Method of determining coupling characteristics of studded tires with slipping and experience of its application

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Abstract. Test procedures allowing to determine coupling characteristics of passenger car's studded tires by using a road method are described in the article. The tests were carried out on the ice field of NAMI Test Center. The test object is "Nissan X-Trail III" automobile with "Yokohama IceGUARD Stud iG55" tires. Measuring and recording equipment used during the test procedures was examined in detail. A new method of determining of rear axle slipping angle consisting in comparing the automobile course angle and azimuth of speed vector of automobile's body above the center of rear axle is suggested. "φ - S" diagrams show the drift of studded and non-studded tires on ice. Their distinctive features are also considered.

Introduction.
Research and investigation procedures of coupling characteristics of studded tires without slipping were carried out during [1, 2, 3] the studies. As a result, an interrelation between studding of winter tire protector and effectiveness of anti blockier braking system ("ABS") when automobile slows down on ice was determined. It was shown that effectiveness of "ABS" system may be reduced. Test procedures allowing to determine the "φ-S" diagram of studded tire on ice were also performed, their features were defined as well.

Taking into consideration that Electronic Stability Control System ("ESC" system) involves the same braking units as "ABS", brakes the wheels using the same principle and keeps their sliding, it can be suggested that "ESC" efficiency may depend on the shape of the "φ-S" diagram [4]. To analyze this fact, it is necessary to determine the "φ-S" diagram not only for longitudinal direction, but also for transverse one (i.e. during slipping of elastic wheel).

In open sources there is no information concerning coupling characteristics of studded tires moving with slipping. For tires without studs, the "φ-S" diagrams were determined using the test bench method [5, 6]. However, it is not possible to test studded tires on existing test benches as studs create an ice crumb on the surface of the drum, which leads to incorrect test results. Therefore, it was decided to determine "φ - S" diagram using the road method. Scientific and research work was carried out according to the State task of Ministry of Education and Science of Russian Federation.

Test object.
To carry out experimental research work by "Nissan Europe" technical center, "Nissan X-Trail III" vehicle was chosen. Authors of this article are very grateful to "Nissan Europe" technical center and
especially to its chief engineer Mr. Dyakov Philipp Kirillovich for his kind assistance in preparing the test procedure and his comments on technical features of the test object. The vehicle’s weight during the test procedure was 1670 kg (including driver's weight, operator's weight, and measuring and recording equipment weight). Weight on the front axle was 939 kg and on the rear axle - 731 kg. The height of center of mass was 650 mm. To perform the test drives transmission was operated with the front axle height of vehicle’s drive mode only (2WD). The following measuring and recording equipment was installed on the test object:

- remote sensors of angular wheel velocity "WPT"; brake pedal force sensor "CPFTA"; acceleration and angular velocity sensor "Tri-Axial Navigational Sensor: (TANS); dynamometric measuring steering wheel "MEASUREMENT STEERING WHEEL" (MSW) - produced by KISTLER Company;
- GPS/GLONASS antenna, produced by JAVAD Company (USA) and GPS-antenna, produced by GARMIN Company;
- universal registration and data processing system "CS 1016 FAMOS Online", produced by IMC Company.

The equipment was powered by the automobile's on-board network via power distribution switchboard" Small 12V Power Distributor Box", produced by KISTLER Company.

Automobile's angular velocity sensors were mounted on each wheel. Sensor's moving part was inflexibly connected with the mounting disc by collets, which were fixed on wheel disc nuts. The static sensor's part was attached to vehicle's body with special vacuum brackets through telescopic rods. "TANS" sensor was installed in spare wheel's housing above the center of the vehicle's rear axle, as all calculations were performed relative to the uncontrolled axis. The sensor was fixed with a hot-melt glue. The "MSW" measuring steering wheel is mounted on the vehicle's steering wheel through a special adapter with collar clamps. The measuring module consists of rotor, stator and is equipped with strain gauges to determine the force applied onto the steering wheel, as well as it has an impulse sensor to determine rotation angle of the steering wheel. The rotor can rotate freely relative to the stator and is connected with "MSW" steering wheel. The stator housing is connected with a vacuum bracket by a cable to provide immobility, and it is fixed to the vehicle's windshield.

Installation of "CPFTA" sensor is necessary to control the brake pedal force during test procedures to determine "φ S" diagrams. The sensor was fixed on the brake pedal with a special clip and was connected by cable with "IMC" system, which displayed the sensor's data in real time on computer monitor using the "IMC DEVICES 2.7R3" software. The main GPS/GLONASS antenna, produced by JAVAD Company was installed on the vehicle's body over the rear axle. The signal data received were directly used for calculations. A reserve GPS-antenna GARMIN was mounted on the bonnet above the front axle.

The compact mobile data registration and processing system "IMC CS 1016 FAMOS Online" is required for recording the registered parameters and their preliminary processing procedure. Data recording frequency is 100 Hz. The main module of the system was located on the rear seat of the vehicle and fastened with seat belts to prevent its movement. For easy installation, the "IMC" module is firmly connected with "CDG-GPSCLLOGMA" module and with "MSW" steering wheel processor module.

Processing of recorded test results was carried out by using the "IMC FAMOS Signal Analysis Software" program.

In close cooperation with "YOKOHAMA RUSSIA LLC", two sets of Yokohama winter tires of "IceGUARD Stud iG55" model 225/55 R18 were prepared for testing. At the same time, one of the tire sets was not studded at the manufacturer’s site. Thus influence of other factors on the overall process of tire interaction with the supporting surface was excluded.

Special clamps were used for clamping brake hoses to block the vehicle's brake system during test procedures. This method is thoroughly described in [2, 3]. Disconnection of the "ESC" was carried out by dismantling of the electric fuse of the "ESC" "VDC SOL-30A" valve circuit (max amperage rate is 30 A) from additional mounting block located in the vehicle's engine compartment. As "VDC SOL - 30 A" fuse is united with the other two safety fuses "EPS 1" and "EPS 2" (for 50 A), that protect the
electrical circuit of the steering system booster, it was modified to retain operation functions of the steering system booster.

**Characteristics of test procedures.**

To determine coupling characteristics of tires with drift, the following tests on ice were carried out:

1) braking with one rear wheel - to determine adhesion coefficient in the longitudinal direction ($\phi_x$);
2) braking with rear axle when turning with 30-meters radius at the speed of 30 ± 10 km/h - to determine the adhesion coefficient in the transverse direction ($\phi_y$).

Series of tests consisting of 40 braking actions were performed with one rear wheel in forward and reverse directions and 40 braking actions with the rear axle when turning to one side and another. Braking was performed with different forces impacting on control units of the working braking system, that are necessary to obtain the entire range of the longitudinal and transverse sliding ($S_x, S_y$). The test vehicle was alternately equipped with studded and non-studded tires. Ice was frozen on the special road section of eastern circular site of NAMI testing area. Ice temperature during the tests was from -4° C to -7° C.

The following parameters of the vehicle’s movement were measured and recorded during the tests:
- time "t";
- speed of vehicle's body movement over the rear axle "$V_x$";
- circumferential speed of rear right wheel $V_{rr}$ and rear left wheel $V_{rl}$;
- vehicle’s angular velocity relative to vertical axis (yaw rate) $\omega_z$;
- steering force ($a_{s}$);
- impact force onto braking system control unit "$P_b$";
- longitudinal "$j_p$" and transverse "$j_t$" acceleration of vehicle's rear axle;
- vehicle's body geographical coordinates over the center of rear axle according to GPS/ GLONASS data;
- "$\alpha_{GPS}$" angle between the vehicle's body speed vector direction above the center of rear axle and direction to the north (velocity vector azimuth).

**Processing of test results.**

The slipping angle of rear vehicle's axle "$\delta$" is determined by the following formula:

$$\delta = \alpha_{GPS} - \gamma,$$

where "$\gamma$" is route angle of the vehicle's body. Route angle "$\gamma$" of the vehicle is determined by special method of time yawing speed integration relative to the initial value of velocity vector azimuth "$\alpha_{GPS}$":

$$\gamma = \int_0^t \omega \cdot dt + \alpha_{GPS},$$

where "$\omega$" is vehicle's angular velocity relative to its vertical axis; $\alpha_{GPS}$ - route speed angle of rear axle at the starting point.

Longitudinal "$S_x$" and transverse slide motion "$S_y$" of the braked wheel are determined by the following formulas described in [6] point:

$$S_x = \frac{V_x \cos \delta - \omega_{vc}}{V_a},$$

$$S_y = \sin \delta,$$

where "$\delta$" is slipping angle, radians; "$V_x$" is vehicle's speed vector modulus relative to support surface, m/s; $\omega$ - angular velocity of the braked wheel, radians per second; $r_{fc}$ - rolling radius of free mode wheel, m.

The longitudinal adhesion coefficient "$\phi_x$" is defined as the ratio of longitudinal braking force "$R_x$" performed at the contact point of the braked wheel to dynamic vertical load on inner wheel (when turning) of the rear axle wheel (Rz2din.inner):
Braging force “R_x” is calculated on the basis of deceleration of the vehicle, taking into consideration the range of rolling resistance of the unbraked wheels [7]. Sections are analyzed in deceleration value range, where “S_x”, “S_y” do not change (the tolerance is ± 1%) at the interval of not less than 0.3 s. As a result, a data array for friction coefficients is obtained in the longitudinal direction (“φ_x”) and relative slide movement in the longitudinal and transverse directions (“S_x”, “S_y”).

According to obtained data, three-dimensional surfaces φ_x (S_x, S_y) can be constructed, the examples are shown in Figure 1 (a, b).

![Figure 1. Surface φ_x (S_x, S_y). a) for winter non-studded tires; b) for winter studded tires](image)

An analysis of the obtained surfaces (Figure 1 a,b) shows that the maximum of surface "φ_x" (S_x, S_y) of studded tire is shifted towards larger sliding characteristics in the longitudinal direction S_x. As sliding increases in the transverse direction S_y, the surface φ_x (S_x, S_y) for a studded tire decreases with a lower intensity than the surface φ_x (S_x, S_y) compared with stud less tire. The surface absolute maximum of the studded tire is increased from 0.165 to 0.180. Adhesion coefficient in the transverse direction φ_y is defined as the ratio of lateral force realized in the contact spot of rear wheels to dynamic vertical load on rear axle R_z2din:

$$\varphi_y = \frac{R_y}{R_z2din}$$

The lateral force R_y/2 is calculated on the basis of lateral acceleration of the vehicle over the rear axle:

$$R_y = j_{y2} m_{a2}$$

where $j_{y2}$ – is a body transverse acceleration above the center of vehicle's rear axle, m/s²; \( m_{a2} \) – is vehicle's weight per rear axle, kg;

Dynamic vertical load on the rear braking axle is calculated based on its unloading when braking takes place [6]. In the vehicle's braking interval, sections are analyzed where S_x, S_y do not change (variation of ± 1% is allowed) in the interval of 0.3 s at least. As a result, an array of adhesion coefficient data is arranged in the transverse direction φ_y and an array of relative sliding actions in the longitudinal and transverse directions (S_x, S_y) is also formed. According to obtained data, three-dimensional surfaces φ_y (S_x, S_y) can be implemented. Their examples are shown at Figure 5 (a,b).
The analysis of constructed surfaces (Figure 2 a, b) shows that the surface \( \varphi_y(S_x, S_y) \) for a tire with studs does not have a pronounced maximum compared to \( \varphi_y(S_x, S_y) \) maximum for tire without studs. The absolute maximum of studded tire surface has increased from 0.162 to 0.18 and continued to grow while sliding was increasing in transverse direction \( S_y \). On the basis of obtained “\( \varphi – S \)” surfaces in the longitudinal and transverse directions, it is possible to construct total “\( \varphi – S \)” surfaces \( \varphi_z(S_x, S_y) \) for studded and non-studded tires (Figure 5 a, b). \( \varphi_z(S_x, S_y) \) dependence of sliding of the wheel in longitudinal \( S_x \) and transverse \( S_y \) directions is calculated using the following formula:

\[
\varphi_z(S_x, S_y) = \sqrt{\varphi_x^2(S_x, S_y) + \varphi_y^2(S_x, S_y)}
\]

Figure 2. Surface \( \varphi_y(S_x, S_y) \). a) for winter tires without studs; b) for winter studded tires

Figure 3. Surfaces \( \varphi_z(S_x, S_y) \). a) on ice for the winter tire without studs; b) on ice for winter tire with studs

The analysis of constructed surfaces shows that the absolute maximum value of adhesion coefficient of studded tire relative to the tire without studs has increased insignificantly from 0.19 to 0.21. However, as the sliding increases in the longitudinal and transverse directions, the surface of the diagram of studded tire does not have such a sudden drop as the tire without studs. The reason is that the stud works only when the wheel slides above 5%, both in the longitudinal and transverse directions. This fact creates much more favorable conditions for the operation of “ESC” system.

Summary

Results of this research can be summarized as:

1) Three-dimensional surfaces of “\( \varphi – S \)” diagrams for studded and non-studded "Yokohama IceGUARD Stud iG55" tires in the longitudinal and transverse directions were obtained and presented;
2) A new method for determining the slipping angle of rear axle wheels, based on a comparison of the vehicle's angle and the velocity vector azimuth was suggested;
3) Diversity of "\( \varphi – S \)” diagrams with slipping for studded and non-studded tires was found. When the slipping angle is 6°, the maximum adhesion coefficient of studded tire in the longitudinal direction...
was 0.14 for a longitudinal slide value of 60%, and for non-studded tire the maximum adhesion coefficient in the longitudinal direction was 0.09 with a longitudinal slide value of 15%. With a slipping angle of 6°, the maximum adhesion coefficient value in the transverse direction for studded tire was 0.175, and for non-studded tire, the maximum adhesion coefficient in the transverse direction was 0.12.

4) A method of obtaining "\( \varphi-S \)" diagrams with longitudinal and transverse retraction, suitable for various support surfaces, including ice, and also studded tires was developed and tested.

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