Keywords: vehicle; SkidCar; wheel; adhesive force; radial force

Petr JILEK
University of Pardubice, Faculty of Transport Engineering
Studentská 95, 532 10 Pardubice, Czech Republic
Jan KRMELA*
Alexander Dubček University of Trenčín, Faculty of Industrial Technologies
Ivana Krasku 491/30, 020 01 Púchov, Slovak Republic
Jan BERG
University of Pardubice, Faculty of Transport Engineering
Studentská 95, 532 10 Pardubice, Czech Republic
**Corresponding author*. E-mail: jan.krmela@tnuni.sk

MODIFICATION OF THE ADHESIVE FORCE BY CHANGING THE RADIAL REACTION ON VEHICLE WHEELS

Summary. This article deals with the possibilities of adhesion force changes of a road vehicle. The authors present the possibilities of reducing the adhesion force of road vehicles and, at the same time, present their own system for changing the radial reaction of the vehicle wheels. This system removes the disadvantages of a commercially available SkidCar system. A representative road test is chosen in the article to determine the stability in a straight-line drive. Furthermore, the authors report the courses of characteristic parameters describing the behavior of a vehicle for driving a conventional car on a sliding surface and compared to the 50 % radial reaction of a vehicle driven with the SlideWheel on dry asphalt. It is clear from the measured runs that it is possible to change the adhesion force by changing the adhesion weight transmitted by the vehicle wheels. The use of the proposed SlideWheel system is possible for the purpose of verifying vehicle stability, while improving the driver's ability to operate the vehicle under reduced-adhesion conditions. The main goal of this paper is to design a system for reducing the adhesive force in an experimental car and perform experimental measurements.

1. INTRODUCTION

When developing not only autonomous vehicles, manufacturers influence the structure of cars. It is therefore necessary to test these vehicles both in the field of safety and in the area of driving stability. These are mainly vehicles that were originally designed for a combustion engine power unit and subsequently adapted to operate on electrical energy.

The position of the center of gravity has a significant influence on the stability of the vehicle. This is precisely the factor that will change significantly for the electric installation. Heavy batteries, which are most often placed in place of the original fuel tank and that occupy a larger part of the luggage compartment of the car [1-3], have a major influence on the change. This moves the center of gravity of the car closer to the rear axle [3] and makes the vehicle more susceptible to oversteer in terms of vehicle stability. Therefore, stability tests are important in this area. Testing of vehicles is possible directly under real conditions [4]. Testing the stability of vehicles under real conditions is the most meaningful test possible. Since this kind of testing depends on suitable weather conditions, it is not possible to carry them out throughout the year. Car manufacturers strive to make vehicle testing as simple as possible and to be possible when designing a car. One of the possibilities is simulation tests using the SW model [5].

The tests have low demands in terms of time and costs. Therefore, these methods of driving stability verification are used at the time when changes are made in car design before any physical vehicles are created or modifications to an existing vehicle are made. In order to achieve the objectives of the European Union to minimize the severity and consequences of road accidents [6] in the long term, it is essential to place sufficient emphasis on the construction of cars. At the same time, irrespective of how well the car is designed, it is still not possible to eliminate driver error [7]; hence, various steps must be taken to develop correct driving habits [2]. These habits include increasing the „co-existence" of a driver and a car. This is a specific state when the driver knows the limits of controlling the car.. In order to increase these non-tangible outputs, it is appropriate to increase the co-existence of the driver and car by means of road tests under reduced-adhesion conditions [8].

2. MATERIALS AND METHODS

The simulation of the adhesive conditions is carried out in order to bring the car to a limit state at a „safe" speed. The limit state is skidding of the vehicle [3]. Safe speed is the speed at which there is no risk of injury to persons in the vehicle or serious damage to the vehicle and other equipment in the event of an accident [9]. Conditions for the adhesion force change F_{ad} transmitted between the road surface and wheels are defined by equation (1) and are determined by the adhesion weight G_{ad} and the coefficient of adhesion φ, which represent the contact properties of the road.

$$F_{ad} = G_{ad} \cdot \varphi = \sum_{i=1}^{n} Z_{k_i} \cdot \varphi \ , \quad (1)$$

where F_{ad} – adhesion force, N; G_{ad} – adhesion weight, N; φ – coefficient of adhesion, Z_{ki} – radial reaction of the car wheel, N; i – number of car wheels.

Equation (1) shows that the adhesive force can be reduced by reducing the coefficient of adhesion or by reducing the adhesion weight of the wheel or wheels of the vehicle.

The coefficient of adhesion may be reduced by means of road tests carried out on roads covered by snow or frost, or on wet surfaces. The driving tests are directly linked to the weather conditions here. In case of reduced dependence on weather conditions, tests are carried out on sliding surfaces [10,11] or on a slide foil [5], which are sprayed with water. In these driving tests, the coefficient of adhesion is constant between 0.2 and 0.5. A disadvantage of the sliding surfaces is that they are visually different from normal roads and that they must be continuously sprayed with water. Despite these disadvantages, sliding surfaces are most commonly used for testing cars because no additional modifications of the vehicle are required. The specific road test involves the use of a reduced-adhesion tire, referred to as EasyDriftRing. Again, the coefficient of adhesion is constant and is determined by the material and the special tire design [12].

The second method of reducing the coefficient of adhesion is to reduce the radial reaction transmitted by the wheels on the road [12]. Today, a commercially available device bearing the SkidCar label is available. In fact, it is an auxiliary frame that is attached to the vehicle. The SkidCar frame includes 4 support wheels attached to the frame using a hydraulic cylinder. The reduction of the adhesive force is achieved by means of a controller in the vehicle's interior, where the operator selects the appropriate driving mode. It is then possible to reduce the adhesive force for the whole vehicle, or only for the selected axle, by raising the car over the support wheels using a hydraulic system. The alternative design of the SkidCar for the experimental vehicle is shown in Fig. 1.

The disadvantages of the SkidCar system are a significant increase in the weight of the car being tested, the support wheels, together with the frame, exceed the top outline of the vehicle, and SkidCar is always manufactured for a particular type of vehicle. The huge drawback is that the frame markedly reduces roll rotation and pitch rotation of the car body.

2.1. SlideWheel system

To overcome the disadvantages of the SkidCar, the SlideWheel (SW) system was designed (Fig. 2). SlideWheel consists of three circuits. The first circuit is the mechanical part of the wheel unit, the second circuit consists of a hydraulic system, and the third circuit is an electrical system used to control the lift of the wheel unit via a hydraulic system.

Fig. 1. Experimental vehicle with the SkidCar system (built according to the commercial form)

Fig. 2. Experimental vehicle with SlideWheel at the static radial reaction setting of the wheels

We have designed a compact wheel unit so that the support wheel, together with the fork, rotates around the axis of the guide pin. Vertical displacement can be changed by sliding between the guide pin and the wheel unit body. The role of the hydraulic circuit is to raise the wheel to the desired radial load value. The electric control is only the basic version, where one switch is used to fill (reduce the radial reaction of the wheel) the wheel unit and the other to drain (increase the radial reaction of the wheel) the wheel unit. The circuits are controlled from the passenger's position.

2.2. Experimental measurements

To verify the behavior of the vehicle with SW, we have chosen panic braking in a straight line as a driving test. The experimental measurements were performed for two cases that were compared with each other. The first set of measurements involves driving of an experimental vehicle on a slide foil (referred to hereinafter as EX) and the second set of measurements involves driving on a dry road with a coefficient of adhesion $\varphi = 0.8$, where we changed the value of the radial reactions to 50% of the static values with SW (referred to hereinafter as SW). The route corridor t_4 was determined by the traffic cones K, which have a distance t_k from each other according to Fig 3.

During driving tests, the following parameters were recorded for monitoring the behavior of the vehicle. The speed v, the directional deviation angle φ, and the yaw rotation speed of the vehicle ω were measured using the Correvit sensor. Transverse a_y and longitudinal a_x acceleration values were measured using a two-axis acceleration sensor. We measured the steering wheel angle β_V indirectly using the analogue position sensor and calculated it using equation (2) according to the cable displacement of the sensor wound on the steering column.

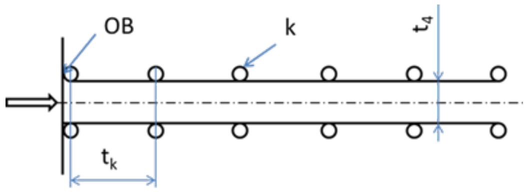

Fig. 3. Test corridor

$$\beta_v = \frac{180 \cdot l_l}{\pi \cdot r_v} - \beta_{vo}, \tag{2}$$

where β_v – actual steering wheel angle, °; β_{vo} – steering wheel angle during the verification measurement, °; l_l – cable extension from the steering wheel angle sensor, m; r_v – steering column shaft radius, m. We calculated the body pitch angle α_i (Fig. 4) from the signals of a pair of ultrasonic proximity sensors located at the center of gravity plane of the vehicle at the front and rear of the vehicle, where H_{1i} (H_{2i}) is the vertical distance of the measuring point from the ground at the front (rear) of the vehicle at *time* t_l, A_x is the distance between the measuring points in the longitudinal plane of the vehicle, and H_{1o} (H_{2o}) is the distance of the measuring point at the front (rear) of the vehicle from the road during a compensatory measurement.

$$\alpha_i = \tan^{-1}\left(\frac{(H_{1i}-H_{1o})-(H_{2i}-H_{2o})}{A_x}\right), \tag{3}$$

where α_i – body pitch angle, °; H_{1i} – vertical distance of the measuring point from the ground at the front of the vehicle, m; H_{2i} – vertical distance of the measuring point from the ground at the rear of the vehicle, m; H_{1o} – distance of the measuring point at the front of the vehicle from the road during a compensatory measurement, m; H_{2o} – distance of the measuring point at the rear of the vehicle from the road during a compensatory measurement, m; A_x – longitudinal distance between sensors, m.

Fig. 4. Body pitch during braking

Before starting the experimental measurements on the corridor, we first performed compensatory measurements. This measurement is used to obtain a set of compensatory data to test the measurement chain for functionality. The compensation data set describes the vehicle's initial state, eliminates inaccuracies during sensor assembly, and corrects measured time courses off-time. Compensatory measurements were performed in the form of ten repeated measurements, with a steady-state drive in a straight line, in both directions, on a 50 m track. In this way, we obtained quasi-static courses of the measured quantities for straight driving on a horizontal road (marked by an index $_0$) and also obtained the course of the longitudinal a_{x0} and transverse acceleration a_{y0}, the height coordinates of the front H_{10} and rear H_{20} of the body of the experimental vehicle, the directional deviation φ_0, the yaw rotation speed ω_0 , and the steering wheel angle β_{vo}, which we used to off-time correct the measured courses from the driving tests. The experimental test drive was performed 10 times for repeatability of the measurements.

3. RESULTS AND DISCUSSION

The moment of braking is recorded as a step change in the BS signal from 0 to 0.8. When the vehicle is braked in a straight line, the forward speed is reduced and a longitudinal deceleration a_x is applied to the vehicle. Deceleration causes inertia force F_i, which causes the body to pitch α about the transverse axis A (Fig. 4).

Fig. 5 shows that there is a difference in the initial speed before braking. This is caused by the driver. The speed of the vehicle is governed by a human factor and not automatically. The difference in speed does not have a significant effect on the measured courses. The speed drop tangent line is very close in both cases. This situation is also apparent in Fig. 6.

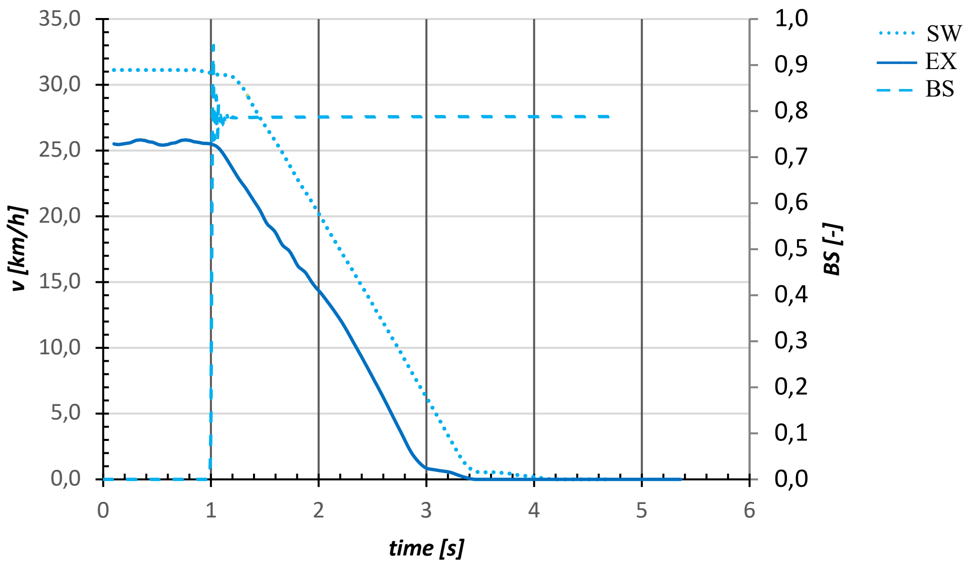

Fig. 5. Forward speed course

Figure 6 shows that the longitudinal deceleration intensity at the start of braking is increased due to the optimum wheel slip. The wheel slip will then increase in relation to the road, causing a slight decrease in deceleration. A similar condition occurs when the vehicle is stopped, when again, for a short time, the wheel has the optimum slip and therefore $-a_x$ increases temporarily. The increase in longitudinal deceleration in extreme positions with the SW does not lead to as significant changes as those with EX due to the limited body roll rotation of the car. The steering wheel angle β_V corresponds to a straight-line drive (Fig. 7).

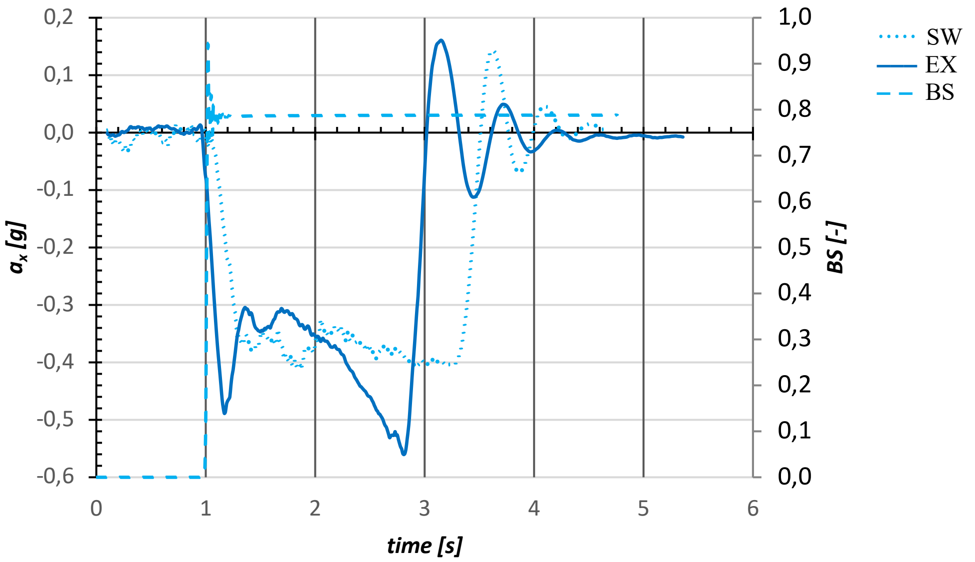

Fig. 6. Longitudinal acceleration course

The default relative difference varies by 14°, again caused by the driver. Any fitting during a road test is within 3 degrees and therefore negligible as it does not affect the measurements performed. The positive steering angle values correspond to the steering to the right. The transversal acceleration a_y values (Fig. 8) are also consistent with the movement of the steering wheel, which achieves very low values.

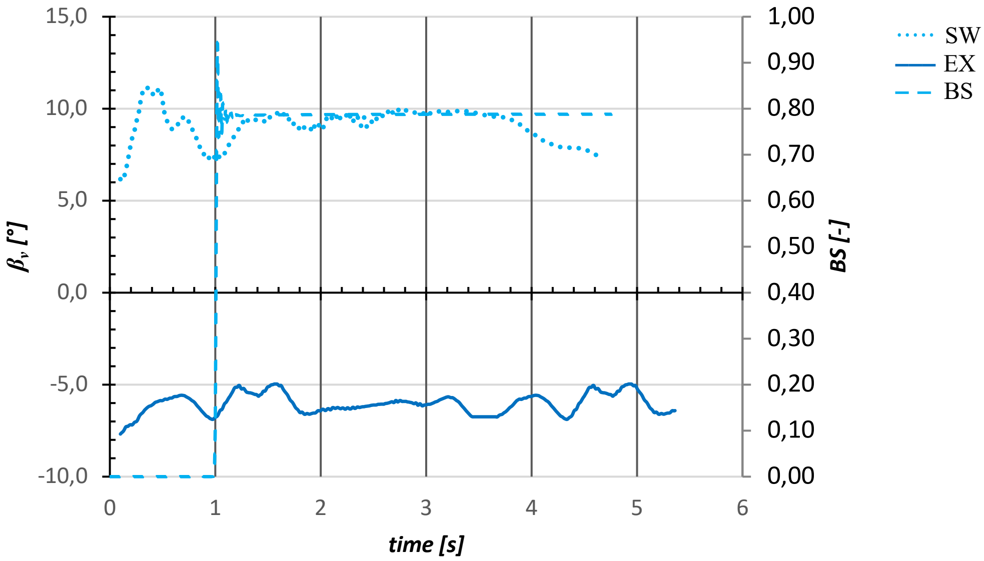

Fig. 7. Steering wheel angle course

Car body pitch rotation course α (Fig. 9) is consistent with the intensity of the forward deceleration.

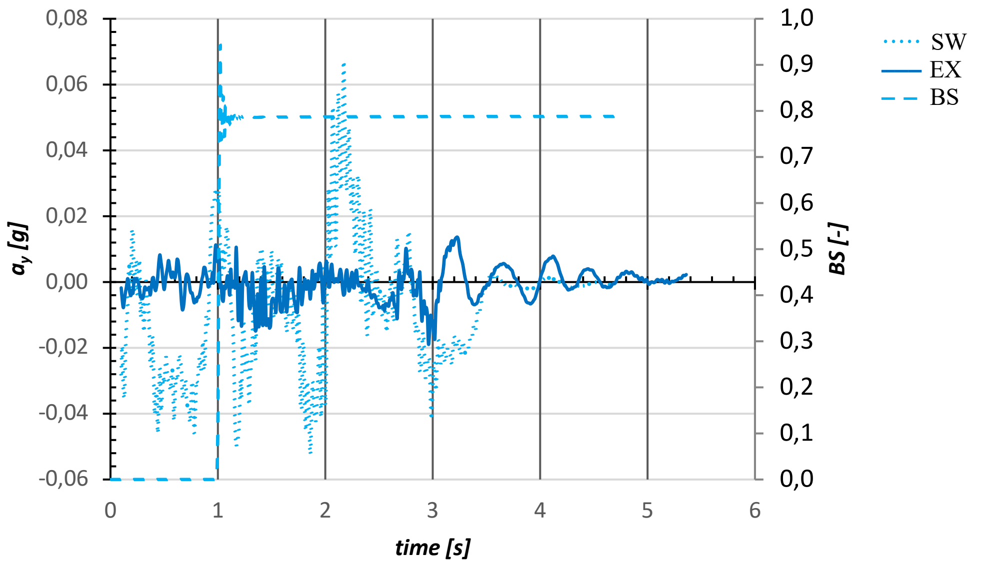

Fig. 8. Transversal acceleration course

When comparing the SW car body's pitch rotation to driving an EX vehicle on a sliding surface, it is apparent that it has a greater angle on the sliding surface. Limited pitch rotation is caused by the design of the SW system. To achieve a comparable angle of pitch rotation, we have also introduced the innovation of SlideWheel. The subsequent design will be tested as simulations in MSC Adams software.

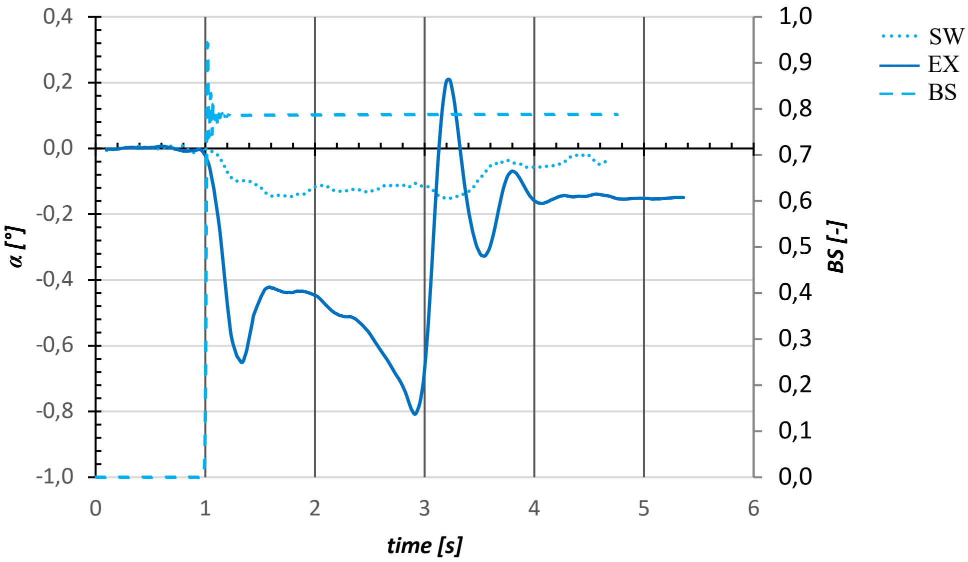

Fig. 9. Car body's pitch rotation course

4. CONCLUSIONS

The experimental data obtained during the road tests confirmed the assumption that by reducing the weight component to the vehicle's wheel by means of additional wheel units, the adhesion force transmitted between the vehicle's tire and the road can be reduced, at a constant coefficient of adhesion. The measured courses show that the vehicle with SlideWheel behaves in a manner similar to a conventional vehicle on a reduced-adhesion surface. The difference in the measured courses is in the car body's pitch rotation. On vehicles with the SlideWheel system, this effect is limited due to the current construction. The design of SW has a significant effect on the limited car body's pitch rotation. To eliminate this, a new version of the SW system is being developed, supplemented by an electronic control of the lifting of the wheel units, depending on the current driving conditions, such as the intensity of the longitudinal and transversal acceleration. The reduction of the adhesive weight due to the lifting of the car with the help of a wheel unit will also cause the tire's contact surface with the road to change. It is therefore impossible to state with certainty that by reducing the radial reaction of a wheel by 50%, the adhesion force is reduced by 50%. The change in the radial reaction in relation to the resulting change in adhesive force for the vehicle should be researched further. In order to generalize the conclusions, experimental measurements must be carried out during different types of driving tests, to the extent of a statistically significant number of measurements. SlideWheel can be used primarily where it is not possible to use a sliding surface or where it is necessary to simulate different adhesion conditions for a particular vehicle wheel.

Acknowledgement

This research work was supported by the Cultural and Educational Grant Agency of the Slovak Republic (KEGA), project No. **KEGA 002TnUAD-4/2019**.

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Received 02.11.2019; accepted in revised form 27.02.2021