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IMPROVING THE MANEUVERABILITY OF VEHICLES BY USING FRONT SWIVEL AXLES WITH SEPARATE ELECTRIC WHEELS

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Abstract

There is a need for vehicles to maneuver when there are traffic jams, to overcome narrow streets and various obstacles. This leads to increased requirements for dynamism and maneuverability of vehicles.

The authors present the results of the development and research of the steering control of the vehicle, which provides increased maneuverability. Such circumstances significantly affect the increase in maneuverability of wheeled vehicles, including tractors, for which the use of front suspension axles is possible in terms of layout. The use of a front swing axle with electric motor-wheels with separate control will increase the maneuverability of a two-axle vehicle and minimize the steering effort when turning.

When solving the task, a mathematical model of the movement of the vehicle on a turn was created. The forces in the contact of the wheels with the road surface were determined, which made it possible to determine the forces and moments of resistance to the rotation of the front axle. Rational laws of control of turning the front axle, providing minimal resistance to the movement of the vehicle, were obtained.

A vehicle turning control option is proposed, in which the wheels of the outer and inner sides are alternately braked when the vehicle enters and exits the turn. In addition, it is possible to alternately create a torque difference on the wheels of the outer and inner sides of the front axle. Using the proposed turn control options, it is possible to create a multi-axle vehicle with a rocking axle.

The materials of the article on the controllability of vehicles depending on the design of the steering and front axle are of interest to researchers, designers of mobile equipment, graduate students and students of engineering specialties.

Keywords: wheeled machine, electric motor-wheel, torque, pivoting axle, front axle, separate control.

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1. Introduction

Motor vehicles perform a large number of tasks, such as: the transportation of passengers and goods, ensuring the reliable functioning of the logistics network, ensuring the competitiveness of national economies, road safety, etc. The intensive development of road transport at the present stage has required a significant increase in speeds and traffic intensity, especially in urban conditions [1]. In such conditions, vehicles need to maneuver in case of traffic jams, overcome narrow passages of streets and various obstacles. This leads to increased requirements for the dynamics and maneuverability of vehicles [2]. In addition, recently, electric vehicles and vehicles with a combined electromechanical drive of the driving wheels have become widespread.

For a number of wheeled vehicles and special wheeled technological machines, it became possible to make the front axle swivel.

An urgent issue in the construction of steering with a front swivel axle with built-in electric motor-wheels is the choice of the type of electric motor. The best type of electric motors are valve [3]. BLDC motors combine the best qualities of AC motors and DC motors. But due to the relatively high cost of these motors, the most widely used in practice are synchronous three-phase brushless electric motors with permanent magnets on the rotor [4].

It is possible to use controllers – three-phase frequency converters with an operating voltage of 400 V, 600 V and 800 V. It is necessary to provide power depending on the mass of the vehicle in the range from 10 kW to 150 kW.

Traction batteries are used with power from 15 to 100 kW, depending on the vehicle class. Lithium batteries of various modifications are mainly used [5].

Depending on the class of the vehicle, there are no features of the choice of electric motors. Traction calculations of a vehicle or other mobile equipment, including those using a front swing axle, do not differ depending on the purpose or class. The calculation method is the same and depends on the mass of the machine, the maximum speed, the moment of resistance to the rotation of the front axle or some other in the case of a multi-axle machine.

The use of a front swivel axle instead of the front swivel wheels allows to increase maneuverability and improve vehicle handling. This is especially important for wheeled vehicles with a track that changes during operation (tractors, self-propelled chassis, utility and road vehicles). The use of an electric motor-wheel with a separate adjustable drive on the front swivel axle makes it possible to minimize the control force when turning.

A significant amount of scientific research has been devoted to the problem of improving the maneuverability of vehicles. In [6, 7], a fundamental analysis of the maneuverability properties of a vehicle and a road train was carried out, their classification was given, which became the basis for further research. The theory of rotation of wheeled and tracked vehicles, including the dynamic method of rotation due to the creation of a difference in torques on different sides of the vehicle, was developed in [8]. In [9], the controllability of a vehicle is considered more broadly than the controllability on a turn. The concept of controllability is extended to control all the dynamic properties of the vehicle. This idea was supported by the work [10], which introduced a generalized definition of the concepts of stability and controllability of a vehicle from the standpoint of their modern technical equipment. The theory of motion of multi-axle vehicles was proposed in [11]. In this study, the influence of the lateral elasticity of tires on the stability indicators of multi-axle vehicles was determined. General issues of maneuverability, as well as controllability and stability of the vehicle were developed in [12–16]. At the modern level, the issues of vehicle dynamics, handling and stability are presented in [17].

It should be noted a new scientific direction, proposed in [13], is the stability of the vehicle against yaw. The author, among other factors influencing the stability of the vehicle against yaw, considered the influence of the imbalance of the steering wheels. The influence of the imbalance of the steering wheels on the stability of the vehicle is also considered in [18, 19].

The dynamics of a wheeled vehicle with a front swivel axle was studied in [12, 20, 21]. The scheme of rotation of a two-axle vehicle in plan and the scheme of the action of forces on it with the front swing axle are shown in **Fig. 1, 2**.

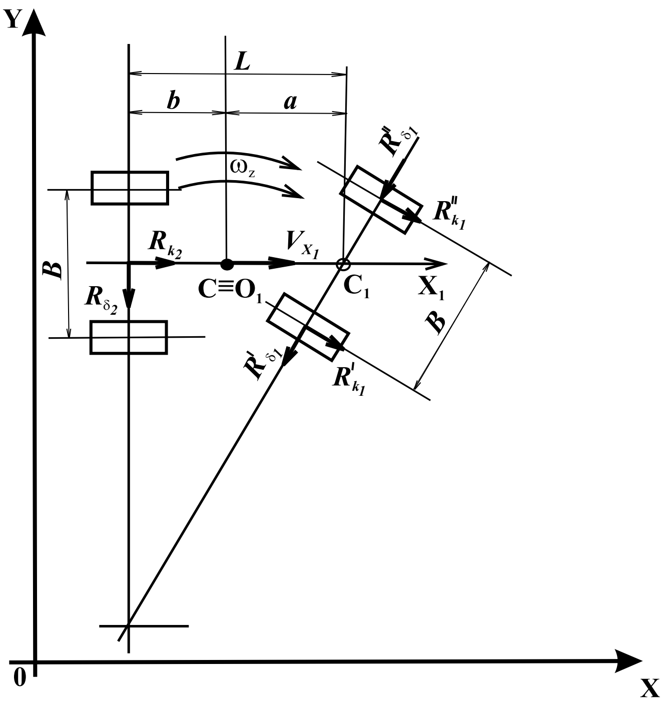

Fig. 1. Scheme of turning a vehicle with a front swing axle

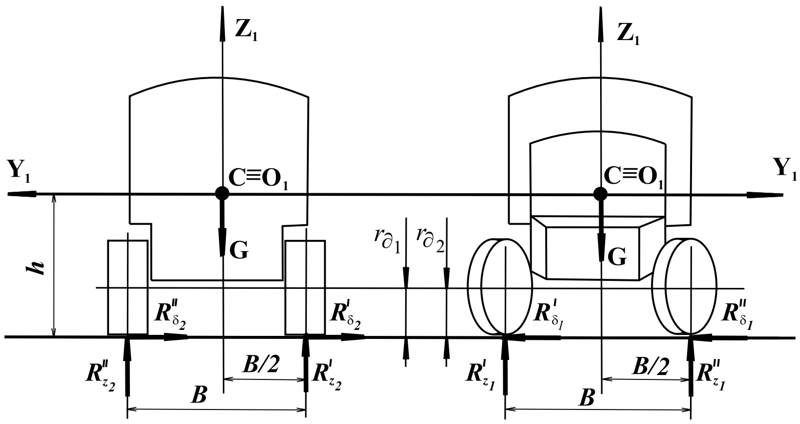

Fig. 2. Scheme of the acting forces on a vehicle with a front swing axle in the transverse plane:
a – rear view; *b* – front view

In [20], differential equations for the plane-parallel motion of a two-axle vehicle with a front swivel axle were obtained:

$$m\left(\frac{d\omega_z}{dt}L\,\text{ctg}(\alpha)-\frac{V_{X_1}^2}{L^2}b\,\text{tg}^2(\alpha)\right)=R_{k_2}+R_{k_1}\cos(\alpha)-R_{\delta_1}\sin(\alpha), \tag{1}$$

$$m\left(\frac{d\omega_z}{dt}b-\frac{V_{X_1}}{L}\,\text{tg}(\alpha)\right)=R_{\delta_1}\cos(\alpha)+R_{\delta_2}+R_{k_1}\sin(\alpha), \tag{2}$$

$$m\frac{i_z^2}{a}\frac{d\omega_z}{dt}=R_{\delta_1}\cos(\alpha)-R_{\delta_2}\frac{b}{a}+R_{k_1}\sin(\alpha), \tag{3}$$

where m – the mass of the vehicle; ω_Z – the angular velocity of the vehicle in the plane of the road (**Fig. 1**); $d\omega_z/dt=\dot{\omega}_z$ – angular acceleration of the vehicle in the plane of the road; α – the angle of rotation of the front swivel axle; V_{x_1} – the linear speed of the vehicle relative to the axis O_1X_1; a, b – the distances from the front and rear axles to the projection of the center of mass of the vehicle on the plane passing through the indicated axles (**Fig. 1**), $a+b=L$; L – the longitudinal wheelbase of the vehicle; i_Z – the radius of inertia of the vehicle relative to the vertical axis O_1Z_1; $R_{\delta_1},R_{\delta_2}$ – the total lateral forces acting on the front and rear axles of the vehicle; R_{k_1},R_{k_2} – the total tangential reactions on the wheels of the front and rear axles of the vehicle (**Fig. 1**, $R'_{k_2}\neq R''_{k_2}$ and the front driving wheels).

Equations (1)–(3) in [21] were obtained from the condition of equality of the tangential reactions on the left and right wheels ($R'_{k_1}=R''_{k_1}$, $R'_{k_2}=R''_{k_2}$). In [21] without taking into account the inertial moments of the wheels, the indicated tangential reactions of the road are determined. With an equal distribution of torques between the left and right wheels:

$$R'_{k_1}=\frac{0.5M_{k_1}}{r_{\partial_1}}-f\,R'_{z_1}, \tag{4}$$

$$R''_{k_1}=\frac{0.5M_{k_1}}{r_{\partial_1}}-f\,R''_{z_1}, \tag{5}$$

$$R'_{k_2}=\frac{0.5M_{k_2}}{r_{\partial_2}}-f\,R'_{z_2}, \tag{6}$$

$$R''_{k_2}=\frac{0.5M_{k_2}}{r_{\partial_2}}-f\,R''_{z_2}, \tag{7}$$

where M_{k_1}, M_{k_2} – the total torques on the wheels of the front and rear axles, respectively; r_{∂_1}, r_{∂_2} – the dynamic radii of the front and rear wheels, $r_{\partial_1}\cong r_{\partial_2}$; f – the wheel rolling resistance coefficient; R'_{z_1}, R''_{z_1}, R'_{z_2}, R''_{z_2} – the normal reactions of the road on wheels.

However, the papers [12, 20] did not consider the use of the difference in tangential reactions on the wheels of the front swivel axle to control the processes of entering and exiting the turn. This was also not considered in [21] when assessing the ease of control of the front swivel axle of a promising tractor self-propelled chassis. The use of an electric motor-wheels with separate control on the front swing axle allows solving this problem.

Thus, there is an urgent need to determine the physical forces acting on the vehicle when using a front swing axle with electric motor-wheels with separate control of the latter. In addition, it is necessary to develop an optimal algorithm for managing such transport.

The aim of research is to increase the maneuverability of a two-axle vehicle by using a front swivel axle with electric motor-wheels that have separate control.

To achieve this aim, it is necessary to solve the following objectives:

1. To determine the forces and moments acting on the front swing axle.

2. To develop an algorithm for controlling the tangential reactions on the wheels of the front axle when turning the vehicle.

2. Materials and methods

2. 1. Research of forces and moments acting on the front swivel axle of a two-axle vehicle

To calculate the maneuverability indicators of such vehicles, it is necessary to create a mathematical model of the movement of a two-axle vehicle on a turn. With separate control of the electric motor-wheels of the front swing axle, the forces in the contact of the wheels with the road and the moments acting on the axle are determined.

Moment on the front swing axle (**Fig. 1**) – at the entrance to the turn:

$$M_1 = \frac{B}{2}\left(R''_{k_1} - R'_{k_1}\right), \tag{8}$$

where B – the track width of the front axle.

When creating a torque difference on the outer and inner wheels of the front swing axle (due to the use of electric motor-wheels with a separate drive), equations (4), (5) will take the form:

$$R'_{k_1} = \frac{M'_{k_1}}{r_{\partial_1}} - f R'_{z_1}, \tag{9}$$

$$R''_{k_1} = \frac{M''_{k_1}}{r_{\partial_1}} - f R''_{z_1}, \tag{10}$$

where M'_{k_1}, M''_{k_1} – the torques generated on the front inner and outer wheels, respectively; $M'_{k_1} \neq M''_{k_1}$.

Normal road reactions on the inner and outer wheels of the front axle:

$$R'_{z_1} = 0.5R_{z_1} - R_{\delta_1}\frac{h}{B}, \tag{11}$$

$$R''_{z_1} = 0.5R_{z_1} + R_{\delta_1}\frac{h}{B}, \tag{12}$$

$$R_{z_1} = R'_{z_1} + R''_{z_1}, \tag{13}$$

where R_{z_1} – the total normal reaction of the road on the wheels of the front axle; h – the height of the center of mass of the vehicle (**Fig. 2**).

After substituting expressions (11), (12) into equations (9), (10), and the resulting relationships into equation (8), let's obtain the final expression for the moment acting on the swing bridge:

$$M_1 = 0.5B\frac{M''_{k_1} - M'_{k_1}}{r_{\partial_1}} - fhR_{\delta_1}. \tag{14}$$

Equation (14) can be written in the following form:

$$M_1 = M_{sw_1} - M_{res_1}, \tag{15}$$

$$M_{sw_1} = 0.5B\frac{M''_{k_1} - M'_{k_1}}{r_{\partial_1}}, \tag{16}$$

$$M_{res_1} = fhR_{\delta_1}, \tag{17}$$

where M_{sw1} – the moment turning on the front axle; M_{res1} – the moment of resistance to the rotation of the front axle.

When the inner wheel is braked $M_{k_1} = -M_{B_1}$, expression (16) will take the form:

$$M'_{sw_1} = 0.5B\frac{M''_{k_1} + M'_{B_1}}{r_{\partial_1}}. \tag{18}$$

Comparing expressions (16) and (18), it is possible to conclude that when braking the inner wheel, the turning moment is greater than when creating a torque difference $\left(M'_{sw_1} > M_{sw_1}\right)$.

It is obvious that at a steady angle of rotation of the front swivel axle $\alpha = \text{const}$ (**Fig. 1**) and $M_1 = 0$, equating the right side of equation (16) to zero, let's obtain:

$$0.5\frac{B}{r_{\partial_1}}\left(M''_{k_1} - M'_{k_1}\right) - fhR_{\delta_1} = 0. \qquad (19)$$

From expression (19), let's determine the required torque difference:

$$\Delta M_k = M''_{k_1} - M'_{k_1} = 2f\frac{h}{B}r_{\partial_1}R_{\delta_1}. \qquad (20)$$

Analyzing equation (20), it is possible to see that at a steady turn, the required torque difference is proportional to the rolling resistance coefficient f, the geometric parameter h/B, and the dynamic radius of the front wheels r_{∂_1}. In addition, the amount of the required torque difference is affected by the total side force acting on the front axle R_{δ_1}.

In [18], the total lateral force acting on the front axle of the vehicle is determined:

$$R_{\delta_1} = m\sec(\alpha)\left[\frac{d\omega_z}{dt}\frac{b^2 + i_z^2 + fhb}{L} + V_{x_1}^2\frac{b}{L^2}\left(1 + f\frac{h}{b}\right)\text{tg}(\alpha)\right] - R_{k_1}\text{tg}(\alpha). \qquad (21)$$

After substituting (21) into (20), let's obtain the following equation:

$$\Delta M_k = 2f\frac{h}{B}r_{\partial_1}\left\{m\sec(\alpha)\left[\frac{d\omega_z}{dt}\frac{b^2 + i_z^2 + fhb}{L} + V_{x_1}^2\frac{b}{L^2}\left(1 + f\frac{h}{b}\right)\text{tg}(\alpha)\right] - R_{k_1}\text{tg}(\alpha)\right\}. \qquad (22)$$

With steady rotation $d\omega_z/dt = 0$, equation (22) will be simplified:

$$\Delta M_k = 2f\frac{h}{B}r_{\partial_1}\text{tg}(\alpha)\left(mV_{x_1}^2\frac{b + fh}{L^2}\sec(\alpha) - R_{k_1}\right). \qquad (23)$$

The total tangential reaction of the road on the front wheels:

$$R_{k_1} = R'_{k_1} + R''_{k_1}. \qquad (24)$$

Taking into account equations (9) and (10), the tangential reaction is determined as follows:

$$R_{k_1} = \frac{M'_{k_1} + M''_{k_1}}{r_{\partial_1}} - fR_{z_1} = \frac{M'_{k_1} + M''_{k_1}}{r_{\partial_1}} - mgf\frac{b}{L}. \qquad (25)$$

After substituting (27) into (25), let's obtain the following expression:

$$\Delta M_k = 2f\frac{h}{B}r_{\partial_1}tg(\alpha)\left(mV_{x_1}^2\frac{b + fh}{L^2}\sec(\alpha) + mgf\frac{b}{L} - \frac{M'_{k_1} + M''_{k_1}}{r_{\partial_1}}\right). \qquad (26)$$

It is obvious that $\Delta M_k =$ provided:

$$mV_{x_1}^2\frac{b + fh}{L^2}\sec(\alpha) + mgf\frac{b}{L} - \frac{M'_{k_1} + M''_{k_1}}{r_{\partial_1}} = 0, \qquad (27)$$

$$M_{k_1} = M'_{k_1} + M''_{k_1} = \frac{mr_{\partial_1}}{L}\left(V_{x_1}^2\frac{b + fh}{L}\sec(\alpha) + gfb\right). \qquad (28)$$

When condition (28) is met, $\Delta M_k = 0$ at the stage of steady rotation. For the case when the vehicle exits the turn $M_1 < 0$, expression (16) will take the form:

$$M_1 = 0.5B\frac{M''_{k_1} - M'_{k_1}}{r_{\partial_1}} + fhR_{\delta_1}. \quad (29)$$

When creating a braking torque on the outer wheel:

$$M''_{k_1} = -M''_{T_1}. \quad (30)$$

Expression (29) taking into account (30) will take the form:

$$M_1 = 0.5B\frac{M''_{k_1} + M'_{T_1}}{r_{\partial_1}} + fhR_{\delta_1}. \quad (31)$$

The influence of the turning parameters on the magnitude of the turning moment M_1 in the unsteady stage of turning can be determined after substituting equation (21) into relations (14), (31), but this will be considered in subsequent studies.

3. Results and discussion

3. 1. Results of application of algorithms for controlling tangential reactions on the wheels of the front swing axle

Fig. 3, 4 show the diagrams of the action of forces on the vehicle with the front swing axle on the outer and inner wheels when entering the turn and exiting the turn.

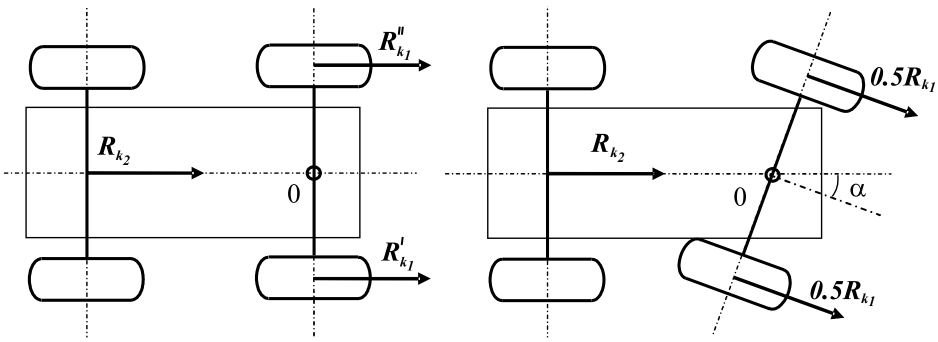

Fig. 3. Schemes of the action of forces on the vehicle with the front swing axle at the entrance to the turn: *a* – at the entrance to the turn; *b* – with a steady turn

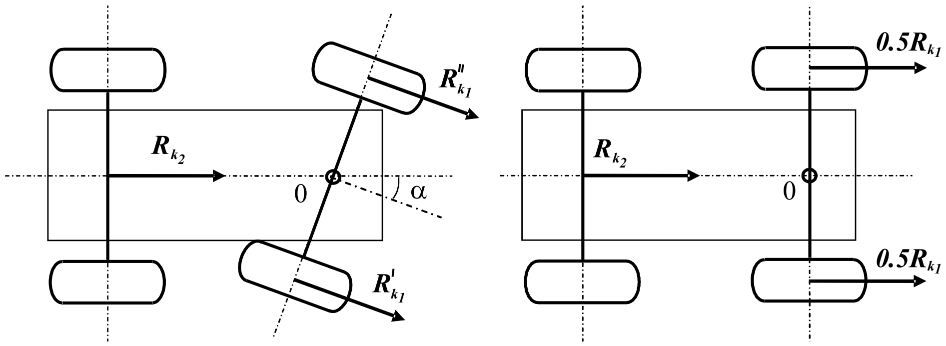

Fig. 4. Schemes of the action of forces on the vehicle with the front swing axle when exiting the turn: *a* – when exit from the turn; *b* – upon completion of the turn

At the turn of the wheel of the rear drive axle, a constant traction force is created (**Fig. 3, 4**), R_{k_2} which ensures the forward movement of the wheeled vehicle. If $R'_{k_1} > R''_{k_1}$ (entry into a turn), a moment is created on the front axle that turns it in the direction of decreasing turning radius.

If $R'_{k_1} < R''_{k_1}$ (exit from a turn), a negative torque is generated that turns the front axle in the direction of the larger turning radius.

Fig. 5 shows, calculated using the formulas given above, diagrams of the change in torque on the outer and inner wheels at the entrance to the turn, the steady turn and the exit from the turn.

The simulation package Autodesk Inventor was chosen for the numerical experiment. The technology of digital prototypes proposed in it offers a flexible set of tools for instrumentation, analysis and calculations. The following parameters were used as input parameters for the numerical experiment: $f7 = 0.054$, $m = 190$ kg; $L = 2.36$ m; $\alpha = 45°$, $V = 1.85$ m, $h = 0.54$ m. Calculations were made in the speed range of 10–30 m/s (36–108 km/h), then the values were averaged and reduced to relative units.

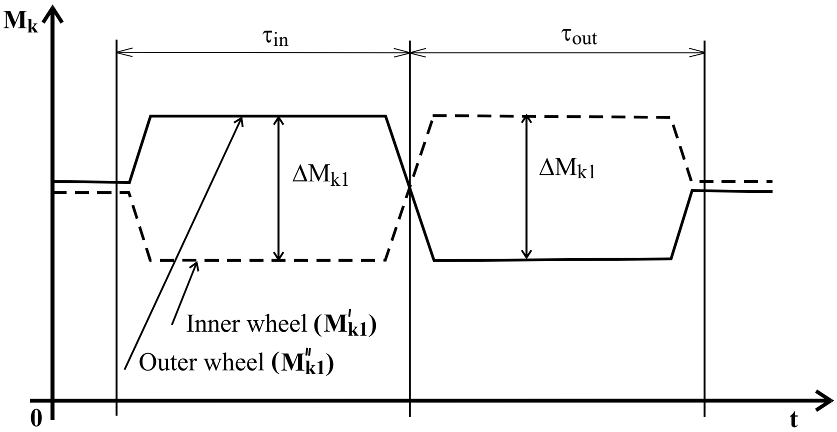

Fig. 5. Diagram of torque changes on the front wheels

In principle, this diagram is a variant of the control of tangential reactions on the wheels by changing the ratio of torques, which leads to an improvement in the controllability of the vehicle when entering and exiting the turn.

In this case (**Fig. 5**), when entering a turn, a greater torque is created on the outer wheel M''_{k1}, and a smaller torque on the inner wheel M'_{k1}. When exiting a turn, less torque is generated on the outer wheel M''_{k1}, and more torque is generated on the inner wheel M'_{k1}.

The second option for solving the problem is that a difference in braking torques is created alternately on the wheels of the outer and inner sides of the front swing axle. In addition to braking torques, torques are also generated on the wheels of the front guiding swing axle.

Fig. 6 shows a diagram of the action of forces on a vehicle on the front swing axle when entering a turn and during alternate braking of the inner and outer wheels.

At the same time, during the entry into the turn, the inner wheel is braked, and a torque is created on the outer one (**Fig. 6**). To improve maneuverability in the steady state of turning the wheeled vehicle, torques are created on both wheels of the front swing axle. The ratio of the torque on the outer wheel of the front axle to the torque on the inner wheel of this axle is equal to the ratio of the radii of movement of these wheels.

Fig. 7 presents calculated diagrams of changes in torque and braking moments on the outer and inner wheels when turning. The diagram defines τ_{in} – the time of entering the turn, τ_{st} – the time of the steady turn, τ_{out} – the time of exiting the turn.

During turn entry, the traction force R''_{k_1} on the outer wheel and the braking force R'_{T_1} on the inner wheel generate a torque that ensures that the front axle rotates through an angle α. While reaching the angle of rotation, traction forces R'_{k_1} and R''_{k_1} are created on both wheels, which are equal to each other in magnitude.

During the set cornering, it is necessary to maintain a constant torque difference ΔM_{k_1} between the outer and inner wheels. The difference between the torques on the outer and inner wheels in this case corresponds to the difference in the forces of their rolling resistance. This ensures that the steering angle of the front axle α is constant. At the exit of the turn, traction force R'_{k_1}

is generated on the inner wheel, and braking force R''_{T_1} is generated on the outer wheel. Due to the creation of a negative torque, the front axle returns to the position α = 0. After reaching this position of the front axle, the effect of the difference in torque and braking torques is suspended.

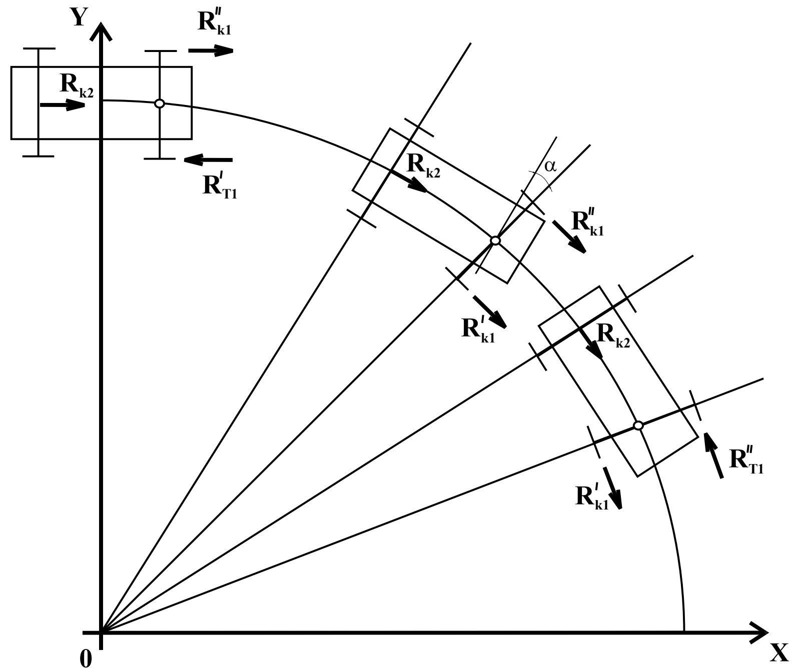

Fig. 6. Diagrams of the action of forces on the vehicle when entering a turn with alternate braking of the wheels of different sides

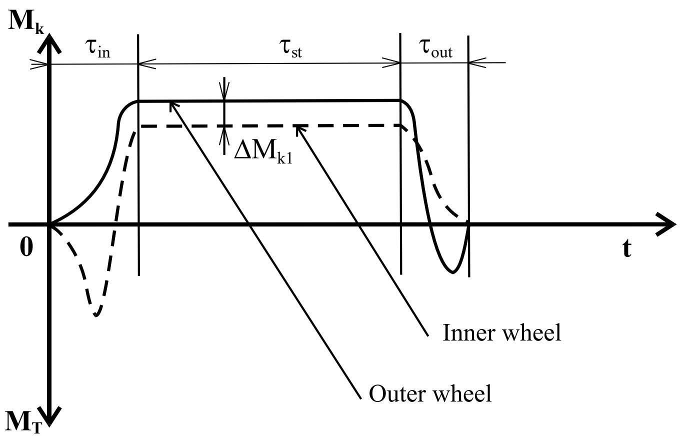

Fig. 7. Diagram of changes in torque and braking torques on the outer and inner wheels

At the moment, to confirm the theoretical calculations, experimental studies are being carried out on a full-scale scale model. For their implementation, a theory of the choice of scale factors has been developed. The analysis of the obtained results is supposed to be carried out in the course of further studies.The results of the theoretical study, which are presented in the article, are presented for special-purpose vehicles, mostly armored. Other types of vehicles (agricultural, municipal, etc.) have their own design features, which require the search for new technical solutions, including when choosing an electric motor-wheel.

In this study, the general case of control with the help of electric motor-wheels is considered, without taking into account the features of various types of electric motors. Further studies will take into account the characteristics of existing electric motors, controllers and traction batteries.

4. Conclusions

It is shown that the use of the front swivel axle instead of the front swivel wheels can increase the maneuverability and improve the controllability of vehicles. The use of an electric motor-wheel with a separate adjustable drive on the front swivel axle makes it possible to minimize the control force when turning. In the course of the research, a mathematical model of the movement of a vehicle with a front swivel axle on a turn was obtained. The turning process of the machine is divided into three stages: the turn entry stage, the steady turn stage, and the turn exit stage. Taking into account the forces that arise when the wheels come into contact with the road surface, the forces and moments acting on the front axle in various stages of turning a two-axle vehicle are determined. The results obtained can be used in the design of the steering of both two-axle and multi-axle vehicles with swing axles without changes and additional calculations.

As a result of the study, control algorithms for the front swivel axle of a two-axle vehicle were developed. The sequence of creating the difference in the tangential reactions of the road on the front wheels when the vehicle makes a turn is determined. Rational laws for controlling the front axle turning are obtained, which provide the minimum resistance to the movement of the vehicle. A variant of vehicle turning control is proposed, in which the wheels of the outer and inner sides alternately brake when entering and exiting the vehicle turn. In addition, it is possible to alternately create a torque difference on the wheels of the outer and inner sides of the front axle. Using the proposed options for steering control, it is possible to create a multi-axle vehicle with an oscillating axle. The developed mathematical models make it possible to conduct research without making additional changes.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

References

[1] Klets, D. M. (2017). Providing the stability of motor vehicles maneuverability properties. Avtomobil i elektronika. Suchasni tekhnolohiyi, 12, 106–111. Available at: https://dspace.khadi.kharkov.ua/dspace/handle/123456789/5897

[2] Klets, D., Gritsuk, I. V., Makovetskyi, A., Bulgakov, N., Podrigalo, M., Kyrychenko, I. et al. (2018). Information Security Risk Management of Vehicles. SAE Technical Paper Series. doi: https://doi.org/10.4271/2018-01-0015

[3] Tkachuk, V. I., Biliakovskyi, I. Ye., Makarchuk, O. V. et al. (2011). Teoriia ta syntez ventylnykh dvyhuniv postiinoho strumu. Lviv: Vyd-vo Lviv. politekhniky, 288. Available at: https://vlp.com.ua/node/8533

[4] Lindegger, M. (2009). Economic viability, applications and limits of efficient permanent magnet motors. Swiss Federal Office of Energy, 31. Available at: http://www.circlemotor.ch/downloads/summaryinenglish.pdf

[5] Ganova, A. S., Khmelev, R. N. (2020). Compara yive analysis of characteristics of traction batteries for modern electric vehicles. Izvestiya TulGU. Tekhnicheskie nauki, 10, 318–322. doi: https://doi.org/10.24411/2071-6168-2020-00156

[6] Zakin, Ya. Kh. (1986). Manevrennost' avtomobilya i avtopoezda. Moscow. Mashinostroenie, 136.

[7] Litvinov, A. S. (1971). Upravlyaemost' i ustoychivost' avtomobilya. Moscow: Mashinostroenie, 416.

[8] Farobin, Ya. E. (1970). Teoriya povorota transportnykh mashin. Moscow: Mashinostroenie, 176.

[9] Ellis, D. R. (1975). Upravlyaemost' avtomobilya. Moscow: Mashinostroenie, 216.

[10] Podrigalo, M. A. (2008). Upravlyaemost' i ustoychivost' avtomobilya. Opredelenie ponyatiy (v poryadke obsuzhdeniya). Avtomobil'naya promyshlennost', 11, 22–23.

[11] Antonov, D. A. (1978). Teoriya ustoychivosti dvizheniya mnogoosnykh avtomobiley. Moscow: Mashinostroenie, 216.

[12] Klets, D., Dubinin, Y., Pelypenko, Y., Baidala, V. (2021). Determination of the partial acceleration of a two-axle vehicle with all-handled wheels. Bulletin of the National Technical University «KhPI». Series: Automobile and Tractor Construction, 2, 23–33. doi: https://doi.org/10.20998/2078-6840.2021.2.03

[13] Gats'ko, V. I. (2013). Vliyanie konstruktivnykh parametrov na ustoychivost' i upravlyaemost' avtomobilya pri ustanovivshemsya pryamolineynom dvizhenii. Visnyk Skhidnoukrainskoho natsionalnoho universytetu imeni Volodymyra Dalia, 2 (15 (204)), 254–259.

[14] Turenko, O. I. (2016). Evaluation of passenger cars controllability in service brake mode on the horizontal straight sections of the road. Naukovi notatky, 55, 402–406. Available at: http://nbuv.gov.ua/UJRN/Nn_2016_55_80

[15] Boboshko, A. A. (2007). Issledovanie dvizheniya avtomobilya so vsemi upravlyaemymi kolesami pri povorote ikh v odnu storonu. Visnyk Kharkivskoho natsionalnoho avtomobilno-dorozhnoho universytetu, 38. Available at: https://cyberleninka.ru/article/n/issledovanie-dvizheniya-avtomobilya-so-vsemi-upravlyaemymi-kolyosami-pri-povorote-ih-v-odnu-storonu

[16] Strelnik, Y. N. (2015). Analysis of stability of rectilineal motion of the model vehicle with driven rear axle (absolutely rigid management model). Vestnik donetskoy akademii avtomobil'nogo transporta, 4, 42–49. Available at: http://nbuv.gov.ua/UJRN/Vdiat_2015_4_8

[17] Jazar, R. N. (2008). Vehicle Dynamics: Theory and Application. Spriger, 1015. doi: https://doi.org/10.1007/978-0-387-74244-1

[18] Kim, K., Park, J., Lee, S. (2005). Tire Mass Imbalance, Rolling Phase Difference, Non-Uniformity Induced Force Difference, and Inflation Pressure Change Effects on Steering Wheel Vibration. SAE Technical Paper. doi: https://doi.org/10.4271/2005-01-2317

[19] Liu, C., Orzechowrski, I. (2007). Acle Inbalance Measurement and Balancino Strategies. SAE Technical Paper.

[20] Podrigalo, M. A., Volkov, V. P., Kirchatyy, V. I., Baboshko, A. A. (2003). Manevrennost' i tormoznye svoystva kolesnykh mashin. Kharkiv: KhNADU, 403.

[21] Podrigalo, M., Boboshko, O., Razaryonov, L., Zakapko, O., Zinchenko, O., Krasnokutskiy, V. (2020). Estimation of the ease in control of a perspective tractor's selfpropelled chassis. Bulletin of the National Technical University «KhPI». Ser.: Engineering and CAD, 2, 84–89. doi: https://doi.org/10.20998/2079-0775.2020.2.10

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