). Especially profitable would be the possibility of determining such characteristics in real time, directly on the automobile, in order to better adapt the algorithm of the wheel slip regulation system to actual adhesion characteristic (Chen, Wang 2011; Guan *et al.* 2014; Lee *et al.* 2004; Tanelli *et al.* 2008; Villagra *et al.* 2011). Another issue is the measurement of friction coefficient between tyre and road surface covered by snow, that was presented by Kawato *et al.* (2015). The experiment was performed here on the vehicle using different tyres in different winter conditions. A method using the sensor signals that are available in automobile for obtaining tyre-to-road friction coefficient is described by Li *et al.* (2013). However, the authors underline here that this method helps to estimate the average friction coefficient for the whole automobile. Similar methodology is presented by Shadrin *et al.* (2014).

In case of civil engineering the anti-skid properties of road surface are being used as the most important

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parameters for evaluation of its quality. Therefore, the friction coefficient of road surface is being measured during the acceptance investigations of roads. Very important are also the routine measurements, because the skid-resistance of road surface decreases due to polishing and it can have a consequence on the decrease of traffic safety (Artamendi *et al.* 2012; Do *et al*. 2007).

Several methods of measurement of friction properties of road surface are used over the world (Canudas de Vit *et al*. 2003; Mechowski, 2009; Wallman, Åström 2001). Some methods are much simplified and are based only on estimating the adhesion coefficient. In the simplest method a special type of pendulum, the so called *British Pendulum,* is used (Asi 2007). Other method is based on pulling a piece of rubber (similar to the tyre material) on the road surface. More complicated methods consist of measuring forces acting on the measurement wheel installed on the vehicle or on the trailer. The measurement wheel can be used in different ways: in some measurement systems the wheel is pulled with constant fixed slip; in other systems the wheel is aligned with a constant side slip angle and generates side force, which is measured and used for the assessment of friction. More advanced systems allow to brake the wheel until it is locked. The longitudinal force and vertical load are measured during the whole braking procedure, which makes it possible to obtain full adhesion characteristic (friction coefficient versus wheel slip). Different methods used over the world for investigation of anti-skid properties of road surface generate problems with the repetitiveness of the measurements results (Wallman, Åström 2001).

In Poland for road surface adhesion investigation the measurement system developed in the Institute of Vehicles of Warsaw University of Technology in cooperation with the Road and Bridge Research Institute is used (Grzesikiewicz *et al*. 2003; Pokorski, Szwabik 2001; Szwabik *et al.* 2000). The first version of such system called SRT (skid resistance tester) was designed and built in the seventies of the last century. And although since that time the system has repeatedly been updated, the essential measurement principle remained unchanged. At present, in Poland and in Lithuania the next version of the system called SRT-3 is used for the routine and acceptance investigation of roads. This system took part in the European programme of improving methods of road measurements and in the comparative tests of different measurement systems conducted by World Road Association PIARC (Antle *et al.* 1995). Tests confirmed the high accuracy, the repetitiveness of achieved results, the easiness and the speed of measurements conducted using the SRT-3 system.

At present, the latest version of the system has been developed. The system called SRT-4, thanks to the new software and the possibility of applying different sizes of wheel rims has widened measuring possibilities. In particular, the possibility of applying different rim sizes enables us to investigate not only roads, but also tyres. The system is equipped with the GPS positioning system aiding the location of measurement points on the investigated road.

2. Presentation of SRT-4 measurement system

The measurement system SRT-4 consists of the towing vehicle and the dynamometer trailer (Fig. 1). On the towing vehicle a water tank and a compressed air supplying system are installed. Here also control and acquisition systems are put.

The main part of the dynamometer trailer is the measuring wheel with disk brake system. Different sizes of the wheel rims can be used on the trailer, which makes it possible to investigate different types and sizes of tyres.

The scheme of the dynamometer trailer is shown in Fig. 2. The measurement wheel is being led by the trailing arm, which is supported on the trailer frame by the coil spring and the shock absorber. The disc brake is installed on the trailing arm in the way enabling its rotation around the wheel axle in relation to the arm. The braking force is transferred to the frame and to the trailing arm with the system of links and levers. Two force sensors are installed in the links and lever system. The first of them (F_{C1}) measures braking force W of the disc brake, the second (F_{C2}) measures friction force T between tyre and road. Additional force sensor (F_{C3}) measures vertical force in the suspension.

The obligatory procedures in Poland require that the measurement of anti-skid properties of road should be made on wet surface. In order to fulfill these requirements the trailer is equipped with the system of moistening the road surface.

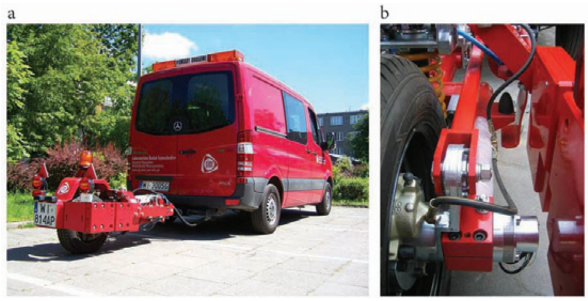

Fig. 1. Measurement system – SRT-4: a – dynamometer trailer and towing vehicle; b – measurement wheel with brake callipers and trailing arms

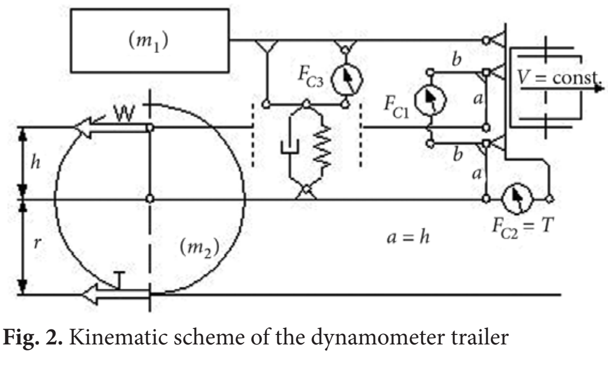

Fig. 2. Kinematic scheme of the dynamometer trailer

3. Measurement principles

The test procedure is conducted by the system that is based on braking the trailer wheel while the trailer is towed with constant speed. This measurement system together with the data acquisition and processing system make it possible to obtain full adhesion characteristic in one braking process, namely a diagram of the adhesion coefficient as a function of wheel slip.

The adhesion coefficient μ is defined as a quotient of the adhesion (friction) force T and vertical load F_z (Fig. 2):

$$\mu = \frac{T}{F_z}, \tag{1}$$

and the wheel slip s by braking (expressed in %) as follows:

$$s = \frac{v - r\omega}{v} \cdot 100, \tag{2}$$

where v - longitudinal velocity, m/s; r – tyre radius, m; ω – wheel angular velocity, rad/s.

It is possible to indicate two characteristic points on the graph:

μ_s – sliding adhesion coefficient for locked wheel (s = 100%),

μ_p – peak adhesion coefficient (its maximum value for optimum slip s_p).

Test procedure is based on gradual increasing of braking force W until the wheel is locked. Forces acting on the wheel during the braking process can be described by the following equation:

$$W\,h = T\,r + J\,\dot{\omega}, \tag{3}$$

where h – arm of the braking force W, m; J – mass moment of inertia of the wheel, kgm^2; $\dot{\omega}$ – wheel angular deceleration, rad/s^2.

When the wheel is locked and $\dot{\omega}$ = 0, the relation between braking force and friction force is as follows:

$$T = \frac{h}{r} W. \tag{4}$$

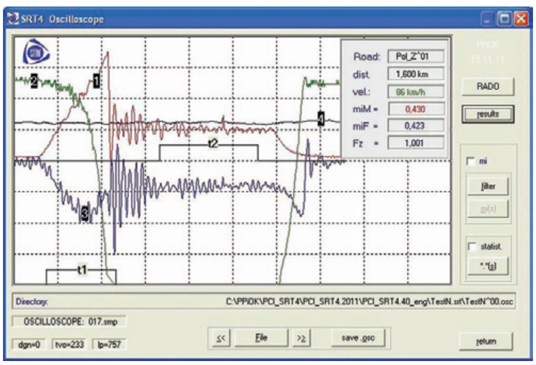

Fig. 3. Exemplary results obtained during braking process (view of the screen): 1 – braking torque Wh; 2 – wheel velocity ω; 3 – wheel friction force T; 4 – wheel normal load F_z; t_1 – time in which μ(s) adhesion characteristic is determined; t_2 – time in which average values of friction force are obtained

And thus it is possible to calculate adhesion coefficients by the use of the installed sensors in two ways:

– on the basis of friction force:

$$\mu_T = \frac{T}{F_z}, \tag{5}$$

– on the basis of braking force:

$$\mu_W = \frac{W\,h}{F_z\,r}. \tag{6}$$

Exemplary results obtained during the braking process are shown in Fig. 3. On the graph the plots of both adhesion coefficients μ_T and μ_W and plots of vertical load and wheel rolling speed as functions of time are presented. Time interval t_1 in which adhesion characteristic μ(s) is determined and time interval t_2 for which average values of sliding adhesion coefficient μ_s are calculated, are marked additionally on the graph.

The analog signals (marked as 1, 3 and 4) are measured with frequency 500 Hz. Wheel rotational velocity sensor (2) has 2500 pulse/rotation. Measurement system makes it possible to obtain adhesion coefficient with resolution of 1%. Wheel slip is measured with accuracy of 2%.

The braking process can be divided into three phases. At first, the braking force W is gradually increased, thus, the adhesion coefficient μ_W calculated on its base is increasing simultaneously. The wheel rolling speed is decreasing until the wheel is locked. In this phase the plot of the adhesion coefficient μ_T calculated on the base of the friction force T differs evidently. It is caused by deceleration of the wheel and the appearing inertial torque of the wheel $J\,\dot{\omega}$, according to Eq (3). In the second phase the wheel remains locked and the inertial torque equals zero. Thus, except for the period in which vibration of the sliding tyre will be dumped, theoretically both values of the adhesion coefficients should be equal. In the third phase the brake is released and the wheel is accelerating until its rolling speed equals the forward speed of the trailer.

The measurement system uses the first phase to determine the full adhesion characteristic, as it is shown in Fig. 3. In this case the adhesion coefficient is calculated from Eq (1) on the basis of the friction force T and the wheel slip from the Eq (2).

The value of the sliding adhesion coefficient μ_s relevant to the evaluation of road surface is calculated in two ways: on the basis of friction force from Eq (5) and on the basis of braking force from Eq (6). For both coefficients their mean values are determined in the process of filtering in the time interval shown in Fig. 3. Comparison of these mean values of sliding adhesion coefficients obtained on the basis of friction force and on the basis of braking force is used for the assessment of the accuracy of the measurement. It is assumed that the maximum difference between both values should not exceed 0.05. If the difference is higher, the measurement is not accepted.

4. Exemplary results of the measurements

The measurement system can deliver, depending on the needs, either the graphs of the sliding adhesion coefficient versus wheel slip μ(s) or the mean value of sliding adhesion coefficient. In Fig. 4 there is shown the result of determining the diagram of adhesion coefficient versus the wheel slip for the chosen section of the investigated road. In the section a number of braking procedures were conducted. The results of each braking procedure are presented in the graph as separate curves (blue). The differences between lines attest to the differences in the friction properties of the separate points of the same road section. On the graph there is also shown the average line (red) which is the result of approximation prepared for all measurement points of the investigated road section.

The full adhesion characteristics (adhesion coefficient versus wheel slip) in a form shown in Fig. 4 are very useful in automotive technique, for example in designing anti-skid systems (ABS). However, in road engineering and its maintenance the adopted criterion of anti-skid properties of the road surface is the value of the sliding adhesion coefficient, measured for the wheel lockup. The value of this coefficient depends above all on the technology in which the upper layer of road surface was made. In Table 1 the values of adhesion coefficients measured for different types of road surface technology are shown.

It should be underlined that all the results presented in the article refer only to the measurements on wet road surface, according to methodology used in Poland (Mechowski 2009). If not indicated, the forward velocity during the measurement was v_s = 60 km/h. Measurements on dry surface are conducted only in extraordinary situations because of the excessive wear of the measurement tyre. A series of the measurements made on one of Warsaw bridges showed that sliding adhesion coefficient μ_s was equal 0.37 on wet SMA surface and 0.72 on dry SMA surface.

Widely used on Polish national roads SMA (Stone Mastic Asphalt) technology is characterized by a wide range of values of adhesion coefficient μ_s = 0.33…0.54. The highest values of adhesion coefficients were observed for the upper layer made from sintered bauxites. For this type of surface wet adhesion coefficients are up to μ_s = 0.86 and are higher than the values of adhesion coefficients measured on dry surface made from SMA. Technology of sintered bauxites is used very rarely at the moment on national roads in Poland. Relatively high values of adhesion coefficient can be observed for road surface strengthening – in the range μ_s = 0.53…0.71. These road surfaces are used only temporarily and practically only on local roads. Cement concrete road surfaces have relatively good adhesion (μ_s = 0.50) provided that the technology of grooving was implemented.

The road adhesion coefficient depends also on many other factors such as: exploitation time, traffic intensity, road lane (Luty, Prochowski 2002; Pokorski, Szwabik 2001), season and sliding velocity during braking.

The sliding adhesion coefficient decreases with the increase in the sliding velocity, which is equal to the forward velocity of the towing vehicle. Table 2 presents the results of the measurements of adhesion coefficient on the road made in the SMA technology for different sliding velocities. However, in the diagram in Fig. 5 these results are compared with the requirements obligatory in Poland according to (Mechowski 2009).

Table 1. Sliding adhesion coefficients μ_s for different road surfaces. SMA – Stone Mastic Asphalt

No. of section	Type of road surface	Adhesion coefficient μ_s
1	Sintered bauxites	0.86
2	Single strengthened road surface	0.71
3	SMA – new road surface	0.54
4	Double strengthened road surface	0.53
5	Cement concrete	0.50
6	SMA	0.48
7	SMA – old road surface	0.33

Table 2. Adhesion coefficients μ_s on the road made in SMA technology

Velocity, km/h	Left lane	Right lane
30	0.64	0.76
60	0.48	0.59
90	0.42	0.51

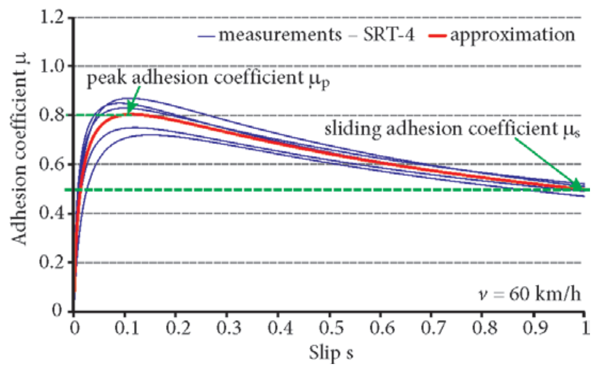

Fig. 4. Adhesion characteristics μ(s) of one road section: blue – curves obtained for separate points; red – average characteristic

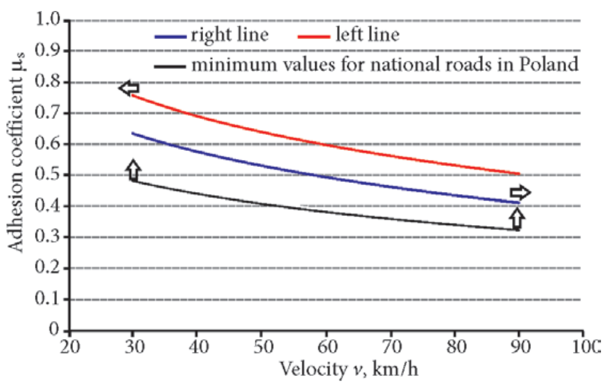

Fig. 5. Adhesion coefficient as a function of sliding velocity (see Table 1)

It should also be underlined, that even if the roads are made in the same technology and if they do not differ visually, their anti-skid properties may differ in a wide range. In order to demonstrate it, the measurements of adhesion coefficient on some Warsaw streets were made. The locations of measurement points, which were collected from the GPS system, are shown on the map presented in Fig. 6.

The results of the measurements are presented in Fig. 7. Wide differentiation of adhesion coefficient on the testing section results from different exploitation periods of the following road surface sections and their degree of wear. It is intentional to show such results in order to make the user aware of possible changes of adhesion coefficient and hence the braking conditions. The measured values of adhesion coefficient refer to the points shown on the trajectory in Fig. 6. The values of sliding adhesion coefficient of investigated road vary in the range from 0.28 to 0.46, and the mean value equals 0.36.

The knowledge about the changeability of the adhesion coefficients of the road surfaces is important not only on account of the assessment of their quality. The possibility of the accurate estimation of the adhesion coefficient is also very useful for automotive experts analyses, e.g. in accident reconstruction, when the braking distance must be calculated. In some cases, especially when it is evident that the braking course is very dynamic, the full adhesion characteristic, as it was shown in Fig. 4, should be taken into consideration. The measurement system presented in the paper makes it possible to measure the adhesion coefficient and adhesion characteristic exactly in the place of accident or collision.

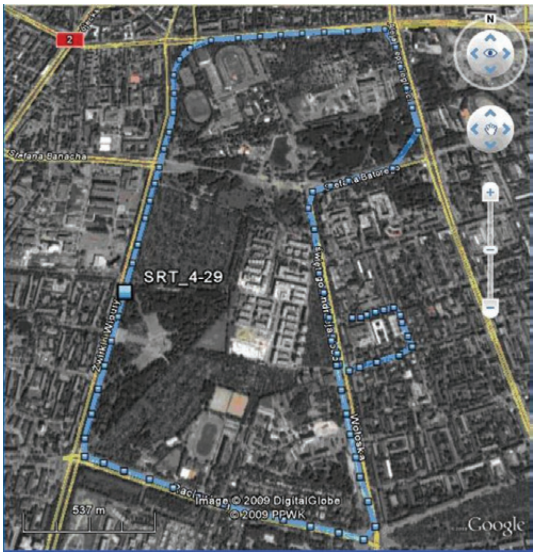

Fig. 6. Location of the measurement points obtained from the GPS system

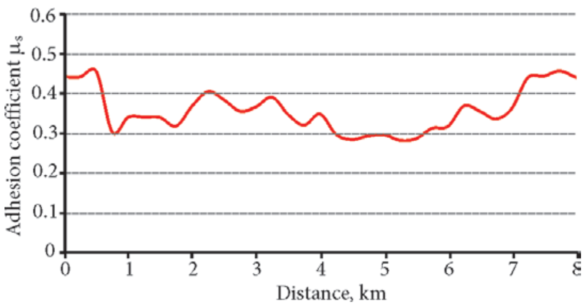

Fig. 7. Changeability of the sliding adhesion coefficient in the measurement points shown on the map in Fig. 6. The mean value of the coefficient equals 0.36

5. Conclusion

1. Measurement system presented in the paper makes it possible to estimate very precisely the values of adhesion coefficients and adhesion characteristics not only for the purpose of road surface assessment but also for the purpose of automotive experts analyses.

2. Results of the measured values of adhesion coefficient show its differentiation in dependence not only on the upper layer surface technology but also on the location of the measurement, traffic conditions, road surface exploitation time and many others.

3. Because of this, estimation of road adhesion coefficient for the needs of accidents reconstruction, for the judgement experts' opinions, should be taken with maximum attention. The most appropriate solution seems to be the measurement of adhesion coefficient exactly in the place of collision or traffic accident with the use of the tyre taken from the vehicle that took part in the collision or accident.

4. Simulating non-steady-state vehicle motion, it is necessary to include full adhesion characteristic $\mu(s)$.

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