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Development of an Automatic Differential Lock Based on the Tangential Inertial Forces Principle

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Abstract - *This paper is dedicated to solving the problem of increasing vehicles traction and cross-country ability and reducing the likelihood of road traffic accidents.*

All the conventional car differentials operate normally only as long as the grip exceeds the resistance forces. If the drive wheels operate on surfaces with different coefficients of adhesion between tires and road or one of the wheels of the drive axle is suspended, then the presence of a differential has a negative impact on the car movement. The vehicle stops or moves more slowly and skids because its grip is determined by the adhesion of the wheel on poor road surfaces. Most often, one wheel hits a slippery area, while the other one is in an area with a higher grip coefficient. If in this position of the car the axle shafts are coupled, then the tractive effort will be increased due to the grip of the wheel, which is in more favorable conditions.

Most of the existing differential locks have a complex design or require skill in driving and have other disadvantages.

As a solution to this problem, the authors proposed the automatic device for locking an open differential, operating on the tangential inertial forces principle, which is distinguished by its simplicity of design. This mechanism turns on and off automatically, has low internal friction, and is reliable in operation. Its positive side is that it does not impair the conventional differential operation under the vehicle's various modes of motion.

Keywords - *traction force, grip, cross-country ability, differential lock, drive wheel, angular acceleration, tangential inertial forces.*

I. INTRODUCTION

The open differentials (simple gear differentials) are found in most vehicles transmissions. Bevel-gear differentials are now prevalent because they are more reliable, simpler, and more compact. Spur-gear differentials are less common [1]. But all differentials normally work only as long as the grip exceeds the resistance forces. If the drive wheels operate on surfaces with different coefficients of adhesion between tires and road (grip coefficients) or one of the wheels of the drive axle is suspended, then the presence of a differential has a negative impact on the car movement [2]-[5]. The vehicle stops or moves more slowly and skids because its grip is determined by the adhesion of the wheel on poor road surfaces.

In order to increase the vehicle's traction force under these conditions, it is necessary to lock the differential and thereby eliminate or reduce the difference in the axle shaft angular acceleration. Most often, one wheel hits a slippery area, while the other one is in an area with a higher grip coefficient [6], [7]. If in this position of the car the axle shafts are coupled, then the tractive effort will be increased due to the grip of the wheel, which is in more favorable conditions.

II. LITERATURE REVIEW

All existing differential locks can be divided into two groups, differing in the locking method and effectiveness: full locks and partial ones.

Partial locks include limited-slip differentials, Torsen differential, viscous couplings, gov-lock, etc.

Full locks include Lockright, Lokka, Spartan Locker, Aussie Locker, Yukon Grizzly Locker, Detroit Locker, Kaiser, and other systems. In these devices, the axle shafts are constantly coupled and are separated only when cornering, when one wheel begins to "overtake" the other. These devices are reliable, unpretentious, withstand heavy loads, but require skill in driving. If when the axle shafts are uncoupled, and the wheels are traveling along different trajectories at different speeds, the gas is pressed, then the differential will instantly engage, the wheels will try to go synchronously, and the car will lose control [8]-[10].

There are also manual differential locks. According to the activation method, four types are distinguished: pneumatic, electrical, mechanical, and hydraulic ones [11], [12]. Their disadvantage is that the driver may forget to activate the device off-road and to turn it off when driving on a good road. This leads at least to the increased tires, and parts wear, as well as problems when cornering.

In addition, most of the considered devices have a complex design [13], [14].

In connection with the above, the purpose of this research is to develop an automatic differential lock, which is distinguished by its simplicity of design and does not impair the conventional differential operation.

III. PROPOSED METHODOLOGY

A. General Description

In order to increase the vehicle's traction and cross-country ability, the authors of this paper carried out theoretical studies, developed an automatic differential lock, conducted a series of experiments, and processed experimental data (Table 1).

B. Algorithm

After theoretical research, the automatic device for locking an open differential, operating on the tangential inertial forces principle, was developed.

The first stage of experimental research was to determine the coefficient of separate skidding in various driving conditions (on icy and slippery areas, on snow, on a dry stubble field, on rolled snow, on icy and dirt roads after rain, on clayey virgin soil after rain, as well as when driving on turf). The road tests of the ZIL-433100 truck in standard configuration and of the truck equipped with the proposed automatic differential lock (laden and unladen) were carried out.

At the second stage, the speed characteristics of acceleration in various driving conditions(on the icy road, on snow, and on a turf) were evaluated.

During the third stage, the maximum traction force on the drive wheels of the ZIL-433100 truck in series production condition and of the truck with developed differential lock (laden and unladen) was determined.

C. Flow Chart

TABLE I. RESEARCH ALGORITHM

No.	Name of the research phase
1	Theoretical research
2	Development of an automatic differential lock
3	Experimental studies
3.1	Determination of the coefficient of separate skidding in various driving conditions
3.2	Determination of speed characteristics of acceleration in various driving conditions
3.3	Determination of the maximum traction force on the drive wheels in various driving conditions
3.4	Experimental data processing

IV. RESULT ANALYSIS

A. Theoretical research

The authors propose an automatic device for locking an open differential, operating on the tangential inertial forces principle. The developed differential lock can be classified as a full one.

This mechanism turns on and off automatically, has low internal friction, and is reliable in operation.

Since the principle of the differential lock is based on the use of tangential inertial forces that appear in it due to the skidding wheel angular accelerations, the drive wheel angular acceleration, at which the lock is activated, is the most important parameter for determining its sensitivity.

If the differential lock sensitivity is reduced, then this can lead in some cases to the failure of this mechanism when the drive wheels slip separately, that is, to incomplete use of the automatic lock advantages in some driving conditions.

This suggests that the device's optimal sensitivity should be such that it would not turn on if the car is moving without slipping, but its automatic activation would be ensured when the drive wheels skid separately.

The angular acceleration of a non-skid drive wheel when the vehicle is moving can be determined by the following equation:

$$\varepsilon = \varepsilon_{\varphi} + \varepsilon_{\theta} + \varepsilon_{o} + \varepsilon_{\delta}, \quad (1)$$

Where ε_{φ} – drive wheel angular acceleration during acceleration of the vehicle at the limit of grip; ε_{θ} – drive wheel angular acceleration when the vehicle goes into a bend; ε_{o} – drive wheel angular acceleration when hitting an obstacle; ε_{δ} – drive wheel angular acceleration when slipping or taking off from the road.

Let's consider several main phases of a car's movement: intensive acceleration and cornering drive wheels over an obstacle, one of the drive wheels slipping.

If the current value of the drive wheels rotation speed in time is denoted by $\frac{d\omega}{dt} = \frac{1}{r_w} \cdot \frac{dV}{dt}$ then, substituting it into the equation $\gamma \cdot G_v \cdot \varphi = \delta \cdot \frac{G_w}{g} \cdot \frac{dV}{dt}$, it is possible to determine the drive wheel angular acceleration during the car's acceleration of maximum intensity at the limit of grip [15]:

$$\varepsilon_{\varphi} = \frac{g \cdot \gamma \cdot \varphi}{\delta \cdot r_w}, \quad (2)$$

Where g – acceleration of gravity, m/s^2; γ – load factor of the drive wheels by the weight of the vehicle; φ – maximum grip coefficient; δ – rotating mass coefficient (for the ZIL 433100 truck $\delta = 1{,}04 + 0{,}05 \cdot i^0$, where i^0 – gearbox gear ratio [16]); r_w – warped wheel radius; G_v –the weight of the vehicle; G_w –weight on the drive wheels; $\frac{dV}{dt}$ – vehicle's translational acceleration.

The maximum drive wheel angular acceleration during acceleration of the ZIL-433100 truck, calculated using the formula (2), is $\varepsilon_{\varphi} = 4{,}8$ r/s^2.

When the car goes into a bend, the increment in the outer wheel angular velocity will be:

$$\Delta\omega = \frac{V \cdot (R + 0{,}5B)}{R \cdot r_w} - \frac{V}{r_w} = \frac{B \cdot V}{2R \cdot r_w}, \quad (3)$$

Where V – vehicle's rear axle center speed; B – driving wheels average track width; R – vehicle's turning radius.

The drive wheel angular acceleration can be determined by the equation:

$$\varepsilon_{\theta} = \frac{\Delta\omega}{t} = \frac{B \cdot V}{2R \cdot t \cdot r_w}, \quad (4)$$

Where t – time of turning the steering wheel to the extreme position (5 s).

The maximum possible car speed from the condition of the roll-over:

$$V = \sqrt{\frac{g \cdot B \cdot R}{2h_g}}, \quad (5)$$

Where h_g – vehicle's center of gravity height.

The outer drive wheel receives a positive angular acceleration when the vehicle goes into a bend.

Making the appropriate substitution, we obtain the final formula for determining the outer drive wheel maximum angular acceleration:

$$\varepsilon_\theta = \frac{B}{2R \cdot t \cdot r_w} \cdot \sqrt{\frac{g \cdot B \cdot R}{2h_g}}. \quad (6)$$

The differential, as a mechanism with two degrees of freedom, receives control both from the engine and from the road through the drive wheels and axle shafts.

Regardless of whether the car is accelerating or slowing down with separate slipping of the drive wheels, the skidding wheel in these cases receives an additional increment in angular acceleration.

When skidding, as well as when the drive wheel is taking off the road, the maximum angular acceleration, limited by the supplied engine torque, is determined by the following formula:

$$\varepsilon_\delta = \frac{M \cdot i_t \cdot \eta_t \cdot (1-\xi)}{J_{red}} - \frac{0{,}5 \cdot G_W \cdot r_w \cdot \varphi_{min}}{J_{red}}, \quad (7)$$

Where J_{red} – a total moment of inertia of the rotating parts of the engine, transmission, and drive wheel reduced to the drive wheel $J_{red} = (J_e + \lambda) \cdot \eta_t \cdot i_t + J_w$; J_e – the moment of inertia of the engine; i_t – total gear ratio of the transmission from the engine to the separate skidding wheel; M – engine torque; λ – transient engine operation coefficient; φ_{min} – skid wheel grip coefficient; J_w - the moment of inertia of the drive wheel; ξ– differential's coefficient of internal friction.

The drive wheel angular accelerations of the ZIL-433100 truck when taking off from the road and when skidding on ice in the first five gears are presented in Table 2.

TABLE II. DRIVE WHEEL ANGULAR ACCELERATIONS (ε) OF THE ZIL-433100 TRUCK WHEN TAKING OFF FROM THE ROAD AND WHEN SKIDDING ON ICE

ε, r/s^2	laden					unladen				
	gears									
	1	2	3	4	5	1	2	3	4	5
taking off from the road	148	93	64,5	41,6	34,6	148	93	64,5	41,6	34,6
skidding on ice	115,5	53,4	35,2	-	-	130,3	80,5	44,5	33,9	28,6

The limit values of the skidding wheel grip coefficient, at which the differential lock activation in different gears is ensured, can be determined by the following equation:

$$\varphi_{\lim} = \frac{(\varepsilon_\delta - \varepsilon_d) J_{red}}{0{,}5 \cdot G_w \cdot r_w}, \quad (8)$$

Where $\varepsilon_d \geq \varepsilon_\varphi + \varepsilon_\theta$ is the design value of the skidding wheel angular acceleration, at which the lock is activated?

The values of φ_{lim} at the engine rated torque at $\varepsilon_d = 10$ in the first four gears of the ZIL 433100 truck are presented in Table 3.

TABLE III. LIMIT VALUES OF THE SKID WHEEL GRIP COEFFICIENT AT ε_D = 10 FOR THE ZIL 433100 TRUCK

gears	laden				unladen			
	1	2	3	4	1	2	3	4
φ_{lim}	0,4	0,2	0,1	0,06	1,0	0,5	0,25	0,15

The foregoing allows us to conclude that the differential with a lock to limit the skidding wheel separate angular acceleration is well suited to the vehicle's operating conditions, both in ensuring the freedom of the drive wheels separate movement and in ensuring the maximum traction force.

B. Structure and Operation of the Device

The developed differential lock (Fig. 1) includes outer ring 1, cage 2 with rollers and springs, sprocket 3. The outer ring of a cylindrical type is screwed with bolts to the differential housing 4 end.

The cage with rollers axial displacement is limited by a lock washer 5, which is installed into the outer ring inner groove. The sprocket splines are put on the splines of the axle shafts with a sliding fit, which is necessary when installing the device. The differential lock's parts in the manufacturing process undergo heat treatment in order to obtain hardness, strength, and durability.

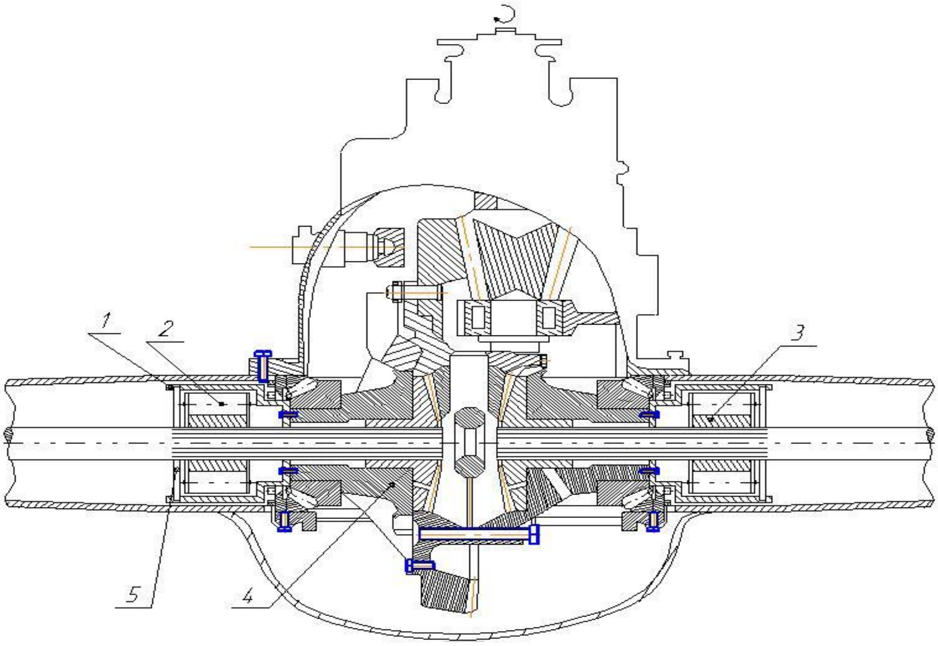

Fig.1 Schematic diagram of the differential lock:1 – outer ring; 2 – cage with rollers and springs; 3 – sprocket; 4 – differential housing;5 – lock washer

The holes for the roller shafts are made elliptical in order to avoid their breakage due to overloads during the locking process. The rubbing parts of the device are lubricated from the rear axle housing. The differential lock is installed on the axle shafts and the differential housing on the right and the left sides.

When driving straight ahead, cornering, unequal drive wheel radius, or unequal tire pressure, the differential operates normally like a simple gear differential. At the same time, in the differential lock, the cage with rollers is rolled along the outer ring. Due to the springs, the rollers are in the middle position in relation to the place of jamming.

When one of the drive wheels hits a slippery area of the road, it starts to skid. The axle shaft with a sprocket receives an acceleration of 10 ... 25 r/s². Due to the inertial-dynamic forces, the cage with rollers remains in place, and the rollers get into a jammed position between the sprocket edges and the outer ring.

The torque is evenly distributed to the skid and non-skid wheel. When the skidding wheel leaves the slip phase, the forces acting on the jammed rollers are reduced, the cage with rollers returns to its initial position by springs, the rollers come out of the jammed position.

C. Experimental Studies

To determine the proposed differential lock effectiveness, road tests were carried out, during which the parameters of movement of the ZIL-433100 truck in standard configuration and of the truck equipped with an automatic differential lock (Fig. 2 and 3) were determined on icy and slippery areas, on snow, on a dry stubble field, on rolled snow, on icy and dirt roads after rain, on clayey virgin soil after rain, as well as when driving on turf [17], [18].

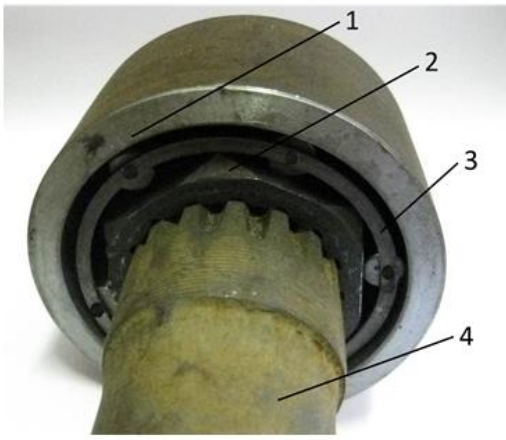

Fig.2 General view of the differential lock: 1 – outer ring; 2 – sprocket; 3 – cage with rollers; 4 – the axle shaft

Fig. 3 Cage with rollers

Analysis of the graphs presented in Figs. 4 and 5 allows us to make the following conclusions. The coefficient of separate skidding δ_s at different vertical loads (laden or unladen truck) decreases with an increase in the grip coefficient. At the same time, the use of an automatic differential lock makes it possible to reduce the value of this coefficient on various types of carrying surfaces by an average of 20 ... 30%.

It can also be noted that a decrease in the vertical axle load leads to an increase in the coefficient of separate skidding for the same test conditions.

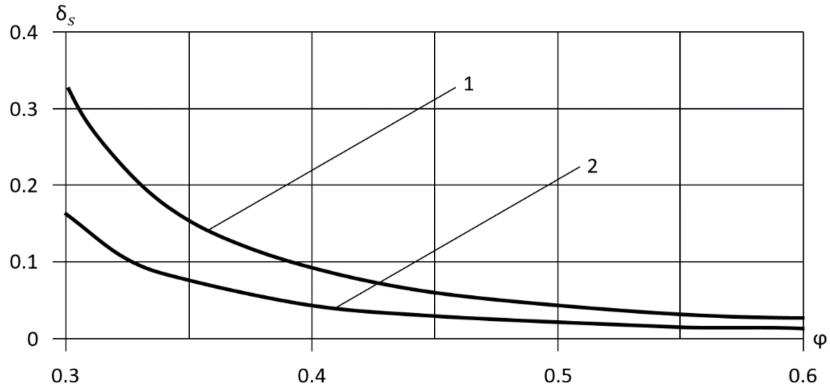

Fig.4 Changing the coefficient of separate skidding depending on grip coefficient: 1 - laden ZIL-433100 truck in standard configuration; 2 - laden ZIL-433100 truck with a differential lock

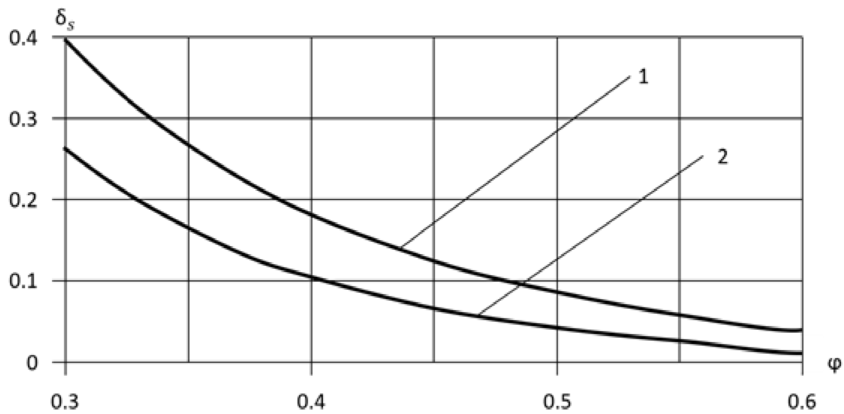

Fig. 5 Changing the coefficient of separate skidding depending on grip coefficient: 1 - unladen ZIL-433100 truck in standard configuration; 2 - unladen ZIL-433100 truck with a differential lock

The technical efficiency of the developed device when accelerating a vehicle can be assessed by the speed characteristic on a certain area of the carrying surface. The specified characteristics of the ZIL-433100 truck, determined experimentally, are shown in Figs. 6, 7, 8, and 9.

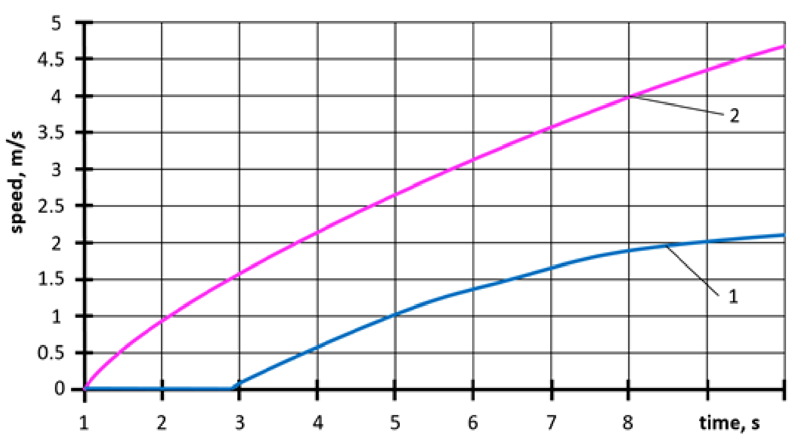

Fig.6 Speed characteristics of acceleration in an icy road: 1 - ZIL-433100 truck in series production condition; 2 - ZIL -433100 truck with a differential lock

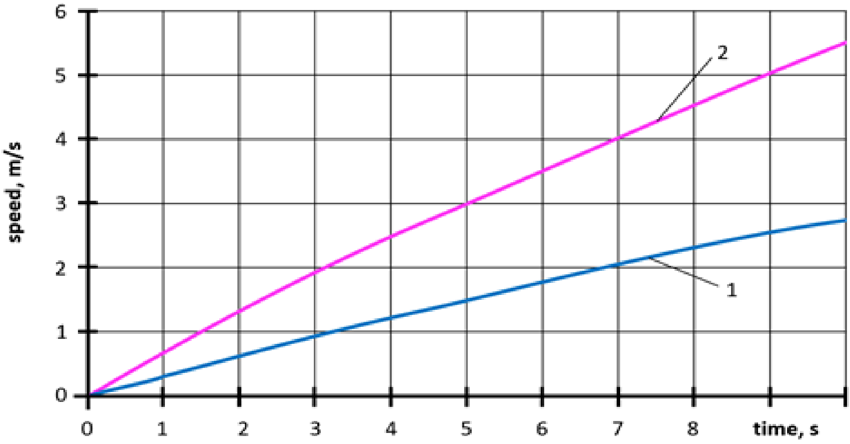

Fig. 7 Speed characteristics of acceleration on snow: 1 - ZIL-433100 truck in series production condition; 2 - ZIL - 433100 truck with a differential lock

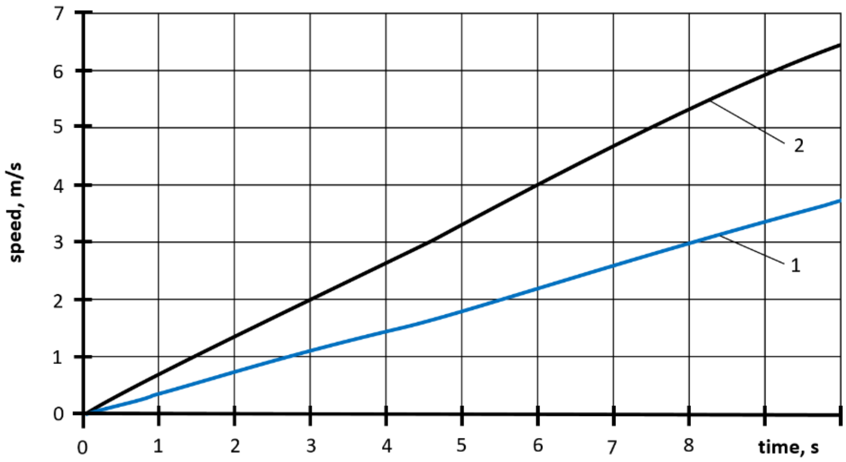

Fig. 8 Speed characteristics of acceleration on a slippery area: 1 - ZIL-433100 truck in series production condition; 2 - ZIL -433100 truck with a differential lock

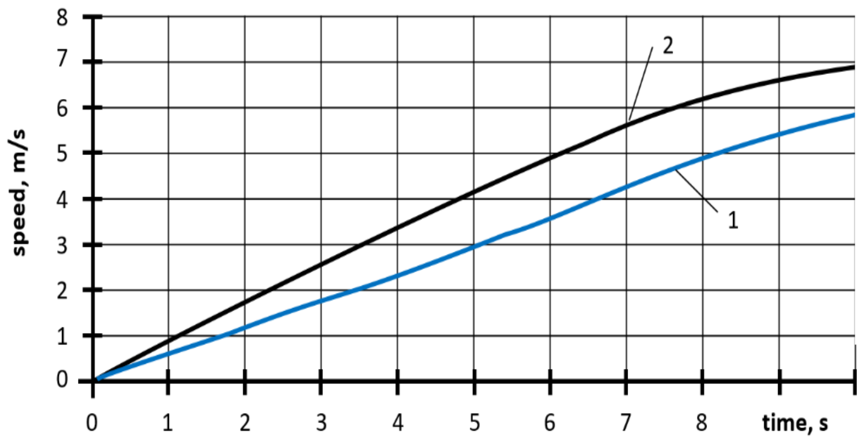

Fig.9. Speed characteristics of acceleration on turf:1 - ZIL-433100 truck in series production condition; 2 - ZIL-433100 truck with a differential lock

The maximum traction force on the drive wheels was also determined during the experimental studies [19]-[22]. The results are presented in Fig.10.

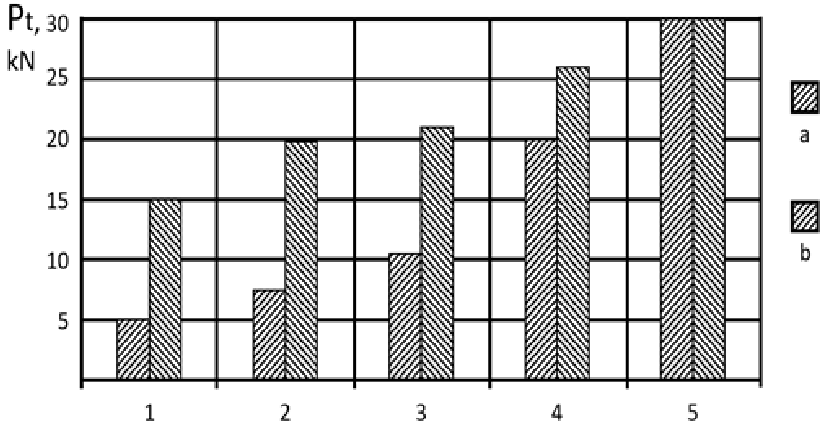

Fig. 10 Maximum traction force on the ZIL-433100 truck drive wheels in various driving conditions: 1 – driving on ice; 2 – driving on snow; 3 – driving on a slippery area; 4 – driving on turf; a – ZIL-433100 truck in series production condition; b – ZIL -433100 truck with a differential lock

From the data shown in Fig. 10, it follows that the use of the proposed method for increasing cross-country ability on the ZiL-433100 truck equipped with an automatic differential lock provides 1.24 ... 2.45 times greater traction force values compared to a series production vehicle.

V. CONCLUSION

Thus, the results of experimental studies indicate the developed device's effectiveness in various road conditions, as well as in off-road conditions.

The research results allow us to conclude that the developed automatic differential lock does not impair the conventional differential operation under the vehicle's various modes of motion.

It allows increasing the vehicles' traction and cross-country ability and reducing their skidding when driving on slippery roads and deformable soils and thereby reducing the likelihood of road traffic accidents.

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