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Maneuverability and off-road capability of a four-axle vehicle with swivel bogies and electrically driven wheels

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Annotation. Problem. *The issues of maneuverability and off-road capability in four-axle vehicles involve ensuring their efficient operation on rough terrain, in narrow or confined spaces, and under challenging operating conditions. Key challenges include reducing the turning radius, achieving even load distribution across axles, and minimizing energy losses during movement. Additionally, it is crucial to ensure the reliable performance of all drivetrain components, particularly under increased wear and exposure to external factors.* ***Goal.*** *The objective of the study is to develop and substantiate technical solutions aimed at improving the maneuverability and off-road capability of four-axle vehicles by optimizing the design of the running gear, implementing innovative drives, and enhancing the control system. This will ensure the efficient operation of vehicles under challenging conditions, improve their energy efficiency and reliability, and expand the scope of their applications.* ***Methodology.*** *The methodology for implementing the maneuverability and off-road capability of a four-axle vehicle with swiveling bogies and electric wheel drive includes the analysis and modeling of the vehicle's reaction to various operating conditions, as well as optimizing the drive and control systems to ensure high movement efficiency on challenging routes.* ***Results****. The results of the research on the maneuverability and off-road capability of a four-axle vehicle with swiveling bogies and electric wheel drive have improved the turning efficiency of such a vehicle on challenging terrain with steep slopes and uneven areas without road coverage. By optimizing the design of the bogies and implementing electric wheel drives, it was possible to reduce the weight and geometric parameters of the vehicle, allowing for more precise maneuvers in confined spaces while maintaining stable movement with sufficiently high off-road capability and maneuverability of the four-axle vehicle.* ***Originality****. The originality of the research lies in the comprehensive approach to improving the maneuverability and off-road capability of a four-axle vehicle with swiveling bogies and electric wheel drive. For the first time, innovative methods for optimizing the design of the running gear and implementing electric drives were applied, which significantly reduced energy losses and improved motion control on challenging terrain. New approaches to modeling movement ensured high maneuvering efficiency under various operating conditions. These results provide new opportunities for the application of such vehicles in specialized industries where the requirements for off-road capability and maneuverability are extremely high.* ***Practical value****. The practical significance of the research lies in the potential implementation of the developed technical solutions in the production of four-axle vehicles for operation in challenging conditions, such as construction, agriculture, and military applications. The improvements developed allow for enhanced equipment efficiency, reduced energy consumption, and high maneuverability and off-road capability on difficult routes.*

Key words: *maneuverability, off-road capability, four-axle vehicle, swiveling bogies, electric drive, development, modeling*

Introduction

The maneuverability and off-road capability of vehicles are key characteristics that determine their efficiency under challenging operating conditions.

Four-axle vehicles with swiveling bogies, in particular, are of significant interest due to their ability to overcome obstacles, navigate complex terrains, and operate in confined spaces.

These designs are widely used in agricultural, construction, military equipment, as well as specialized fields such as rescue operations or heavy cargo transportation.

The relevance of research into maneuverability and off-road capability is driven by the need to enhance the mobility and efficiency of vehicles in diverse environments. The growing demand for equipment capable of operating on rough terrain stimulates the development of innovative solutions, such as the use of swiveling multi-axle bogies and electric drives. Studying these aspects enables the creation of more economical, reliable, and versatile transport systems that meet the requirements of the modern market.

Research in this area not only facilitates the improvement of existing technologies but also opens up new opportunities for implementing highly efficient technical solutions capable of addressing a wide range of transportation needs.

Analysis of publications

The off-road capability of four-axle vehicles is an important characteristic that determines the vehicle's ability to overcome complex, rugged terrain, including mountainous, marshy, or off-road areas. A number of studies on vehicle off-road performance [1-5] focus on the impact of suspension design, drive systems, and weight distribution on vehicle mobility. Some works [2, 3, 5] emphasize the modeling of vehicle movement under varying loads, as well as testing in extreme conditions.

The maneuverability of four-axle vehicles is often analyzed in the context of reducing the turning radius [6], stability during motion [7, 8] at different vehicle speeds, and the ability to navigate confined spaces. Maneuverability research also relates to the optimization of steering systems and the distribution of traction forces between axles to improve maneuverability [9-14]. The role of active control systems that adapt to different driving conditions is also crucial [7, 9, 11, 13].

The "Crab Mode" [15] allows the vehicle to move sideways while maintaining stability, which is especially important in confined spaces or on challenging routes. This mode is actively studied in the context of improving maneuverability, particularly for specialized vehicles.

Vehicles with swiveling bogies have a significant advantage in maneuverability due to the ability to rotate the wheel axles [15]. This allows for a reduced turning radius and enables movement in tight spaces. Research in this field focuses on enhancing the design of such bogies and optimizing their operation to ensure stable movement under varying load conditions [15].

Purpose and Tasks

The objective of the study is to develop and substantiate technical solutions aimed at improving the maneuverability and off-road capability of four-axle vehicles by optimizing the design of the running gear, implementing innovative drives, and enhancing the control system.

To achieve the set objective, the following tasks need to be completed:

– examine the issue of the off-road capability of a four-axle vehicle;

– analyze the maximum width of a trench that a four-axle vehicle can cross;

– explore the theoretical aspects of selecting distances between the axles of the steering bogie of a four-axle vehicle;

– develop a layout diagram for a steering bogie with electrically driven wheels;

– develop a concept for the layout of a four-axle vehicle with steering bogies and electrically driven wheels;

– conduct an analysis of the maneuverability and off-road capability of a four-axle vehicle with steering bogies and electrically driven wheels.

The off-road capability of a four-axle vehicle

The design of the suspension system for a multi-axle vehicle and the determination of the characteristics of its main components depend on the geometric parameters of the vehicle's off-road capability. Therefore, it is necessary to examine these parameters to develop approaches for selecting the distances between the vehicle's axles, a key feature of which is the ability of the steering bogies with electric wheel drives to rotate up to 90º.

The profile off-road capability of a special or specialized vehicle refers to its ability to navigate uneven and challenging road surfaces as well as overcome various obstacles. This capability is largely determined by the vehicle's geometric characteristics, which influence how effectively it can handle irregular terrain without compromising stability or mobility. Such features play a critical role in the operational efficiency of vehicles designed for specific purposes, especially in demanding conditions.

These geometric parameters include critical dimensions like ground clearance, approach and departure angles, wheelbase, and axle spacing. Each of these aspects contributes to the vehicle's ability to traverse obstacles such as ridges, trenches, and slopes. A vehicle’s ability to adapt to varying terrain conditions is not only a result of its geometric design but also depends on the specific engineering solutions implemented in its construction.

The structural and layout characteristics of a special or specialized vehicle significantly influences these parameters. For example, the placement of axles, the arrangement of suspension systems, and the distribution of weight all play a role in defining the vehicle's off-road performance. These design considerations ensure the vehicle maintains optimal contact with the ground while navigating uneven surfaces.

The detailed geometric parameters of a special or specialized vehicle, which reflect the interplay between its design features and functional requirements, are illustrated in Figure 1. This figure provides a visual representation of the key dimensions and proportions that contribute to the vehicle's off-road capability, highlighting the importance of careful planning and precision in the design and configuration of such vehicles.

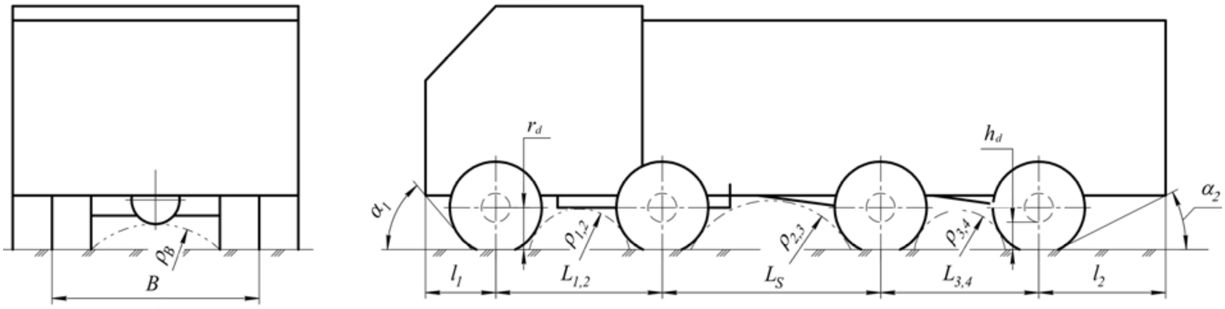


Fig. 1. Geometric parameters of a special or specialized vehicle

The geometric parameters of a special or specialized vehicle include:

Ground clearance h_d: The vehicle's ability to move without coming into contact with concentrated obstacles (such as rocks, stumps, bumps, etc.) and its ability to traverse soft soils. The majority of off-road vehicles have a ground clearance ranging from 315 mm to 400 mm. Ground clearance can be increased or decreased under extreme conditions by adjusting the diameter of the wheel drives through inflating or deflating pneumatic tires mounted on the vehicle's wheels. Additionally, ground clearance can be increased by reducing the gear ratio of the final drive or by replacing the final drive with wheel reducers or hub motors.

Front l_1 and rear l_2 overhang of the vehicle: The distance from the outermost point of the vehicle's front (rear) projecting part along its length to a plane perpendicular to the support surface, which passes through the centers of the vehicle's front (rear) wheels.

Angles of front (α_1) and rear (α_2) overhang: These are the angles formed by the road surface and the planes tangent to the front and rear wheels, respectively, as well as to the lowest projecting points of the vehicle's front and rear parts. These angles characterize the vehicle's ability to traverse uneven roads when ascending or descending obstacles. For high-mobility vehicles, the values of the front and rear overhang angles are typically within the range of ($\alpha_1 > 60°…70°$) and ($\alpha_2 > 60°…70°$).

Longitudinal ($\rho_{1,2}$), ($\rho_{2,3}$), ($\rho_{3,4}$) and transverse (ρ_B) clearance radii: These are the radii of cylinders tangent to the wheels and the lowest points of the vehicle in the longitudinal and transverse planes, respectively. These radii define the contours of obstacles that the vehicle can overcome without making contact. The smaller the radii, the higher the vehicle's off-road capability. For special and specialized high-mobility vehicles, the values of the longitudinal and transverse clearance radii are typically within the following ranges: ($\rho_{2,3}$) from 2.0 m to 3.5 m, and ($\rho_{1,2}$), ($\rho_{3,4}$), (ρ_B) less than 2.0 m.

When designing vehicle's off-road with improved maneuverability, attention should be paid to the so-called axle articulation angle (β_m) of the vehicle. This angle represents the sum of the rotation angles of the front and rear axles relative to the longitudinal axis of a multi-axle off-road vehicle (see Fig. 2). Proper consideration of this parameter is crucial for ensuring the vehicle's ability to navigate complex terrains effectively.

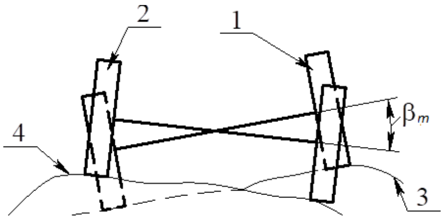


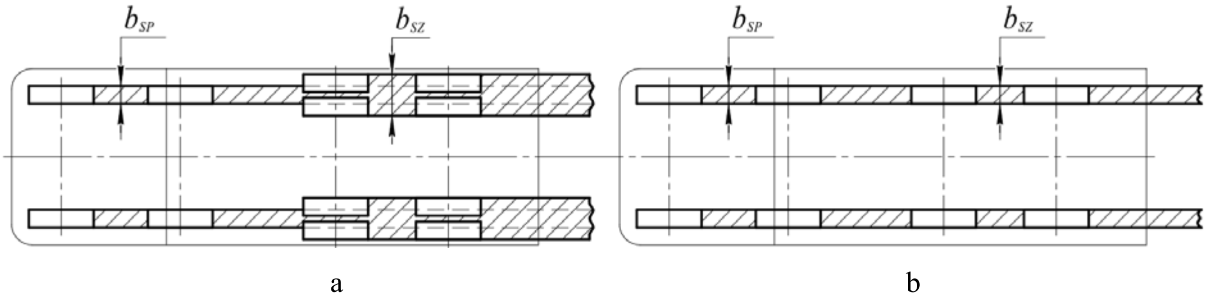
Fig. 2. Axle articulation angle (view of the vehicle from the rear or front): 1, 2 – the front and rear axles of the vehicle, respectively; 3, 4 – the support surface under the wheels of the corresponding front and rear axles.

The greater the axle articulation angle (β_m), the better the vehicle's wheels adapt to irregularities of the support surface and maintain contact with the road surface. With small axle articulation angles, significant load redistribution among the wheels or even the "hanging" of one wheel may occur on rough terrain. The values of axle articulation angles are not regulated by standards but are determined by the purpose of the special or specialized vehicle.

Another parameter that characterizes the off-road capabilities of a vehicle is the coefficient of overlap (η_s) of the tracks of the front and rear wheels. The coefficient of overlap of the tracks of the front and rear wheels indicates the rolling resistance of the vehicle's wheels on deformable soils. The coefficient of overlap is determined by the formula ($\eta_s = b_{SP}/b_{SZ}$) (see Fig. 3). The closer the value of the coefficient (η_s) is to one, the lower the rolling resistance of the wheels on deformable soils. An exception is movement on swampy terrain.

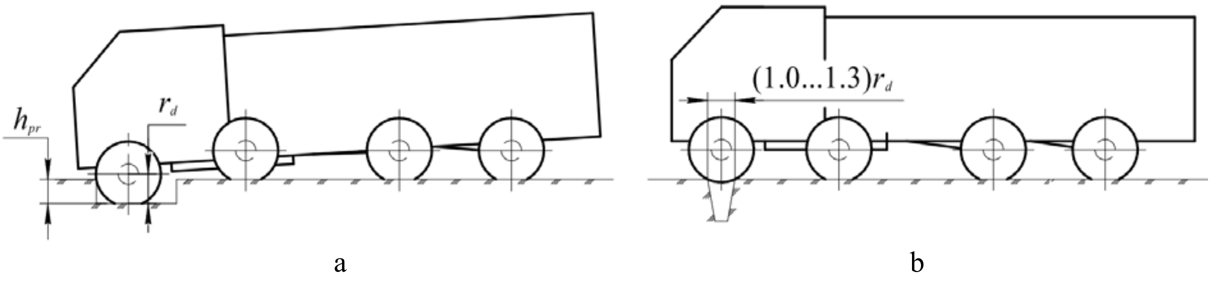
It is known that the longitudinal mobility of a vehicle, including when overcoming the maximum width of a ditch, depends on the radius of the vehicle's wheel. If the depth of the ditch does not exceed the radius of the wheel, the ability to overcome it is determined by the size and type of the vehicle's wheels. In this case, overcoming the ditch consists of sequentially overcoming a step (lip) with a height h_{pr} (see Fig. 4a). The ability to overcome a deep ditch is determined by the size and type of wheels, the number and arrangement of the drive axles (see Fig. 5), and the position of the center of gravity along the length of the vehicle. In multi-axle vehicles, the position of the center of gravity depends on the coordinates of the axle locations and the weight-geometric parameters.

For high-mobility vehicles, if the center of gravity is not located above one of the middle axles, the width of the ditch (with firm edges) that can be crossed does not exceed 1.0 to 1.3 times the radius of the wheel (see Fig. 4b).



a b

Fig. 3. Tracks of the front and rear wheels of the vehicle: a – tracks that do not overlap; b – tracks that overlap; b_{SP}, b_{SZ} – the width of the track of the front and rear wheels, respectively



a b

Fig. 4. Diagrams of overcoming a ditch by a four-axle vehicle: a – a shallow and not high ditch; b – a deep but not wide ditch.

For off-road vehicles with an 8x8 wheel configuration, the width of the ditch that can be crossed depends on the placement of the wheel axles and the vehicle's center of gravity (Fig. 5). The lowest mobility is found in vehicles with two front and two rear axles placed closely together (see Fig. 5a), while the best mobility is achieved in vehicles with three closely spaced rear axles (see Fig. 5d). In this case, the suspension design should limit the lowering of the wheels, and the vehicle's center of gravity should be positioned between the middle axles. These statements apply to classic vehicles where the axles do not have the ability to rotate relative to the vehicle’s longitudinal plane of symmetry.

The vehicle's mobility can be improved for the configuration shown in Fig. 2.5a by implementing special steering mechanisms (see Fig. 6) in the wheel steering mechanism. These allow the direction of movement of the vehicle to be adjusted relative to its longitudinal plane of symmetry. Such technical solutions for the configuration depicted in Fig. 5a or 5b or 5c not only enable changes in the vehicle's direction of movement but also enhance its maneuverability.

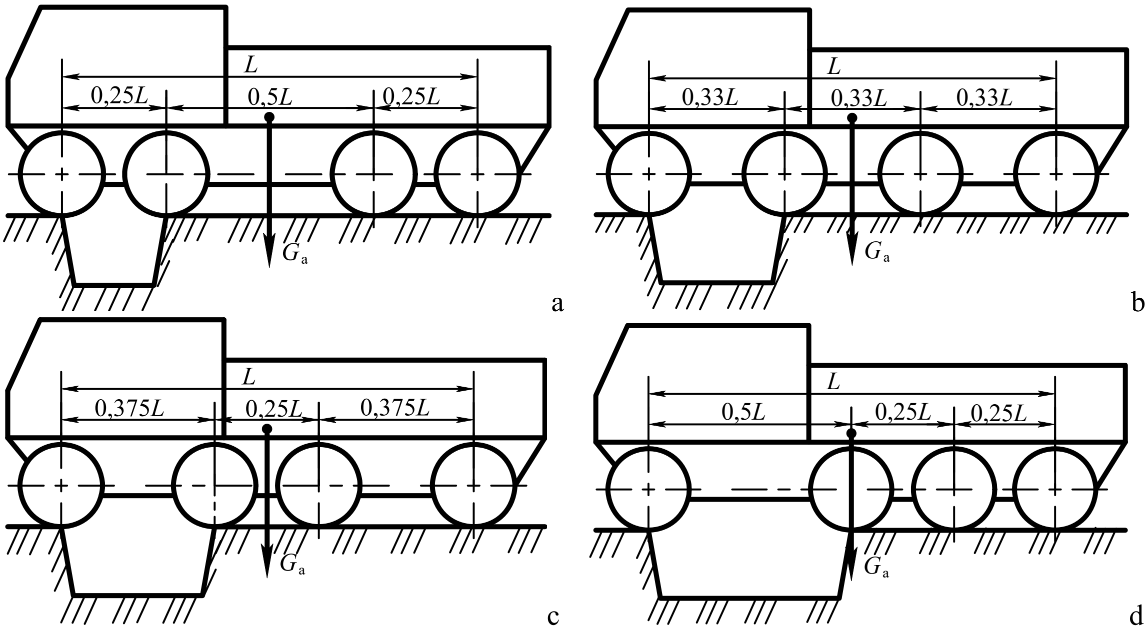


Fig. 5. Diagrams of ditch crossing by multi-axle vehicles

a b

Fig. 6. Wheel steering systems: a – e-Corner system from Hyundai; b – wheel steering system from Tatra

Theory of axle spacing selection for a four-axle off-road vehicle with swivel bogies

To determine the coordinates of the center of gravity of a four-axle vehicle with steering axles, we will use the force diagram acting on an n-axle wheeled vehicle, as proposed in the work [10]. This approach provides a framework for analyzing the forces and moments that influence the position of the center of gravity.

From the diagram (Fig. 7), it can be observed that the coordinates of the center of gravity are directly influenced by the positions of the vehicle's axles and the distribution of weight across these axles. The way the weight is distributed, both in terms of the number of axles and their arrangement, plays a crucial role in determining how the forces act on the vehicle during motion and braking. Additionally, the type of suspension system and load-bearing configuration can further affect the overall balance and performance of the vehicle.

Thus, the accurate calculation of these coordinates requires a detailed understanding of the vehicle's structural design and load distribution characteristics.

In Figure 7, the following are denoted: R_{S1} – virtual normal road reaction acting on the virtual front axle of the vehicle, N; R_{S2} – virtual normal road reaction acting on the virtual rear axle of the vehicle, N; R_{z1} and R_{z2} – vertical load on the first and second front axles of the four-axle vehicle, N; R_{z3} and R_{z4} – vertical load on the first and second rear axles of the four-axle vehicle, N; ΔR_{z1} and ΔR_{z2} – respective increments in the normal load on the first and second front axles of the four-axle vehicle, N; ΔR_{z3} and ΔR_{z4} – respective increments in the normal load on the first and second rear axles of the four-axle vehicle, N; R_{x1} and R_{x2} – braking forces generated between the road surface and the tires of the first and second front axle wheels, N; R_{x3} and R_{x4} – braking forces generated between the road surface and the tires of the first and second rear axle wheels of the vehicle, N; $L_{1,2}$ and $L_{3,4}$ – distances between the respective axles of the four-axle vehicle, m; L_{S1} – distance by which the virtual (theoretical) front axle of the four-axle vehicle is displaced from the last front axle located to the left of the vehicle's center of gravity, m; L_{S2} – distance by which the virtual (theoretical) rear axle of the multi-axle vehicle is displaced from the first rear axle located to the right of the vehicle's center of gravity, m; L_S – distance by which the first rear axle is displaced from the last front axle of the multi-axle vehicle, m; x and y – distances from the vehicle's body pivot center to the last front and first rear axles of the multi-axle vehicle, m; Δb – distance by which the spring system's center of elasticity is displaced from the center of gravity of the multi-axle vehicle, m; h_g – the height of the vehicle's center of gravity relative to the road surface.

The maximum allowable vertical coordinate (h_g) of the center of gravity for a four-axle wheeled vehicle with steering axles is determined based on the diagram shown in Figure 8.

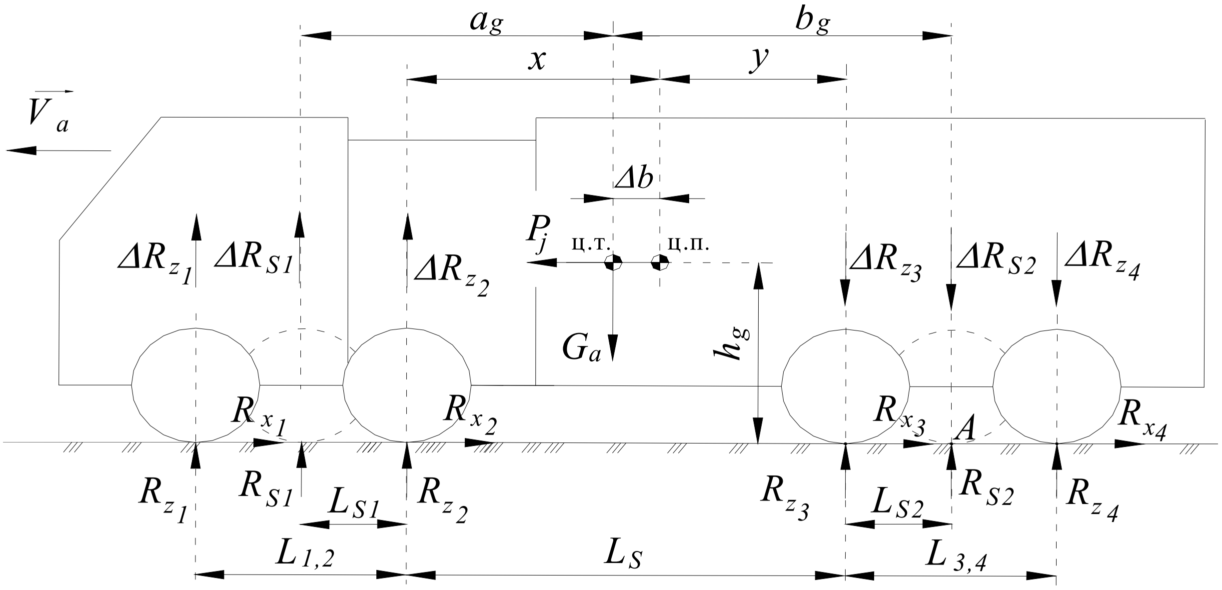


Fig. 7. Calculation diagram of forces acting on a four-axle wheeled vehicle during its braking [10]

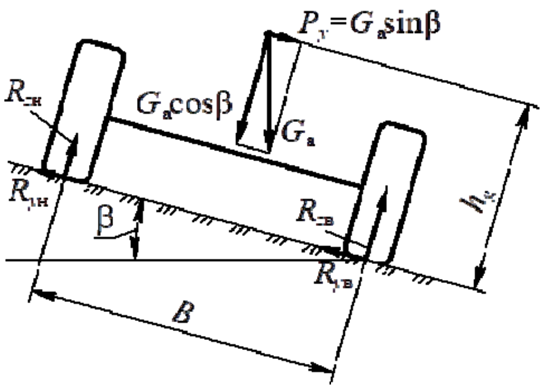


Fig. 8. Diagram for determining the coordinate h_g based on the critical angle of the road's transverse slope

Given that β = β_{op}, and considering that the critical angle of the road's transverse slope for trucks is no more than 30–40 degrees, from equation (1), the following applies

$$h_g = \frac{0.5 \cdot B}{\tan\left(\beta_{op}\right)}; \rightarrow h_g^{\max} \approx 0.6 \cdot B\,, \tag{1}$$

where B is the track width of the steering axle of the four-axle vehicle.

From the force diagram shown in Figure 7, it is evident that the distances L_{S1} and L_{S2} are directly related to the coordinates a_g and b_g, which represent the position of the system's center of elasticity (the roll center of the four-axle vehicle's body), assuming the vehicle body to be a completely rigid structure.

Thus, the distances L_{S1} and L_{S2} can be determined using the equation provided in [10].

$$L_{S1} = a_g - x + \Delta b\,, \tag{2}$$

$$L_{S2} = b_g - y - \Delta b\,. \tag{3}$$

The coordinates a_g, b_g, x, and y can be determined from equations (4) – (8) [10] by formulating the equations of moments relative to the center of gravity of the four-axle vehicle with steering axles and expressing the left and right sides of the resulting equation through the weight-geometric parameters of the vehicle.

$$x = L_S - y\,, \tag{4}$$

$$y = \frac{a_g \cdot \left(R_{z1} + R_{z2}\right) - L_{3,4} \cdot R_{z4}}{R_{z3} + R_{z4}}\,, \tag{5}$$

$$a_g = \frac{\left(L_S - \Delta b\right) \cdot \left(R_{z3} + R_{z4}\right) - L_{3,4} \cdot R_{z4}}{R_{z1} + R_{z2} + R_{z3} + R_{z4}} + \frac{L_{1,2} \cdot \left(R_{z3} + R_{z4}\right) \cdot R_{z1}}{\left(R_{z1} + R_{z2} + R_{z3} + R_{z4}\right) \cdot \left(R_{z1} + R_{z2}\right)}\,, \tag{6}$$

$$b_g = \frac{\left(L_S - \Delta b\right) \cdot \left(R_{z1} + R_{z2}\right) + L_{1,2} \cdot R_{z4}}{R_{z1} + R_{z2} + R_{z3} + R_{z4}} + \frac{L_{3,4} \cdot \left(R_{z1} + R_{z2}\right) \cdot R_{z4}}{\left(R_{z1} + R_{z2} + R_{z3} + R_{z4}\right) \cdot \left(R_{z3} + R_{z4}\right)}\,, \tag{7}$$

$$\Delta b = x - \frac{L_S \cdot \left(C_3 + C_4\right) + L_{3,4} \cdot C_4 - L_{1,2} \cdot C_1}{C_1 + C_2 + C_3 + C_4}\,. \tag{8}$$

where C_1, C_2, C_3 and C_4 are the respective stiffness coefficients of the suspensions of the corresponding axles of the four-axle wheeled vehicle, measured in N/m.

Thus, all the components required to determine the coordinates of the center of gravity of the four-axle wheeled vehicle are defined. Based on these, the increments in normal axle loads during acceleration or braking can also be calculated.

Stiffness coefficients play a crucial role in the dynamic behavior of the vehicle, as they influence load transfer and stability during various maneuvers. Additionally, understanding the distribution of normal loads on the axles during acceleration or braking allows for better suspension tuning, improved handling characteristics, and enhanced overall vehicle performance.

Features of the suspension system implementation for a four-axle off-road vehicle with swivel bogies

The implementation of the suspension system for a four-axle vehicle with swivel bogies, which allows it to turn at a 90-degree angle, is not possible without considering the geometric parameters that limit its suspension travel, as well as the specifics of the vehicle's center of gravity placement and the geometric parameters of the axles located on swivel bogies.

To ensure the stability of the four-axle wheeled vehicle's movement sideways, at a 90-degree angle to the vehicle's longitudinal axis of symmetry, its wheelbase was chosen as the geometric parameter for the axle positioning within the swivel bogies. Based on this geometric parameter, and considering the maximum displacement of the wheel, an independent torsion suspension system was selected for the swivel bogies wheels. Unlike other suspension types, this system has minimal dimensions and allows for independent suspension of all swivel bogies wheels. In the implementation of the suspension system swivel bogies wheels, the concept of placing the torsion bar at the lower part of the swivel bogies was chosen, as the upper part of the swivel bogies houses the mechanism that provides the steering function, preventing the torsion bar from being placed at the top (see Fig. 9). The chosen suspension scheme for the drive wheels of the swivel bogies also allows for the implementation of an electric drive for all the swivel bogies wheels, ensuring independent control of each wheel and enabling the swivel bogies to turn up to 90 degrees relative to the longitudinal axis of symmetry running along the frame of the four-axle vehicle.

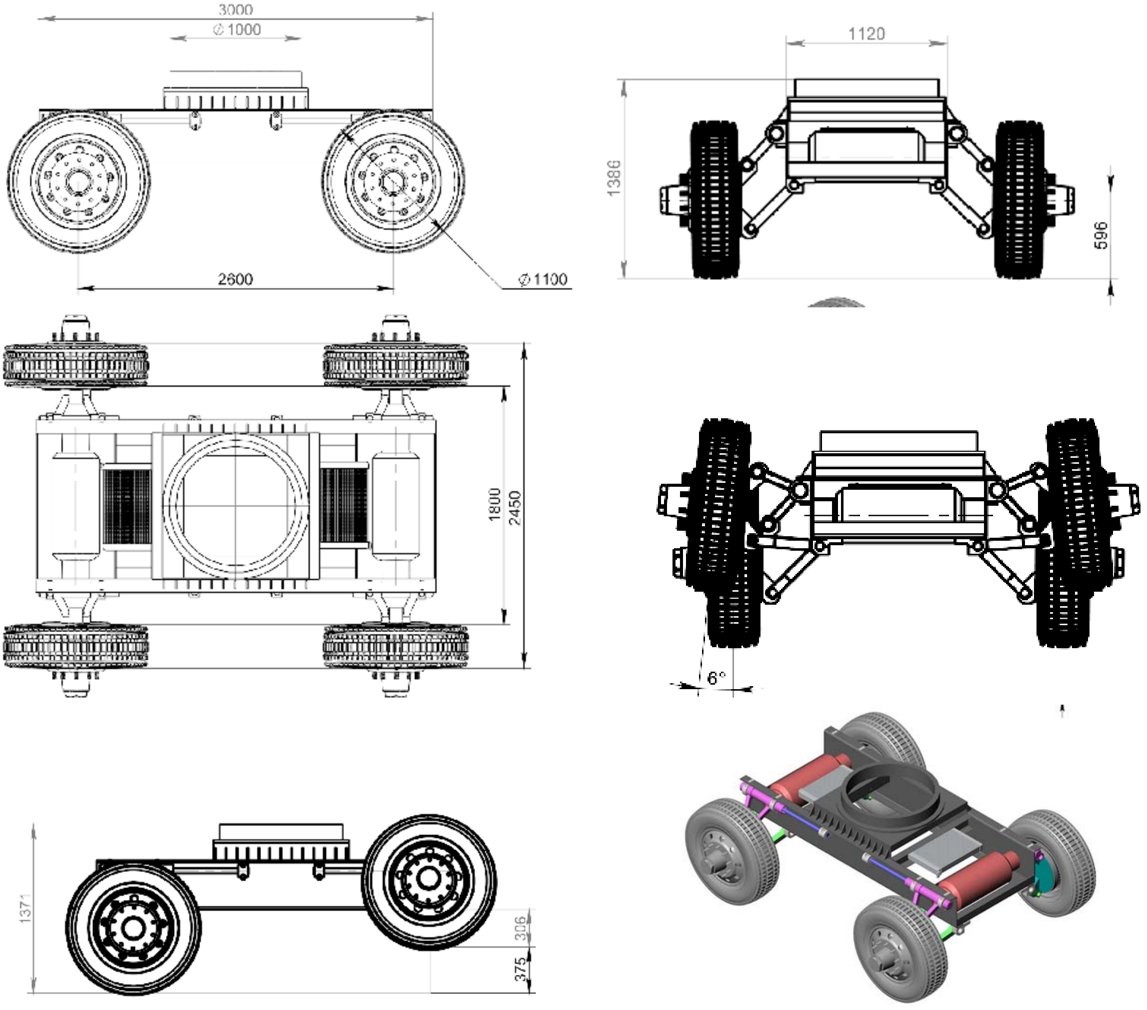


Fig. 9. Overall and geometric dimensions of wheel movement in an independent torsion suspension system of the wheels swivel bogies

Creation of a 3D model of a four-axle vehicle with a combined electromechanical drive

Using modern computer 3D modeling systems, it is not difficult to construct individual components of a vehicle, including those with kinematic connections to moving and non-moving parts.

These automated or semi-automated computer systems allow not only the evaluation of mutual kinematic movements of elements relative to each other but also the determination of the dynamic parameters of these elements within the vehicle. However, it is essential first to establish the concept for vehicle design.

The concept for creating a 3D model of a four-axle vehicle with a combined electromechanical drive and independent suspension for its drive wheels involves the following considerations:

1. High Off-Road Capability: The designed vehicle (Fig. 10) should have exceptional off-road performance, featuring an independent electromechanical drive for the drive wheels, independent suspension for each wheel, and a steering system based on swivel bogies.

2. Powerful Engine Placement: A preliminary sketch of the vehicle revealed the need for a powerful engine that could be integrated within the vehicle's frame. Thus, an opposed engine with multiple generators was proposed to generate the electrical energy required for the electromechanical drive of the wheels.

3. Battery and Auxiliary Systems: Provisions must be made for the placement of batteries, elements of an environmental temperature regulation system to ensure stable battery operation, and energy management systems to monitor energy consumption and reserves.

4. Fuel and Cooling Systems: Space must also be allocated for the fuel tank and systems for air purification and cooling before it enters the internal combustion engine cylinders.

5. Integrated Design of Steering Components: Due to spatial constraints and the geometric limitations of the vehicle, certain elements of the electromechanical wheel drive system should be integrated into the swivel bogies. For instance, components such as collectors and some elements of the steering system with an electromechanical wheel drive can be housed within the bogie frame.

This comprehensive approach ensures that the 3D model accurately represents the structural, functional, and spatial requirements of a high-performance, off-road capable, four-axle vehicle.

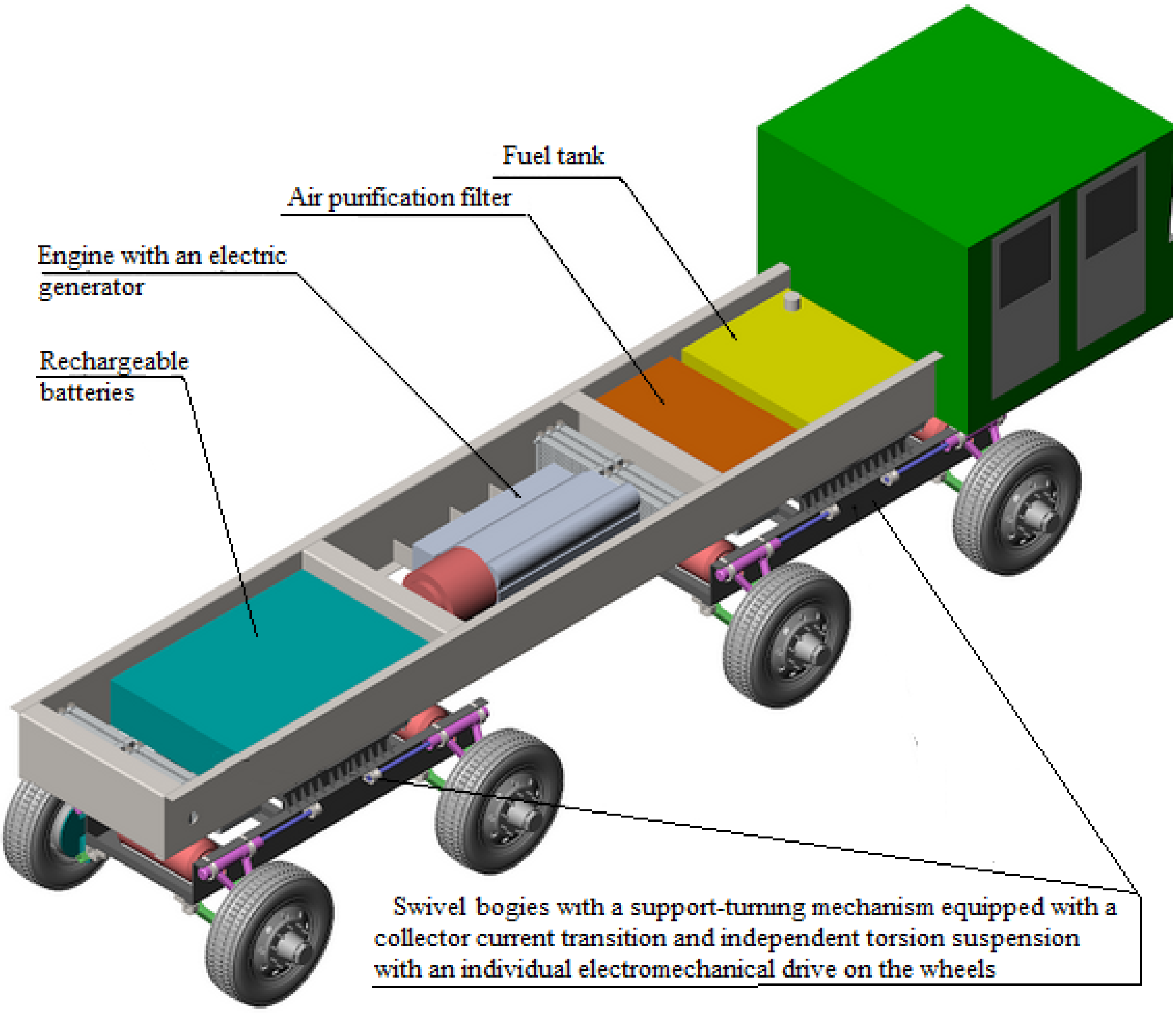


Fig. 10. General view of a four-axle vehicle with swivel bogies (3D model)

Analysis of the maneuverability of a four-axle vehicle with swivel bogies

The attachment of a swivel bogie to the frame of a four-axle vehicle enables modeling its maneuverability under various operating conditions, including off-road scenarios, based on the geometric parameters of the suspension components' movement.

For example, when overcoming an obstacle such as a ditch or trench, as shown in Figure 11, two swivel bogies attached to the frame can provide a maximum longitudinal passability radius of no more than 29 meters, with an entry angle to the obstacle not exceeding 11 degrees, assuming all vehicle wheels remain in contact with the road surface.

If some wheels are assumed to lose contact with the road surface, the entry angle of the four-axle vehicle can increase to 41 degrees (Figure 12).

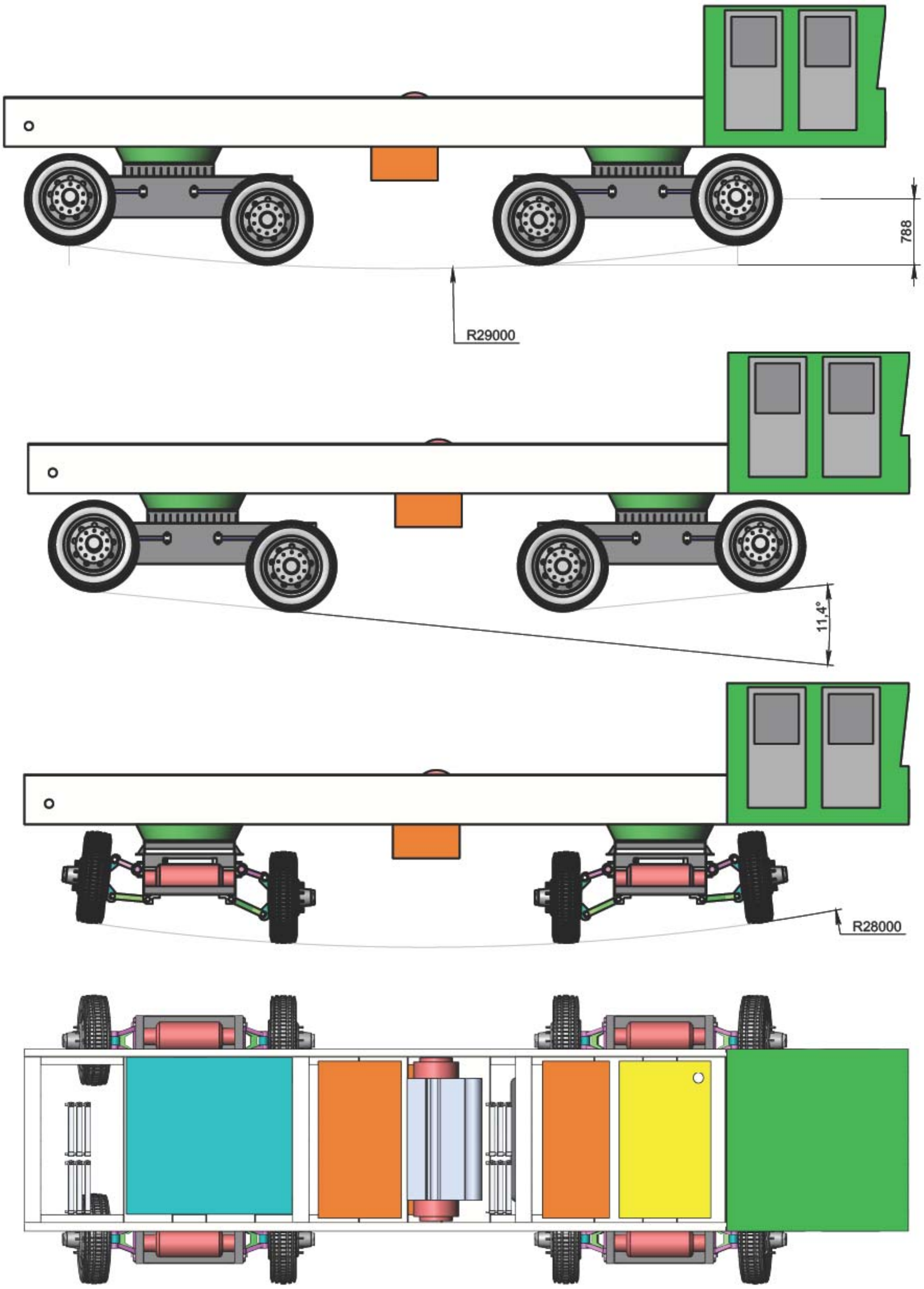


Fig. 11. Geometric parameters for overcoming an obstacle, such as a ditch or trench, by a four axle vehicle

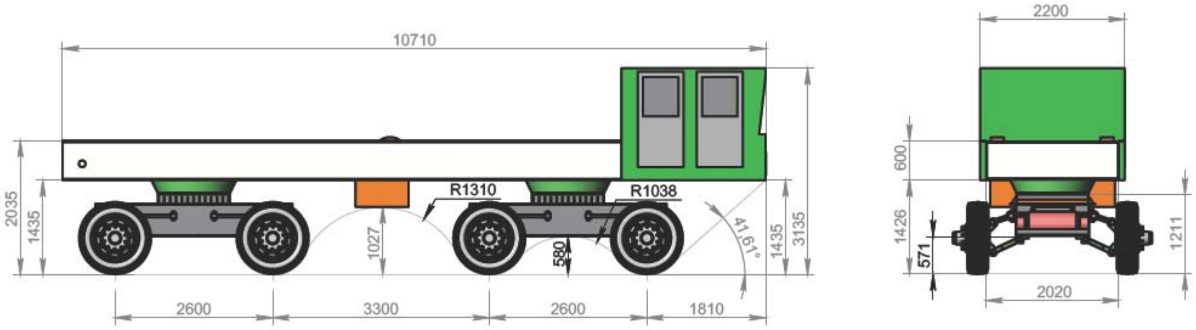


Fig. 12. Geometric parameters of a four-axle vehicle with swivel bogies that characterize its maneuverability off-road

When overcoming an obstacle in the form of a hill or embankment (Fig. 13), two swivel bogies attached to the frame can provide a maximum longitudinal passability radius of no more than 30 meters when the bogies are positioned parallel to the vehicle's frame.

This is the case when the vehicle is moving along a flat surface, and the bogies are aligned with the direction of travel. However, when the vehicle moves along the hill or embankment, with the bogies turned 90 degrees relative to the longitudinal direction of the vehicle's frame, the maximum passability radius is reduced to no more than 25 meters.

It should be noted that turning the bogies 90 degrees allows for improved passability of the four-axle vehicle when overcoming obstacles such as a ditch (trench) or a hill (earth embankment). This is due to the increased maneuverability provided by the bogies when they are rotated relative to the vehicle's frame. The displacement of the outermost point of the bogie in this case does not exceed 4.2 meters (Fig. 14).

This enhanced maneuverability allows the vehicle to navigate more difficult terrain with greater ease, making it more versatile in off-road conditions and providing better adaptability when facing various types of obstacles, especially when the bogies are adjusted to optimize the vehicle's approach angle and ground clearance. As a result, the four-axle vehicle can maintain stability and efficiency while navigating hills, embankments, and ditches, even when confronted with challenging off-road environments.

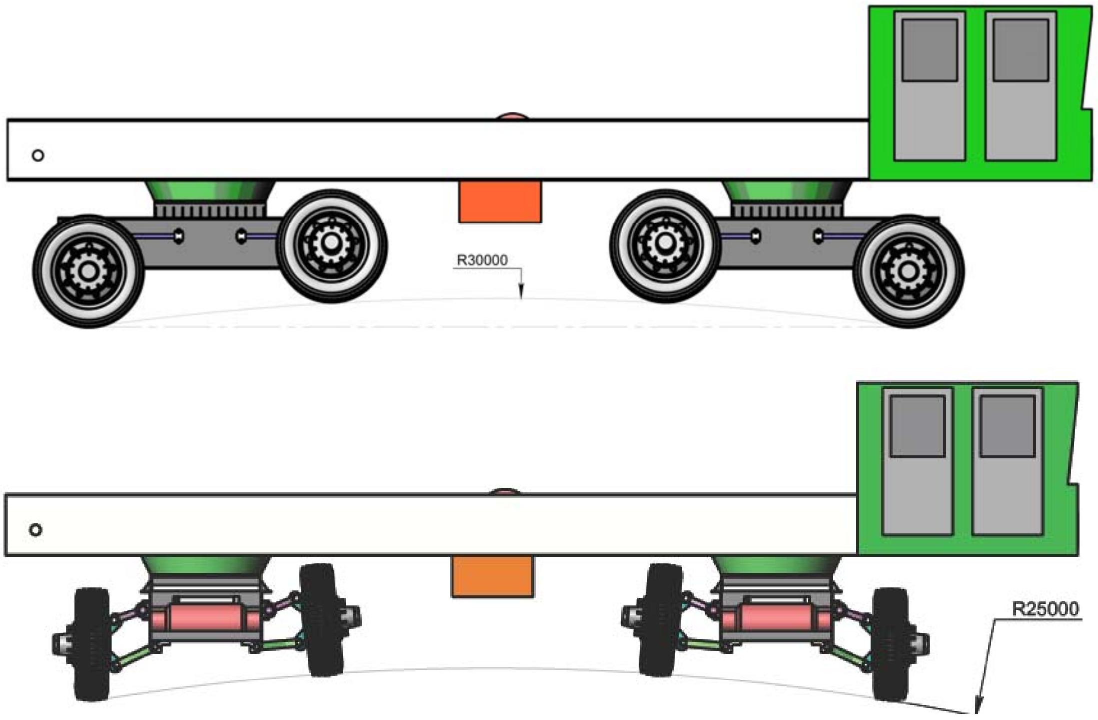


Fig. 13. Geometric parameters for overcoming an obstacle in the form of a hill or embankment

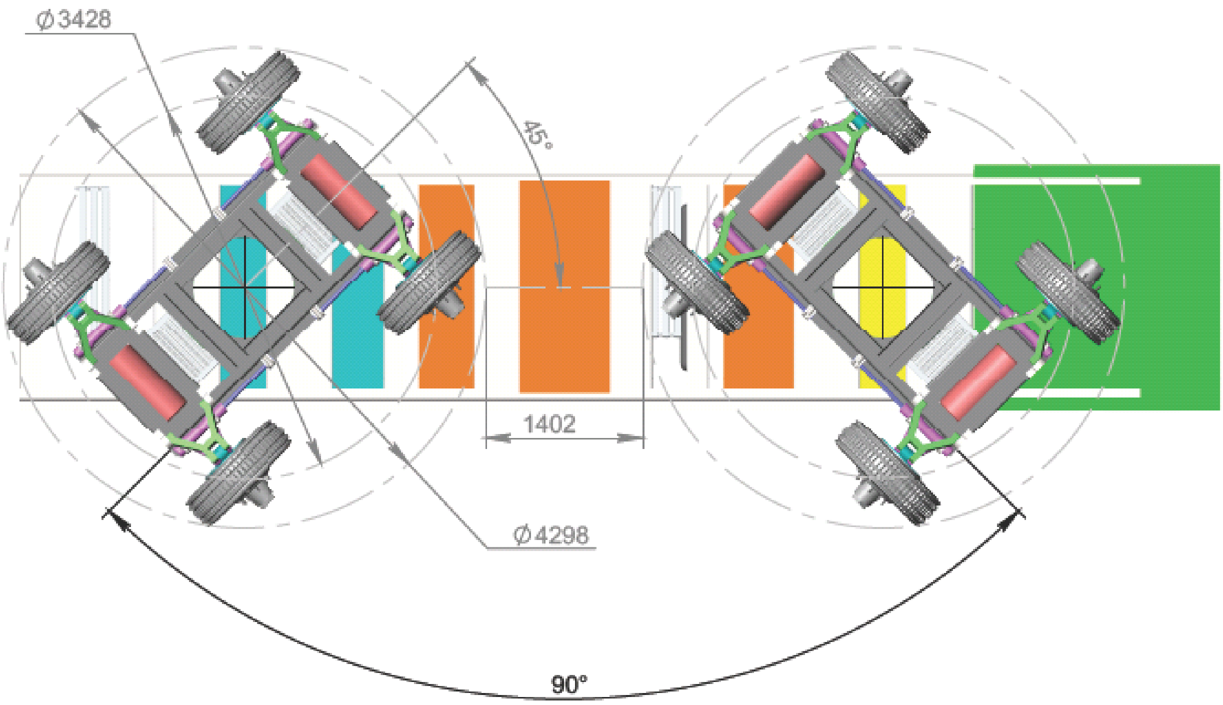


Fig. 14. Maximum geometric parameters of the bogie rotation relative to the vehicle frame

Therefore, the maneuverability of a four-axle vehicle with swivel bogies and an electromechanical drive for the driven wheels provides significant flexibility and efficiency when moving through difficult and confined terrain. The swivel bogies allow for a reduced turning radius, which is crucial for maneuvering in tight spaces or off-road conditions. Thanks to the individual electromechanical drive for the driven wheels, each wheel can operate independently, enhancing the stability and controllability of the vehicle when changing direction. This solution significantly reduces energy consumption when moving across complex sections and improves the vehicle's passability. Furthermore, the electric drive enables precise and smooth control, helping to maintain optimal traction during movement over challenging obstacles.

The swivel bogies contribute to an even distribution of load across the wheels, which in turn increases the durability and longevity of the chassis. Combined with the independent torsion suspension, this design allows the vehicle to effectively overcome both flat and uneven terrain. It also maintains stability even at higher speeds, making the vehicle versatile for different operating conditions. Thanks to these technical solutions, the four-axle vehicle with swivel bogies and an electromechanical drive can be effectively used in various industries where high maneuverability and reliability are required.

These characteristics make it ideal for use on challenging routes, in urban environments, and on off-road terrain.

Conclusion

Based on the analysis of the maneuverability of a four-axle vehicle with swivel bogies and an electromechanical drive for the driven wheels, several key conclusions can be drawn.

1. High maneuverability in challenging conditions: The four-axle vehicle with swivel bogies and an electromechanical drive for the driven wheels can provide a maximum longitudinal passability radius of up to 30 meters when the bogies are parallel to the frame, ensuring maneuverability in confined areas or off-road conditions.
2. Minimization of the turning radius at large steering angles: Thanks to the ability to rotate the bogies by 90 degrees, the vehicle can reduce the passability radius to 25 meters when moving along a hill or embankment, effectively overcoming obstacles with minimal space requirements.
3. Improved passability in obstacle conditions: The swivel bogies and electromechanical drive for the driven wheels enhance passability over obstacles such as ditches or trenches, allowing the vehicle to overcome obstacles at maximum entry angles of up to 41 degrees when some wheels may lose contact with the surface.

4. Optimization of energy consumption and maneuverability: The individual electro-mechanical drive for each wheel reduces energy consumption when moving over complex sections while improving maneuverability through precise and smooth control, especially in difficult terrain.

5. Stability at high speeds: The independent torsion suspension and the reduced movement of the outermost point of the bogie, up to 4.2 meters, ensure the vehicle's stability even at high speeds, making it versatile and reliable for various operating conditions.

Confirmation.

The work was carried out within the framework of the scientific research topics of the Department of Vehicles named after A.B. Gredeskul at the Kharkiv National Automobile and Highway University.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

1. Zeng, D., Luo, W., Yu, Y., Hu, Y., Zhang, P., Carbone, G., Xie, D., Fang, H., & Gao, L. (2024). Dynamic Analysis and Equivalent Modeling for a Four-Axle Vehicle. *Actuators*, 13(12), 473. https://doi.org/10.3390/act13120473
2. Stańco, M., & Kowalczyk, M. (2022). Analysis of Experimental Results Regarding the Selection of Spring Elements in the Front Suspension of a Four-Axle Truck. *Materials*, 15(4), 1539. https://doi.org/10.3390/ma15041539
3. Yin, D., Wang, J., Du, J., Chen, G., & Hu, J. -S. (2021). A New Torque Distribution Control for Four-Wheel Independent-Drive Electric Vehicles. *Actuators*, 10(6), 122. https://doi.org/10.3390/act10060122
4. Li, W., Yang, F., Mao, E., Shao, M., Sui, H., & Du, Y. (2022). Design and Verification of Crab Steering System for High Clearance Self-Propelled Sprayer. *Agriculture*, 12(11), 1893. https://doi.org/10.3390/agriculture12111893
5. Liu M., Huang J. and Cao M., (2018). Handling Stability Improvement for a Four-Axle Hybrid Electric Ground Vehicle Driven by In-Wheel Motors, *in IEEE Access*, 6, 2668-2682, https://doi.org/10.1109/ACCESS.2017.2784836
6. Podrigalo, M., Artiomov, N., Garmash, V., Horielyshev, S., Boikov, I., Baulin, D., Nakonechnyi, A., Sukonko, S., Gleizer, N., & Yurieva, N. (2023). Improving the maneuverability of vehicles by using front swivel axles with separate electric wheels. *EUREKA: Physics and Engineering*, (3), 29-39. https://doi.org/10.21303/2461-4262.2023.002838
7. Lee, S., Cho, H., & Nam, K. (2024). Dynamic Modeling and Control of a 4-Wheel Narrow Tilting Vehicle. *Actuators*, *13*(6), 210. https://doi.org/10.3390/act13060210
8. Bogomolov, V., Klimenko, V., Leontiev, D., Frolov, A., Suhomlyn, O., & Kuripka, O. (2021). Features of braking of multi-axle vehicles depending on the layout of their axles. *Automobile Transport,* (49), 23–35. https://doi.org/10.30977/AT.2019-8342.2021.49.0.04
9. Yun-Jui Chung, Chung-Hsien Chuang, Yung-Chi Chang, and Tyng Liu (2020) Study of a steering model for 4-axle 8×8 off road vehicles. *International Journal of Heavy Vehicle Systems* 27:5, 663-682 https://doi.org/10.1504/IJHVS.2020.111257
10. Леонтьєв, Д. М. (2021). *Теоретичні основи гальмування багатовісних транспортних засобів з електропневматичною гальмовою системою*. Харківський національний автомобільно-дорожній університет. Leontiev, D. M. (2021). *Teoretychni osnovy halmuvannia bahatovisnykh transportnykh zasobiv z elektropnevmatychnoiu halmovoiu systemoiu* [Theoretical basics of braking of multi-axle vehicles with an electropneumatic braking system]. *Harkovskiy natsionalnyiy avtomobilno-dorozhnyiy universitet.*
11. Тімонін, В. О., Савчук, А. Д., Губарьков, С. С., & Леонтьєв, Д. М. (2019). Оцінка ефективності гальмування чотиривісного транспортного засобу в разі виходу з ладу одного з контурів його робочої гальмової системи. *Автомобіль і Електроніка. Сучасні Технології*, *16*, 26-34. Timonin, V. O., Savchuk, A. D., Hubarkov, S. S., Leontiev, D. M. (2019). Otsinka efektyvnosti halmuvannia chotyryvisnoho trans-portnoho zasobu v razi vykhodu z ladu odnoho z konturiv yoho robochoi halmovoi systemy [Evaluation of the braking efficiency of a four-axle vehicle in the event of failure of one of the circuits of its service brake system]. *Avtomobil i Elektronika. Suchasni Tekhnolohii*, 16, 26-34. https://doi.org/10.30977/VEIT.2019.16.0.26
12. Bogomolov, V. O., Klimenko, V. I., Leontiev, D. M., Kuripka, O. V., Frolov, A. A., & Don, E. Y. (2021). Features of adaptive brake control of the secondary brake system of a multi-axle vehicle. *Automobile Transport*, *48*, 27–37. https://doi.org/10.30977/AT.2219-8342.2021.48.0.27
13. Bogomolov, V. O., Klimenko, V. I., Leontiev, D. M., Frolov, A. A., Suhomlin, O. S., & Kuripka, O. V. (2021). Features of braking of multi-axle vehicles depending on the layout of their axles. *Automobile Transport*, *49*, 23–35. https://doi.org/10.30977/AT.2019-8342.2021.49.0.04
14. Leontiev, D., Klimenko, V., Mykhalevych, M., Don, Y., & Frolov, A. (2019). Simulation of Working Process of the Electronic Brake System of the Heavy Vehicle. *International Scientific-Practical Conference*, *1019*, 50–61. https://doi.org/10.1007/978-3-030-25741-5_6

15. Подригало, М. А., Бережний, А. О., Дубінін, Є. О., & Рогозін, І. В. (2023). Оцінка статичної стійкості багатовісних автомобільних шасі з чотирьохколісними поворотними платформами. *Системи озброєння і військова техніка*, (3 (75), 21-27. Podryhalo, M. A., Berezhnyi, A. O., Dubinin, Ye. O., & Rohozin I. V. (2023). Otsinka statychnoi stiikosti bahatovisnykh avtomobilnykh shasi z chotyrokhkolisnymy povorotnymy platformamy. Systemy ozbroiennia i viiskova tekhnika, [Assessment of static stability of multi-axle automobile chassis with four-wheeled swivel platforms] *Weapons systems and military equipment,* (3 (75), 21-27. https://doi.org/10.30748/soivt.2023.75.02

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Маневреність і прохідність чотиривісного транспортного засобу з поворотними візками та колесами з електроприводом

Анотація. Проблема. *Питання маневреності та прохідності чотиривісних транспортних засобів полягають у забезпеченні їх ефективної роботи на складних ділянках місцевості, у вузьких чи обмежених просторах, а також в умовах складної експлуатації. Основними проблемами є зменшення радіусу повороту, досягнення рівномірного розподілу навантаження по осях і мінімізація енергетичних витрат під час руху. Крім того, необхідно забезпечити надійну роботу всіх компонентів трансмісії, особливо за умов підвищеного зношування та впливу зовнішніх факторів.* ***Мета.*** *Метою дослідження є розробка та обґрунтування технічних рішень, спрямованих на поліпшення маневреності та прохідності чотиривісних транспортних засобів шляхом оптимізації конструкції ходової частини, впровадження інноваційних приводів та удосконалення системи керування. Це забезпечить ефективну експлуатацію транспортних засобів в складних умовах, підвищить їх енергоефективність і надійність, а також розширить сферу їх застосування.* ***Методологія.*** *Методологія реалізації маневреності та прохідності чотиривісного транспортного засобу з поворотними візками та електричним приводом коліс включає аналіз і моделювання поведінки транспортного засобу за різних умов експлуатації, а також оптимізацію систем приводу та керування для забезпечення високої ефективності руху на складних маршрутах.* ***Результати.*** *Результати дослідження маневреності та прохідності чотиривісного транспортного засобу з поворотними візками та електричним приводом коліс дозволили покращити ефективність поворотів такого транспортного засобу на складних ділянках місцевості з крутих схилів та нерівних поверхнях без дорожнього покриття. Завдяки оптимізації конструкції візків і впровадженню електричних приводів коліс вдалося зменшити вагу та геометричні параметри транспортного засобу, що дозволяє здійснювати точніші маневри в обмежених просторах при збереженні стабільного руху з достатньо високою прохідністю та маневреністю чотиривісного транспортного засобу.* ***Оригінальність.*** *Оригінальність дослідження полягає в комплексному підході до поліпшення маневреності та прохідності чотиривісного транспортного засобу з поворотними візками та електричним приводом коліс. Вперше застосовано інноваційні методи оптимізації конструкції ходової частини та впровадження електричних приводів, що значно зменшило енергетичні втрати та покращило керування рухом на складних ділянках місцевості. Нові підходи до моделювання руху забезпечили високу ефективність маневрування за різних умов експлуатації. Ці результати відкривають нові можливості для застосування таких транспортних засобів у спеціалізованих галузях, де вимоги до прохідності та маневреності є надзвичайно високими.* ***Практична цінність.*** *Практична значущість дослідження полягає в потенційній реалізації розроблених технічних рішень у виробництві чотиривісних транспортних засобів для експлуатації в складних умовах, таких як будівництво, сільське господарство та військові застосування. Розроблені вдосконалення дозволяють підвищити ефективність роботи техніки, зменшити енергоспоживання, а також забезпечити високу маневреність і прохідність на важких маршрутах.*

Ключові слова: *маневреність, прохідність, чотиривісний транспортний засіб, поворотні візки, електромеханічний привід, розробка, моделювання.*

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