Machinery & Energetics
Vol. 16, No. 2. 2025

Journal homepage:
https://technicalscience.com.ua/en

UDC 631.372:004.942
Doi: 10.31548/machinery/2.2025.159

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# Modelling of dynamic characteristics of tractor systems to improve stability on uneven fields

**Abstract.** The study aimed to determine the impact of the centre of mass shift, the angle of inclination of the terrain and local disturbances on the spatial stability of the transport system, with the subsequent determination of its equilibrium limit modes. The methodology was based on a combination of theoretical modelling, adaptive control and multi-level validation in a changing environment. The critical vertical displacement of the hull was found to be up to 0.15 m at an 18° tilt due to the asymmetric passage of obstacles, which confirmed the need for accurate dynamics prediction. Stability analysis has established safe roll angles of 25-30° for Ukrainian black soil (friction coefficient 0.6-0.8). The uneven load and soil moisture content (20-30%) affected stability, requiring model calibration. Hybrid methods compensated for seat vibrations by adaptively controlling the damper. Adaptive ground contact improved traction on soft ground, while nonlinear predictive steering optimised the trajectory on slopes. The expediency of the geometry of the reference plane and the position of the centre of mass when developing algorithms for stabilising agricultural machinery, given the impact on stability in variable

Article's History: Received: 27.12.2024; Revised: 31.03.2025; Accepted: 22.05.2025.

**Suggested Citation**:
Duhanets, V., Fedirko, P., Hovorov, O., Pukas, V., & Volynkin, M. (2025). Modelling of dynamic characteristics of tractor systems to improve stability on uneven fields. *Machinery & Energetics,* 16(2), 159-174 doi: 10.31548/machinery/2.2025.159.

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terrain, was established. Stochastic modelling of soil disturbances was used to predict the impact of random environmental changes on the trajectory and stability of the equipment. The proposed theoretical model is suitable for the design and dynamic hull control systems, especially for operation on slopes and complex geometries. The integration of sensor systems with models ensured adaptation to real-time conditions. The practical value of the results was to improve the safety of agricultural machinery and optimise its spatial orientation on slopes by process engineers and developers of active levelling systems when designing new generation machinery

**Keywords**: acceleration; grip coefficient; field testing; stabilisation; adaptive control

## INTRODUCTION

Ensuring the stable operation of transport systems on uneven terrain is a critical condition for increasing the efficiency of agricultural machinery and reducing the risk of accidents. In many regions of Ukraine, soil cultivation takes place on difficult terrain with variable slopes, local elevations and depressions, which significantly affects the behaviour of machinery in the field. The current trend towards automation and the introduction of unmanned tractor systems also requires a deeper understanding of the patterns of loss of spatial stability in dynamic conditions. Therefore, the problem of predicting unstable modes of operation of machines on complex terrain is becoming increasingly relevant.

In the global scientific discourse, there have been studies on the stability of agricultural machinery on uneven surfaces, in particular in the context of safety, navigation efficiency and the introduction of adaptive stabilisation systems. Y. Chi *et al.* (2024) developed a numerical model that combined three-dimensional electromagnetic sensing with terrain parameters to predict the effect of undulating soil on signal propagation. Despite the specificity of the task (radar technology), the detailed development of the topographic profile and its integration into the simulation is valuable from a methodological point of view, especially for the construction of accurate terrain models and their further use in dynamic modelling of transport systems. W. Tong *et al.* (2024) addressed thermal modelling of the engine compartment of agricultural machinery based on temperature field measurements and airflow simulations. The study demonstrated the possibilities of digital simulation of complex internal processes in technical systems, which was methodologically useful for studying the stability of the hull under variable external loads.

The influence of complex topography on the behaviour of the system under conditions of surface changes was crucial in modelling unstable motion modes. In this context, the natural environment was considered a dynamic factor that changed the geometry of the reference plane. Q. Meng *et al.* (2025) proposed a multi-level model of forest evolution that addressed soil erosion and fire, combining different types of natural dynamics in a single simulation environment. This created the potential to apply similar approaches in technical sustainability analysis. Similarly, G.A. Ruetenik *et al.* (2023) optimised models of global landform evolution using $^{10}$Be isotopic labelling of a naturally labelled isotope to estimate erosion rates and landscape changes. This approach improved the accuracy of predicting unstable zones, which is critical for engineering modelling.

The spatial kinematics of the body and structural constraints played a crucial role in assessing the stability of the machines on slopes and bumps. Accurate modelling of the hull behaviour during rolling allowed the identification of limit states. Y.-J. Yang *et al.* (2024) implemented a dynamic model of a miniature crawler tractor to analyse the risk of rollover, considering the geometry, mass distribution, and slope of the terrain. The authors demonstrated the feasibility of body configuration and contact with the terrain when assessing stability. Similarly, A. Manoharan *et al.* (2024) proposed a two-level optimisation of trajectories on uneven terrain that addressed both the trajectory shape and ground interaction parameters through a refined wheel engagement model. These approaches demonstrated high efficiency for creating stabilisation algorithms, which was a relevant basis for developing models of spatial behaviour of vehicles in complex terrain.

In the Ukrainian scientific discourse, the problem of the stability of transport vehicles in difficult operating conditions remained insufficiently addressed. The limited access to modern test benches and models narrowed the possibilities of modelling critical modes. S. Hrushetskyi *et al.* (2024) proposed the concept of modular control of agricultural machinery, which allowed the machine to adapt to changes in load and conditions. Although the mechanism of spatial loss of balance was not highlighted, the authors' approach laid the groundwork for adaptive regulation of stability parameters. O.Y. Rebrov *et al.* (2023) developed a method for determining the optimal tyre size for wheeled tractors, which indirectly affected stability and traction on difficult terrain. Despite the absence of a full-body position model, their work reflected a desire for engineering detail in ground interaction, which is also relevant for tracked systems.

Despite the progress in the study of agricultural machinery stability, there is still a lack of comprehensive approaches to analysing the spatial dynamics of Tracked Robotic Vehicles (TRV) under conditions of variable surface geometry. Insufficient research has been done on how the centre of mass displacement, roll and pitch angles, as well as local disturbances, affect the stability of the body. This limits the ability to predict the critical modes of operation of machinery in terrain and complicates the formation of recommendations for stabilisation control, which is especially relevant in the context of the agricultural environment of Ukraine.

The study aimed to analyse the dynamic behaviour of a transport system on uneven terrain, incorporating the spatial position of the centre of mass, changes in the angle of inclination of the surface, and interaction with the supporting base to identify the limiting modes of stability loss. To achieve this goal, the effect of the centre of mass displacement on the critical loss of stability of the TRV was investigated. The objectives of the study were to determine the critical conditions for the loss of hull stability by analysing the displacement of the centre of mass, the occurrence of roll and the impact of local disturbances on the hull position; to analyse the effect of the terrain configuration and asymmetric loading on the stability of the movement to formulate technical recommendations for stabilising the hull position.

## MATERIALS AND METHODS

The study was conducted between August 2024 and January 2025. The focus was on an integrated approach to assessing the sustainability of TRVs, addressing regional soil and terrain characteristics, and the practical limitations of agricultural and mining infrastructure. The study included 6 stages. At the first stage, three approaches to assessing TRV sustainability were systematised: analytical, experimental and simulation to identify the strengths and weaknesses of each approach, their suitability for real-world application in Ukraine and the potential for further integration. The choice of these approaches was justified by the need to strike a balance between accuracy (analytical), practical reliability (experimental) and flexibility in modelling complex situations (simulation). The combination of the results of the approaches created the basis for further modelling, control optimisation and validation of TRV behaviour. The second stage was to analyse the dynamics of TRVs on complex terrain, for which four main modelling methods were considered: multibody, concentrated parameter, kinematic and inverse dynamics. The choice of a particular approach was based on accuracy requirements, operating conditions and available computing resources.

At the third stage, hybrid adaptive control methods such as Adaptive Neuro-Fuzzy Inference System (ANFIS), Nonlinear Model Predictive Control (NMPC) and Active Disturbance Rejection Control (ADRC) were presented. These approaches allowed for to improvement of the accuracy of TRV control in variable soil conditions, including wet, compacted and uneven surfaces, and to provide adaptation to changing soil and terrain conditions, increasing modelling accuracy and control efficiency. Additionally, analytical methods based on classical physical models of equilibrium, dynamics and interaction with the ground and engineering criteria were considered to determine critical conditions for loss of stability, rollover moments, and traction capabilities of the equipment.

The fourth stage classified technical solutions for optimising tractor traction on difficult soil types. Three key approaches were considered: adaptive contact systems, flexible chassis and trajectory optimisation algorithms. These solutions were chosen due to their ability to increase stability and efficiency in difficult soil and terrain conditions. This approach comprehensively covered both mechanical and algorithmic aspects of improving traction. In the fifth stage, we characterised the approaches to model validation: field, bench and virtual. Each method was chosen for its ability to provide different levels of accuracy, realism and control. The sixth stage systematised the methods of correction, adaptation and validation of TRV motion models in a changing environment. Methods were selected to improve the accuracy of the models by calibrating them on real data, identifying error limits, using parametric approximations, integrating them with sensor systems for real-time adaptation, and stochastic modelling of ground disturbances. This integrated approach addressed both physical and stochastic factors affecting the movement of the TRV, which was important for improving the reliability and accuracy of the models in real field conditions.

Based on the analysis of the advantages and limitations of existing approaches, a multilevel theoretical model of TRV dynamics is developed, considering the mechanics of movement, interaction with the ground, stochastic disturbances and validation. The model architecture provides for the integration of adaptive control methods (ANFIS, ADRC, NMPC) to compensate for dynamic uncertainty. Validation was carried out by comparing simulation results with field and bench test data. This approach ensured the accuracy of the description of TRV dynamics in complex terrain and created the basis for the development of intelligent control, navigation and stabilisation systems, which is also relevant for the agricultural conditions of Ukraine. The Zotero bibliographic manager was used to process the sources, which ensured the ordering of literature, the accuracy of references and the structured classification of materials. The use of data retrieval, analysis and synthesis methods were used to comprehensively investigate the methods of optimisation and validation of tractor systems' motion and stability models, which identified the key factors of influence of the variable environment and formulated sound recommendations to improve their efficiency.

## RESULTS AND DISCUSSION

TRV driving on slopes and inclined surfaces is a key aspect of efficient operation in difficult terrain, including mountainous areas, agricultural land and areas with limited access. One of the main challenges in such conditions is the high risk of loss of stability, which can lead to rollover, slip or complete loss of control. A critical factor affecting the stability of TRVs is the effect of instantly changing dynamic forces. When driving on sloping terrain, complex combinations of gravitational, inertial and frictional forces arise, depending on the angle of inclination, speed and surface type. These forces change the load distribution between the pivot points, which can lead to a partial loss of traction or destabilisation. Another important factor is the position of the centre of mass. On an inclined surface, the centre of mass shifts relative to the support plane, which reduces the safety margin and increases the likelihood of overturning, especially when the position of the body or attachments changes. Interaction with uneven ground creates additional difficulties. Pits, stones, loose or wet areas can cause the tracks to slip, get stuck or lose contact with the ground. This makes navigation difficult, especially in conditions of limited visibility or autonomous control (Zhou *et al.*, 2023).

Typical problems encountered when driving on slopes include vehicle overturning due to exceeding the permissible angle of inclination, slipping of the tires, especially when braking or making sharp turns, and loss of control when changing the load or speed. All these factors significantly complicate the operation of TRVs in real-world conditions and require the introduction of adaptive control systems, algorithms for predicting machine behaviour, and improved design solutions to increase stability. Ensuring stable and safe movement of TRVs on difficult terrain requires an integrated approach that includes dynamic modelling, environmental assessment, and the development of intelligent control systems capable of adapting the machine's behaviour in real time to changing terrain conditions. Assessing the stability of TRVs on slopes and inclined surfaces is a critical step in ensuring their safe and efficient operation. There are three approaches to stability analysis: analytical, experimental, and simulation, each of which has its advantages and limitations and is used depending on the design stage, the level of available information, and accuracy requirements (Table 1).

**Table 1.** Basic approaches to analysing the stability of tracked vehicles on inclined surfaces

| Method | Description | Advantages | Disadvantages | Application examples | Ukraine aspect |
|---|---|---|---|---|---|
| Analytical | Based on mathematical models that describe the balance of forces (gravitational, inertial, frictional) and moments that affect the stability of TRVs on slopes. Includes analysis of load distribution, centre of mass position and critical tilt angles to prevent tipping or slipping | High accuracy for idealised conditions. The ability to quickly predict critical parameters. Does not require physical testing, which reduces costs | Limited accuracy in difficult soil conditions. Does not cover stochastic factors (for example, changes in humidity). Needs simplification of complex nonlinear interactions | Analysis of the stability of a modular tractor with articulated steering on an uneven surface by modelling the distribution of forces. Estimation of critical tilt angles for a tractor-trailer system with consideration of inertial effects | A model of stability of a machine-tractor unit with a critical angle of inclination of up to 25° for Ukrainian black soil (friction coefficient 0.6-0.8) has been developed. The models are adapted to the various terrains of Ukraine, where the average slope angle is 15-20° |
| Experimental | They consist of field tests using load cells, inertial measuring units and video recording systems to assess the behaviour of TRVs on slopes. Can be used to validate theoretical models and identify real limitations | High data reliability due to real-world conditions. The ability to detect unforeseen factors. A framework for calibrating simulation models | The high cost and complexity of organising tests. Depending on the conditions of the test site. Limited reproducibility due to variable soil conditions | Experimental validation of tractor rollover stability on slopes with different soil conditions. Measuring the vertical dynamic characteristics of a tractor to assess the impact of uneven ground on stability | Tests on clay soils (humidity 20-30%), where the maximum deviation of the tractor's centre of mass was 0.15 m at an inclination of 18°, which confirmed theoretical calculations |
| Simulation | Use numerical modelling (e.g., Matrix Laboratory/ Simulink, Automated Dynamic Analysis of Mechanical Systems, RecurDyn) to create virtual models of the TRV and the environment. Can be used to study different driving scenarios, including inclination angles, ground conditions and dynamic loads | The ability to test a wide range of conditions without risk to the equipment. High flexibility in parameter settings. Saves time and resources compared to experiments | Need for accurate input data and model calibration. High computational complexity for complex systems. Possible discrepancies with real-world conditions due to simplifications | Simulate TRV movement on slopes with varying ground conditions to optimise steering. Modelling tractor dynamics to analyse operator seat vibrations on uneven terrain | RecurDyn simulations have shown that for Ukrainian steppe conditions (traction coefficient 0.7), vibrations of the operator's seat are reduced by 12% when the machine-tractor unit suspension is optimised. The simulations covered terrain irregularities of up to 0.3 m, typical for typical agricultural conditions in Ukraine |

**Source:** compiled by the authors based on B. Zhou *et al*. (2023), P.M. Kolahi & M. Nazemizadeh (2023), M. Belloni *et al.* (2023), H. Singh & M. Mehta (2024), G. Carabin *et al.* (2024), L. Duan *et al.* (2025), V. Nadykto *et al.* (2025)

Analytical, experimental, and simulation methods have been used to analyse the stability of tracked vehicles on sloping surfaces, each with unique advantages and limitations. Analytical methods are accurate for idealised conditions, experimental methods provide reliability in real-world conditions, and simulation methods allow for flexible modelling but are dependent on data quality. In combination, they optimise the stability of machinery in

Ukrainian conditions with slope angles of 15-20° and unevenness of up to 0.3 m.

The choice of a particular model depends on the accuracy requirements of the analysis and the capabilities of computing resources. While multibody models provide the highest accuracy, they also require significant computational resources and simulation time. On the other hand, concentrated parameter models and kinematic models are less computationally demanding, but can be limited in accuracy, especially on complex and variable terrain. To ensure stable and predictable behaviour of tracked vehicles on complex terrain, it is necessary to apply appropriate dynamics models that address both the physical properties of the system and variable terrain conditions. There are several approaches to modelling TRV movement, which differ in the level of detail, computational costs, and scope of application. Table 2 shows the types of models used to analyse the dynamics of tracked vehicles on uneven fields.

**Table 2.** Systematisation of approaches to modelling tractor dynamics on uneven ground

| Approach | Description | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| Multibody dynamics models | The most detailed approach that considers the complex rotational and translational relationships between chassis, suspension, articulated joints and tracked propulsion elements. The models describe the interaction of system components with all degrees of freedom, which allows analysing roll, pitch and rollover on uneven terrain | High accuracy in predicting dynamic behaviour. The ability to integrate complex subsystems (suspension, tracks). Suitable for stability analysis on difficult terrain | High computational complexity, requiring powerful resources. A need for careful calibration for specific soil and topographic conditions. Complex real-time implementation | Simulation of a semi-tracked tractor with articulated steering to assess stability on uneven surfaces, including analysis of the effect of obstacles on roll and pitch. Analysing the dynamics of an unmanned vehicle on uneven terrain to predict ground interaction and assess stability |
| Concentrated parameter models | Simplify the system to a set of masses, elasticities and damping elements. Used to analyse vertical dynamics, such as vibrations of the operator's seat, incorporating stochastic disturbances from uneven terrain | Easy implementation and low computational cost. It can be used in real time for adaptive control. Performance for comfort and vibration assessment | Limited geometric flexibility, which reduces accuracy for complex trajectories. Less detailed consideration of interaction with the soil. Unsuitable for difficult terrain with large gradients | Development of a damping system for a tractor seat that compensates for vibrations from bumps using a magnetorheological damper. Modelling tractor vertical vibrations to optimise operator comfort on uneven agricultural fields |
| Kinematic models | Address the trajectory of the movement without taking into account inertial effects. Used to analyse wheel or track rotation, steering angles and drive train speeds, suitable for SLAM systems | Low computational cost, which facilitates integration. Easy to integrate into navigation systems. Effective for predicting trajectory on flat surfaces | Does not address the effect of uneven ground. Limited accuracy on difficult terrain. Not suitable for stability or perturbation analysis | Planning the path of the tractor-trailer system in the garden environment to ensure precise navigation.<br>Used in an autonomous driving system to determine the position of the tractor relative to landmarks on a flat field |
| Inverse dynamic models | Used to simulate the forces and moments required to execute a given trajectory or behaviour. Used for autonomous systems, considering terrain gradients and stability limitations | High accuracy for autonomous control. Integration with sensor systems (LiDAR, IMU). Efficiency for difficult terrain | Require careful optimisation and calibration. Dependence on the accuracy of sensor data. Complex real-time implementation | Trajectory planning for an autonomous vehicle on uneven terrain, incorporating terrain gradients and stability. Development of a control system for a tractor that ensures stable driving on slopes with variable ground conditions |

**Note:** IMU – Inertial Measurement Unit; LiDAR – Light Detection and Ranging; SLAM – Simultaneous Localisation and Mapping

**Source:** compiled by the authors based on S. Han *et al*. (2024), Q. Li & H. Zhu (2024), D.K. Sah & M.F. Selekwa (2024), V. Bulgakov *et al.* (2024), W. Tao *et al.* (2025)

The systematisation of approaches to modelling tractor dynamics on uneven ground has shown that multibody models provide high accuracy for complex terrain, concentrated parameter models are effective for vibration analysis, kinematic models are suitable for navigation, and inverse dynamic models are optimal for autonomous control. The integrated use of these methods was used to effectively solve stability and control problems in Ukrainian agricultural conditions. X. Gong *et al*. (2024) proposed an approach to planning vehicle trajectories on complex surfaces in off-road conditions, based on a joint analysis of spatial and temporal characteristics to determine stability and optimise movement. The study analysed the creation of models that consider changes in terrain, with an emphasis on the development of trajectories important for vehicles operating on uneven surfaces. The proposed approach correlated with the current study, as both methods involved analysing the complex interactions of vehicle components, such as chassis, suspension, and track propulsion, to accurately predict movement in changing surface conditions. T. Sharma & Y. He (2024) studied the modelling, simulation, and optimisation of vibrations during tillage using an interactive active control system. The authors paid attention to the impact of terrain irregularities on the vibrations of agricultural machinery, in particular tractors, during tillage. The study demonstrated that reduction of vibration levels increased operator comfort and improved productivity, which is consistent with the results of this study, both of which are aimed at optimising vibration characteristics and stabilising the operation of machinery, ensuring effective vibration management and minimising its negative impact.

Adaptive modelling techniques such as ANFIS, NMPC and ADRC are key in improving the stability and controllability of TRVs on uneven ground (Ismayilzada *et al*., 2025). These methods combine classical physics models with machine learning algorithms to adapt to changing conditions such as uneven terrain, soil moisture or variable loads. They compensate for random disturbances, improve control accuracy, and contribute to the safety and efficiency of machinery in challenging agricultural and mining environments. A summary of these methods assessed their capabilities and limitations for practical use in modelling TRV dynamics (Table 3).

**Table 3.** Hybrid adaptive control methods for modelling and stabilising tractor movements on difficult terrain

| Method | Description | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| ANFIS | A hybrid method that combines neural networks and fuzzy logic to model nonlinear systems. Used to compensate for disturbances caused by uneven terrain by adaptively adjusting model parameters based on sensor data | Efficient compensation of nonlinear disturbances. Flexibility in adapting to changing conditions (soil moisture). High accuracy with sufficient data for training | Requires a large amount of verified data for training. The complexity of setting up fuzzy rules and network structure. Limited efficiency without quality sensor data | Compensates for vibrations of the tractor operator's seat on uneven agricultural fields employing adaptive damper control. Optimising tractor suspension performance to reduce the impact of stochastic disturbances from uneven terrain |
| NMPC | A predictive control method that uses a nonlinear model to predict system behaviour and optimise control actions in real time. Addresses the limitations of TRV stability and dynamics on slopes and bumps | High control accuracy on difficult terrain. Can account for constraints (e.g., slope angle, traction). Adaptation to changing conditions in real time | High computational complexity for real-time processing. Requires an accurate system model and high-quality data. The complexity of optimisation for nonlinear systems | Ensures truck stability on slopes by predicting the trajectory and adjusting the steering. Optimising the movement of an autonomous tractor on an uneven field, addressing changes in terrain gradients |
| ADRC | A method of active disturbance suppression that assesses and compensates for uncontrollable external influences (e.g., changes in soil structure or load) without a detailed system model. Used to increase the stability of the TRV | Does not require a detailed system model. Efficient compensation of unknown disturbances in real time. Ease of implementation compared to other adaptive methods | It depends on the quality of perturbation estimation. Limited accuracy in difficult nonlinear interactions. Requires careful adjustment of controller parameters | Compensates for the effect of changes in soil moisture on the traction of a crawler tractor when driving on uneven ground. Adapting tractor steering to load changes when towing a trailer on slopes |

**Source:** compiled by the authors based on S. Han *et al.* (2024), G. Qi *et al*. (2025), L. Duan *et al*. (2025)

Hybrid adaptive methods (ANFIS, NMPC, ADRC) effectively compensated for nonlinear disturbances and ensured tractor stability on difficult terrain. Their application optimised steering in the conditions of changing soils and terrain typical for Ukraine but required high-quality data and computing resources. The combination of these methods helped to increase the productivity and safety of the machinery. The results of the study emphasised the importance of accurate models for assessing soil properties and adapting machinery to complex terrain, which was consistent with the study by H.A. Hamersma *et al.* (2024), which demonstrated the importance of Unmanned Aerial Vehicle-based technologies for creating three-dimensional models of uneven surfaces and accurately predicting the interaction of machinery with the ground. Such modelling allowed for soil deformations and changes in traction, which were critical to the efficiency of vehicle movement. B. Puras *et al.* (2024) emphasised the role of virtual models (telehandler models) in improving the accuracy and adaptability of machinery to changing conditions. This supported the current study on the need to use sophisticated mathematical and virtual models to predict the behaviour of vehicles on different types of ground, such as dry or highly compacted surfaces, where adaptive systems can provide optimal traction and stability.

Given the high computational complexity of modern technologies, as evidenced by both the authors' conclusions and this study, it is possible to argue that the effective implementation of such engineering solutions requires significant investment in the development, testing, and integration of sensor systems and digital (virtual) models. Adaptive technologies are accompanied by high costs for design, algorithmic software, and hardware implementation (Vintoniak, 2024). Thus, despite the potential benefits, the implementation of such systems is a financially and technically complex process that requires a comprehensive approach. Soil properties are decisive in ensuring the driving performance of tractor systems and TRVs on uneven surfaces. Parameters such as soil structure, moisture content, degree of compaction and the nature of the mechanical interaction between the propulsion system and the ground surface directly affect the traction coefficient, slope stability and manoeuvrability (Adamchuk *et al.*, 2016). These factors are critical for the development of autonomous and operator control systems that ensure the stability and performance of vehicles in difficult terrain. The contact interaction between the crawler and the soil is characterised by complex nonlinear behaviour due to the penetration of the tracks into the soil, the displacement of its particles and the emergence of three-dimensional soil resistance. The main factors that influence grip include the normal soil response, tangential shear forces and surface deformation. Mathematical models that describe these interactions are often based on Beckman's theory or empirical relationships that address the soil's modulus of deformation and bearing capacity (Dong *et al.*, 2023). For example, nonlinear modelling with propulsion inertia can predict the behaviour of tractor-trailer systems on uneven terrain.

Soil physical properties, such as moisture content, particle size distribution and degree of compaction, are highly variable and depend on seasonal, climatic and agricultural factors (Bulgakov *et al.*, 2017). Soil moisture affects soil cohesion and the angle of internal friction, which directly affects traction. Excessive moisture can reduce traction by reducing the friction between the tracks and the surface, while dry soil can have a higher load-bearing capacity but less plasticity (Hassan *et al.*, 2017). Compaction of the soil caused by previous loads also changes its mechanical characteristics, which requires an adaptive modelling approach (Huseynov, 2024). These patterns are covered in models that use sensor data to assess soil conditions in real time. To compensate for the negative impact of soil conditions, modern TRVs use a number of engineering solutions aimed at increasing traction and stability (Table 4).

**Table 4.** Classification of technical solutions for optimising tractor traction on difficult soil types

| Engineering solution | Description | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| Wheel-step system | A mechanism that adapts the geometry of the vehicle's contact with the surface by dynamically adjusting the position of the wheels or tracks. It uses active or passive elements to change the contact area depending on ground irregularities, which ensures optimal load distribution | Improved traction on soft and uneven ground. Reduced sliding due to adaptive contact. Can be integrated with sensor systems for automatic adjustment | Complexity of design and high cost of implementation. Increased vehicle weight. The need for regular maintenance | Implementation of a wheel-step system in unmanned vehicles to increase traction on sandy or muddy ground. For use in crawler tractors to adapt to uneven terrain when driving on agricultural fields with vegetation residues |
| Yielding chassis | A flexible chassis design that can be used to adapt to changes in terrain by deforming or actively adjusting the suspension. Ensures constant contact of the tracks with the surface, reducing the risk of loss of traction on slopes | Increased stability on steep slopes and bumps. Reduced vibrations and stress on the structure. Improved operator comfort and system durability | The difficulty of designing flexible elements with sufficient strength. High development and implementation costs. Limited effectiveness on extremely uneven surfaces | Application in TRVs for driving on mountain slopes, where the flexible chassis compensates for elevation changes. For use in three-axle mining dump trucks to ensure stability on uneven terrain |
| Trajectory optimisation | Use of motion planning algorithms such as SLAM or NMPC to select optimal paths based on soil maps, terrain gradients and sensor data (LiDAR, IMU). Avoids low-grip areas and minimises slippage | High navigation accuracy in difficult conditions. Adaptation to changing ground conditions in real time. Reduced energy consumption and reduced risk of slipping | High computational complexity for real-time processing. Dependence on sensor data quality and map accuracy. Need for preliminary mapping of the area | Using SLAM to autonomously navigate a tractor in a horticultural environment with uneven terrain. Using NMPC to plan the path of a heavy vehicle on slopes with variable ground conditions |

**Source:** compiled by the authors based on W.-H. Wang *et al.* (2023), L. Duan *et al.* (2025), X. Liu *et al.* (2025)

Basic engineering models and analytical formulas are also used to describe the conditions of rollover, traction loss and dynamic imbalance, which form the basis of engineering models for the stability of tracked vehicles. These models can be used to quantify critical parameters, such as rollover angle or minimum traction coefficient, and predict the behaviour of the vehicle in different conditions. Critical rollover angle (1):

$$\theta_{crit} = \arctan\left(\frac{b}{2h}\right), \quad (1)$$

where $\theta_{crit}$ – critical tipping angle; h – height of the machine's centre of mass above the support surface; b – width of the track or base of the machine, i.e., the distance between the track belts' support points; arctan – artangent of the ratio, which gives the angle at which the gravity moment contributing to the tipping is equal to the stabilising moment.

The formula is based on a simplified analysis of the body's balance on an inclined plane and is used to estimate the critical angle of inclination at which a tracked vehicle can lose stability due to overturning. Static Stability Index (SSI) (2):

$$SSI = \frac{b}{2h}, \quad (2)$$

where SSI – dimensionless value that reflects the propensity to rollover, the higher the SSI value, the higher the rollover resistance.

Vertical dynamics of tracked vehicles (simplified mass-spring-damper model) (3):

$$m \times \ddot{z} + c \times \dot{z} + k \times z = F_{drilling}, \quad (3)$$

where m – reduced mass of the vehicle (including a tractor or robotic platform); c – damping coefficient, which characterises the ability of the system to absorb the energy of vibrations; k – stiffness of the suspension system, which characterises the ability of the system to deformation; z – vertical displacement of the mass; $\dot{z}$, $\ddot{z}$ – speed and acceleration of vertical displacement; $F_{drilling}$ – external disturbing force caused by interaction of uneven terrain.

Overturning moment (moment causing instability) (4):

$$M_{roll} = m \times g \times h \times \sin(\theta), \quad (4)$$

where g – free fall acceleration; θ – slope angle.

Stabilising torque (anti-tipping torque) (5):

$$M_{stabilising} = \frac{m \times g \times b}{2}, \quad (5)$$

Minimum grip coefficient to avoid slipping (6):

$$\mu_{min} = \tan(\alpha), \quad (6)$$

where $\mu_{min}$ – minimum coefficient of adhesion to the surface required to avoid slipping; α – slope angle.

Formula for calculating traction force (7):

$$F_{traction} = \mu \times m \times g, \quad (7)$$

where $F_{traction}$ – available traction, μ – actual coefficient of adhesion.

The efficiency of TRV movement is largely determined by the nature of interaction with the ground. One of the most common approaches to modelling this interaction is the empirical model of M.G. Bekker (1962), which can be used to estimate the pressure exerted on the soil surface during deformation:

$$p = k_c \times \frac{1}{b} + k_\phi \times \left(\frac{z}{b}\right)^n, \quad (8)$$

where p – vertical pressure on the soil; $k_c$ – soil compaction modulus; $k_\phi$ – soil shear resistance modulus; n – deformation nonlinearity index (dimensionless value).

Critical acceleration when tipping forward (9):

$$a_{crit} = \frac{g \times h}{L}, \quad (9)$$

where $a_{crit}$ – critical acceleration at which the front wheels (or the front part of the track base) can leave the ground; g – free fall acceleration (9.81 m/s$^2$ – standard value for engineering calculations at sea level); L – length of the wheelbase or the base of the supports.

The main metrics for identifying error limits are the Mean Relative Error (MRE), Root Mean Square Error (RMSE), and Coefficient of Determination. MRE (10):

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100\%, \quad (10)$$

where $y_i$ – actual value (measured); $\hat{y}_i$ – predicted value (model).

RMSE (11):

$$RSME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}. \quad (11).$$

Determination coefficient R (12):

$$R^2 = 1 - \frac{\sum(i-1)^n(y_i - \hat{y}_i)^2}{\sum(i-1)^n(y_i - \bar{y}_i)^2}. \quad (12).$$

A Gaussian noise model was used to address the effect of microrelief on TRV vibrations:

$$F(t) = F_0 + \xi(t), \quad (13)$$

where F(t) – instantaneous value of the disturbance force; $F_0$ – average (deterministic) value of the force; ξ(t) – random time function whose value at each moment is a random variable with a normal (Gaussian) distribution.

To account for spatial variations in the coefficient of adhesion, a model with spatially correlated noise is used (14):

$$\mu(x, y) = \mu_0 + \delta(x, y), \quad (14)$$

where μ (x, y) – coefficient of adhesion at the point (x, y) of the surface; $\mu_0$ – average value of the coefficient of adhesion; δ (x, y) – stationary Gaussian random field with zero mathematical expectation and spatial correlation structure.

Stochastic differential equations (15) are used to model the TRV response to stochastic disturbances:

$$dx = f(x, t)\,dt + g(x, t)\,dW_t, \quad (15)$$

where f(x, t) – deterministic part of the dynamics (change of state per laws of mechanics); g(x, t) – diffusion coefficient (noise effect); $dW_t$ – stohastic differential of the Wiener process, which models independent normal random increments with zero mathematical expectation and variance proportional to dt.

Lagrange equation of the second kind (generalised form) (16):

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i, i = 1, \ldots, n, \quad (16)$$

where $q_i$ – generalised coordinates of the system (coordinates describing the position of the system in the configuration space); $\dot{q}_i$ – generalised velocities, time derivatives of coordinates; $Q_i$ – generalised forces (or moments) that are not included in the potential energy, for example, friction forces, external forces acting in the direction of $q_i$.

The Newton-Euler equation (generalised vector form). Forward motion (17):

$$\sum \vec{F} = m\vec{a}. \quad (17).$$

Rotational movement (18):

$$\sum \vec{M} = \frac{d\vec{H}}{dt} = I\vec{\alpha} + \vec{\omega} \times (\overrightarrow{I\omega}), \quad (18)$$

where $\vec{M}$ – total moment of forces relative to the point of rotation; $\vec{H}$ – moment of quantity of motion (angular momentum); I – body inertia tensor; $\vec{\alpha}$ – angular acceleration; $\vec{\omega}$ – angular velocity.

For illustrative purposes, Figure 1 shows the distribution of forces acting on the TRV when travelling on an inclined surface and is used to explain the critical rollover angle model.

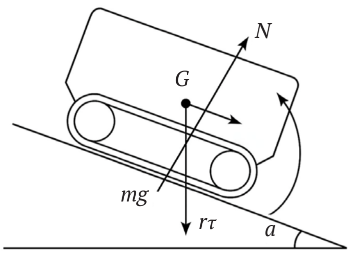


**Figure 1.** Spatial design scheme for determining overturning moments

**Note:** α – angle of inclination of the slope relative to the horizontal surface, which determines the steepness of the slope; G – point of the centre of mass of the machine, on which the distribution of forces depends; mg – force of gravity equal to the product of the mass of the machine (m) and the free fall acceleration (g ≈ 9.81 m/s$^2$), directed vertically downwards; N – normal force of the support reaction, which acts perpendicular to the surface of the slope and balances the vertical component of the weight; rτ – friction reaction directed along the slope, which prevents slipping due to adhesion to the surface

**Source:** compiled by the authors based on generalised provisions of classical mechanics of solid-state equilibrium, incorporating the configuration of tracked vehicles and typical situations of loss of stability on a relief surface

The stability of the TRV is significantly affected by the passage of local terrain irregularities, in particular, elevations and depressions that act asymmetrically on the undercarriage. In such conditions, the centre of mass is displaced and the roll angle φ is formed, which may exceed the permissible value. Figure 2 shows the conditional behaviour of the TRV when hitting a local obstacle, which visualises the change in the spatial orientation of the vehicle and the approach to the limit state of equilibrium.

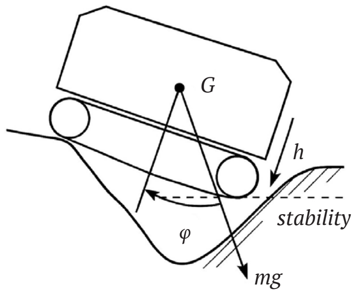


**Figure 2.** TRV limit position in case of loss of stability on the terrain

**Note:** stability – limit of the stable position of the TRV body, a conditional line beyond which the projection of the centre of mass (G) should exceed go, otherwise overturning occurs; mg – gravity, force of attraction equal to the product of the mass of the machine (m) and the acceleration of free fall (g ≈ 9.81 m/s$^2$), directed vertically downwards; h – the height to which the centre of gravity of the object is raised relative to the bottom of the slope; φ – angle of inclination of the trajectory or the angle between the vertical and the line connecting point G to a point on the slope. "Stability" conventionally reflects the ability of an object (tracked vehicle) to maintain balance and not topple over on a slope, which depends on the location of the centre of gravity (G), height (h), angle of inclination (φ) and gravity (mg)

**Source:** compiled by the authors based on generalised provisions of classical mechanics of solid-state equilibrium, incorporating the configuration of tracked vehicles and typical situations of loss of stability on a relief surface

To ensure the practical applicability of theoretical models of the dynamics of TRVs travelling on uneven ground, calibration and validation are necessary steps. Validation involves comparing the modelling results with experimental or simulation data to confirm their validity, while calibration adapts the models to real-world conditions by adjusting the parameters. These processes are critical for accurately predicting the behaviour of TRVs in variable soil and topographic conditions, which ensures safe and efficient operation (Table 5).

Field validation ensured reliability in real conditions, bench-top accuracy of isolated parameters, and virtual resource savings for testing complex scenarios. Their combined use increased the reliability of machine and tractor units adapted to the uneven terrain of Ukraine, which contributed to the accurate prediction of machine stability and dynamics. Experimental or virtual testing is not enough to ensure the high accuracy of tractor movement model validation. An important step is also the use of model processing and adaptation methods that allow for variable operating conditions, reduce forecasting errors and increase the reliability of results. In this context, various approaches are used, ranging from traditional parameter calibration to real-time integration of sensor data. Table 6 shows methods for improving modelling accuracy and adapting models to real-world conditions of agricultural machinery operation and examples of practical use.

**Table 5.** Characteristics of validation methods for models of dynamics and stability of machine-tractor units

| Type | Description | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| Field validation | Real-world field testing using load cells, IMUs, GPS and video recording systems to record driving, traction and stability parameters. Addresses stochastic factors such as soil moisture, uneven terrain and load changes | High reliability due to real-world conditions. Identification of unforeseen factors (crop residues). Basis for calibration of theoretical models | High cost and complexity of the organisation. Dependence on weather and soil conditions. Limited reproducibility due to environmental variability | Experimental validation of the tractor's rollover resistance on a training ground with different soil conditions (clay, sand), which confirmed the critical inclination angles of 25-30°. Field tests of a semi-tracked tractor to assess traction and load distribution on uneven surfaces |
| Bench validation | Tests in controlled laboratory conditions on rigs that simulate uneven terrain, vibrations or dynamic loads. Sensors are used to accurately measure individual parameters, such as vibrations or force distribution | High repeatability due to controlled conditions. Isolation of individual parameters (e.g., damping). Reduced risk to equipment compared to field tests | Inability to fully recreate the real environment. High cost of setting up and maintaining the stands. Limited applicability for complex scenarios | Bench testing of the vertical dynamic characteristics of a tractor to validate the operator seat vibration model. Validation of a magnetorheological tractor seat damper on a bench to compensate for vibrations from bumps |
| Virtual validation | Numerical modelling on platforms (Matrix Laboratory/Simulink, Automated Dynamic Analysis of Mechanical Systems, RecurDyn) to compare simulation results with experimental data. Can be used for testing of various scenarios (slope angles, soil conditions) without physical testing | Saving resources and time. The ability to test extreme conditions without risks. Flexibility in setting model parameters | Dependence on the quality of input data and calibration. High computational complexity for complex systems. Possible discrepancies with real conditions due to simplification | TRV simulation on slopes with variable ground conditions to validate stability and control models. Virtual validation of SLAM algorithms for tractor navigation in a garden environment with uneven terrain |

**Source:** compiled by the authors based on M. Belloni *et al*. (2023), G. Carabin *et al.* (2024), Q. Li & H. Zhu (2024), W. Tao *et al.* (2025), L. Duan *et al.* (2025)

**Table 6.** Methods of correction, adaptation and validation of TRV motion models in a variable environment

| Method | Characteristic | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| Calibration of models | Iterative selection of model parameters (e.g., coefficient of adhesion, soil strain modulus) based on empirical data from field or bench tests to ensure that they match real-world conditions | Improving the accuracy of models by processing real data. Flexibility in parameter settings. Ability to adapt to changing conditions (humidity, terrain) | A need for a large amount of high-quality empirical data. High computational complexity for iterative fitting. Dependence on the accuracy of the measuring equipment | Calibration of a model of a magnetorheological tractor seat damper using vibration data for bump compensation. Selection of traction parameters for a semi-tracked tractor based on field tests |
| Identification of error limits | The process of determining the maximum permissible range of deviations between the calculated (model) and actual values of system parameters | Evaluating the model's compliance with real data can be used to determine its accuracy. Identification of errors in forecasts helps to improve the model. Comparing models with each other can be used to choose the most effective one | Collecting accurate data in the field is difficult because of moisture and uneven terrain. The need to recalibrate the model arises when conditions change, including soil type. The use of inaccurate input parameters leads to a decrease in the reliability of modelling results | Validation of the tractor navigation model in the garden, where error estimation refined the trajectory on different soils. Analysis of TRV stability on slopes, which helped to determine safe slope angles of 25-30°. Assessment of the traction characteristics of a half-track tractor for accurate predictions of possibility |

*Continued Table 1.*

| Method | Characteristic | Advantages | Disadvantages | Application examples |
|---|---|---|---|---|
| Parametric generalisation | Use of approximation structures (neural networks, regressions, ANFIS) to model non-linear relationships between model parameters and external factors such as temperature, soil moisture or vibrations | Coverage of complex factors. High flexibility and adaptability of the models. Ability to process stochastic data | A need for a large amount of data for training. Complexity of setting up approximation structures. Risk of model overtraining | Application of ANFIS for modelling tractor seat vibrations with consideration of stochastic irregularities. Use of neural networks to approximate the effect of soil moisture on TRV traction |
| Integration with sensor systems | Merges models with sensor data (LiDAR, IMU, pressure sensors) to adapt to real-time conditions. Enables dynamic adjustment of model parameters (trajectory, load distribution) | Adaptation to changing conditions in real time. Improved forecasting accuracy. Integration with autonomous control systems | High cost of sensor equipment. Dependence on the quality and frequency of sensor data. Difficulty in synchronising data with the model | Integration of LiDAR and SLAM to adapt the tractor's navigation model to uneven terrain in a horticultural environment. Using the IMU with NMPC to dynamically adjust the TRV path on slopes |
| Stochastic Differential Equation | Use of stochastic models (Gaussian noise, Stochastic Differential Equation, Monte Carlo, Pearl noise) to account for random changes in soil mechanical properties (density, moisture, microrelief) and their impact on TRV trajectory and vibrations | Incorporation of the randomness of the environment. The ability to model complex nonlinear effects. Flexibility in simulating different scenarios (pits, ledges, humidity) | High computational complexity (especially for Stochastic Differential Equations and Monte Carlo). A need for a large amount of data for noise calibration. Difficulty in forecasting for highly heterogeneous soils | Modelling the vibration response of a TRV to microrelief using Gaussian noise. Simulate the tractor's path on uneven ground to assess deviations. Analysing the effect of soil moisture on TRV traction using spatial noise |

**Source:** compiled by the authors based on M.Z. Abdul Manaf *et al.* (2023), D. Dai *et al.* (2023), X. Ma *et al.* (2023)

The analysis of methods showed a variety of approaches to improving the accuracy and adaptability of TRV motion models. Calibration improved accuracy with high-quality data but was resource intensive. Error identification assessed reliability but depended on the data collection conditions. Parametric generalisation (neural networks, ANFIS) was effective for nonlinear relationships, but required large data sets. Integration with sensors (LiDAR, IMU) adapted the model in real time, although it was expensive and difficult to synchronise. Stochastic modelling addressed randomness but was computationally complex. The choice of method depended on the conditions, resources and goals, incorporating the balance of accuracy, adaptability and practicality. The root mean square error (Formula 11) reflects the average deviation between these values, providing a quantitative measure of discrepancy. The coefficient of determination (Formula 12) shows how well the model explains the variation in the data, with values closer to one indicating high accuracy. The influence of micro-terrain on vehicle behaviour is accounted for through a random oscillation model (Formula 13), which adds an element of randomness to the base force to simulate surface irregularities. Spatial variations in grip are modelled (Equation 14) through a baseline level of grip adjusted for spatial variations reflecting uneven terrain. Finally, stochastic effects affecting the system are described by equation (Equation 15), which combines predictable changes with random factors to analyse the vehicle's response to unpredictable conditions.

M. Ahmadian *et al.* (2024) addressed collision avoidance manoeuvres for heavy vehicles with multiple trailers. The authors considered critical manoeuvres to ensure the safety and stability of such vehicles while driving in complex terrain. They proposed algorithms that consider various constraints and variable conditions, such as changes in load and terrain. The study emphasised the importance of accurate control algorithms to ensure driving stability in difficult conditions, which was directly consistent with the results of this study on the need to use adaptive systems to ensure traction and manoeuvrability on slopes and uneven surfaces. D.K. Sah & M.F. Selekwa (2024) examined the improvement of autonomous tractor-trailer driving using dynamic models. These models enabled real-time prediction of system behaviour, optimising movement using autonomous algorithms that adapt to changing terrain and soil conditions. The use of dynamic models to predict vehicle behaviour in real time was important for the development of autonomous control systems for tracked vehicles in difficult terrain. This was confirmed by the current results on the need to integrate such technologies to increase the traction and stability of vehicles on slopes.

Based on the analysis of the advantages and limitations of existing approaches, the concept of a generalised theoretical model of TRV dynamics that integrates key influence factors is formulated. The proposed multifactor integrated model is designed to comprehensively describe the behaviour of TRVs in conditions of complex terrain and heterogeneous soil. The modelling was carried out using multi-body or focused models that considered the characteristics of the suspension, mass-inertial parameters, and articulated frame elements. To describe the mechanics of motion, the Lagrange equations (Formula 16) (for deriving the analytical model and validation) and Newton-Euler equations (Formula 17-18) (for flexible numerical implementation and accounting for rotational effects) were used, supplemented by stochastic disturbances to account for random effects. The model included parameterised dependencies of the grip and drag forces on soil properties, including density, moisture content and texture. Soil heterogeneity was modelled through stochastic effects on contact forces. The model included stochastic terrain disturbances, sensor (LiDAR, IMU) and actuator errors, load fluctuations (changes in cargo weight or soil moisture), and model imperfections. Adaptive control methods such as ANFIS, ADRC and NMPC are used to compensate for these factors. The model was validated by comparing it with real data obtained from field and bench tests. Validation involved estimating the errors between the simulation results and experimental data to ensure dynamic compliance and determine the permissible error limits.

The model had a multi-level organisation that provided a comprehensive consideration of physical, stochastic and experimental aspects of TRV motion. At the first level, the mechanics of the vehicle motion was implemented based on the Lagrange (Formula 16) or Newton-Euler (Formula 17-18) equations, supplemented by stochastic disturbances to simulate real dynamic impacts. The second level included modelling the interaction with the ground, based on empirical or semi-analytical relationships to describe the adhesion and drag forces. The third level included the consideration of random spatially distributed disturbances that simulated variability in relief and soil properties (moisture, density, microrelief). The fourth level served to validate the model by comparing the calculated data with the experimental results and estimating the errors, which was used to adapt the model parameters to improve its accuracy. Among the key advantages of the proposed approach is its comprehensiveness: the model simultaneously addresses TRV dynamics, soil interaction, stochastic disturbances and errors, which significantly increased the accuracy of simulations. The flexible structure of the model made it possible to adapt it to changing external conditions, including different terrain, soil types, and weather effects. This approach also facilitated the development of autonomous navigation, stabilisation and route planning systems. In addition, the framework was universal and could be applied to various types of mobile equipment, from agricultural to forestry and mining. At the same time, the model also had certain limitations, primarily high computational complexity due to the need to model multi-body dynamics and stochastic effects. Its effective operation required a large amount of high-quality experimental data for correct calibration. In addition, the reliability of the results depended heavily on the accuracy of the sensors and the reliability of the input data. Another challenge was the integration and configuration of adaptive control systems (ANFIS or NMPC), which required a high level of expertise and resources.

The results of the study showed that one of the key tasks in the design of TRVs was to ensure their stable operation in complex and variable terrain. This can be achieved through the introduction of adaptive control systems that can address the changing characteristics of the terrain and soil cover. This correlates with the study by Z. Li *et al.* (2024), which considered the use of adaptive stabilisation algorithms in robotic tractors operating under conditions of increased uncertainty, in particular on uneven and dynamically changing surfaces. The model proposed in this paper included sensor feedback, which enabled real-time adjustment of movement parameters, ensuring stability during manoeuvring. Similarly, J.M. García *et al.* (2023) analysed the stability of vehicles when driving on slopes with uneven slopes and heterogeneous surface structures. The study emphasised the critical importance of parameters such as traction and weight balance, which determine manoeuvrability and safety in difficult terrain. Both studies confirmed the feasibility and necessity of using adaptive control systems to improve the efficiency and safety of TRVs, which was fully consistent with the results of this study. B. Wang *et al*. (2024) proposed an effective method for modelling and assessing the terrain of open pits, which included approaches to creating high-precision models of complex surfaces. Such models could be used to calculate the interaction of transport equipment with the ground in open pit mining. Incorporating the specific characteristics of the soil and terrain in the modelling allowed for a significant increase in the accuracy of predicting the stability of vehicle movement on slopes and uneven terrain. The current results of this study correlated with the approaches proposed by the authors and confirmed the importance of detailed digital terrain mapping for improving tracked vehicle control systems in difficult terrain.

Thus, the proposed concept of multifactorial theoretical modelling combines knowledge of mechanics, geotechnics, control theory and sensor systems, allowing not only to accurately describe the behaviour of TRVs in difficult conditions, but also providing a foundation for building smart, adaptive and predictive navigation and control systems of a new generation.

## CONCLUSIONS

The study of approaches to analysing stability and modelling the dynamics of tracked vehicles on uneven surfaces systematised analysis methods, evaluated their effectiveness and developed a spatial model that described the loss of stability depending on the terrain, the position of the centre of mass and the type of disturbance. The analytical methods provided an accurate prediction of critical slope angles (up to 25-30° for chornozems with a friction coefficient of 0.6-0.8) but were limited in stochastic factors such as soil moisture. Experimental tests confirmed a vertical displacement of up to 0.15 m at an 18° inclination on clay soils, which highlighted the importance of accurate dynamics modelling, but high cost and dependence on testing conditions make it difficult to apply them widely. Simulation methods are effective in reducing vibrations by 12% by optimising suspension and adapting to uneven terrain up to 0.3 m but require good quality input data.

Multibody models proved to be the most accurate for complex terrain, although their computational complexity limited their use in real time. Concentrated parameter models are effective for vibration analysis, and kinematic models are suitable for navigation on flat surfaces. Hybrid methods provide adaptability to nonlinear disturbances, which is critical for autonomous systems. Engineering solutions, such as the wheel-step system, increased the cross-country ability on soft ground through adaptive contact, and the flexible chassis reduced the risk of traction loss on slopes. Validation of the models through field tests (using IMU and GPS) and bench tests (to assess damping) confirmed their reliability, although the field tests proved to be sensitive to stochastic factors. The study was limited by the lack of field verification of the model, complicated by the lack of application cases, insufficient infrastructure, high cost of technology, and limited access to empirical data in Ukraine. In the future, the model for predicting unstable modes of tracked vehicles can be improved by experimental validation, considering the dynamics of bogies, soil properties, and the introduction of multiphysics simulations with active stabilisers.

## ACKNOWLEDGEMENTS

None.

## FUNDING

None.

## CONFLICT OF INTEREST

None.

## REFERENCES

[1] Abdul Manaf, M.Z., Hudha, K., Samin, P.M., & Bakar, S.A. (2023). Modelling and verification of a 12-DOF tractor-semitrailer longitudinal model for load transfer analysis. *International Journal of Heavy Vehicle Systems*, 30(5), 525-559.

[2] Adamchuk, V., Bulgakov, V., Nadykto, V., Ihnatiev, Y., & Olt, J. (2016). Theoretical research into the power and energy performance of agricultural tractors. *Agronomy Research*, 14(5), 1511-1518.

[3] Ahmadian, M., Chen, Y., & Zhang, Z. (2024). Emergency collision avoidance maneuvers of multi-trailer articulated heavy vehicles. *Vehicle System Dynamics*, 62(11), 2837-2860. doi: 10.1080/00423114.2024.2305292.

[4] Bekker, M.G. (1962). Mechanics of off-the-road locomotion. *Proceedings of the Institution of Mechanical Engineers: Automobile Division*, 16(1), 9-16. doi: 10.1243/PIME_AUTO_1962_000_009_02.

[5] Belloni, M., Vignati, M., Sabbioni, E., & Cutini, M. (2023). *Characterization of vertical dynamics of a multi-purpose tractor with static and dynamic experimental tests*. Retrieved from https://saemobilus.sae.org/papers/characterization-vertical-dynamics-a-multi-purpose-tractor-static-dynamic-experimental-tests-2023-01-0177.

[6] Bulgakov, V., Aboltins, A., Adamchuk, V., Kuvachov, V., Pascuzzi, S., Kyurchev, V., Rucins, A., & Nesvidomin, V. (2024). Investigation of wide span vehicle technological part movement stability. *Engineering for Rural Development*, 23, 522-530. doi: 10.22616/ERDev.2024.23.TF099.

[7] Bulgakov, V., Adamchuk, V., Nozdrovický, L., & Ihnatiev, Y. (2017). Theory of vibrations of sugar beet leaf harvester front-mounted on universal tractor. *Acta Technologica Agriculturae*, 20(4), 96-103. doi: 10.1515/ata-2017-0019.

[8] Carabin, G., Becce, L., Mandler, A., Nicolosi, F., & Mazzetto, F. (2024). Experimental validation of the influence of obstacles on tractor rollover stability. In R. Berruto, M. Biocca, E. Cavallo, M. Cecchini, S. Failla & E. Romano (Eds.), *Safety, health and welfare in agriculture and agro-food systems* (pp. 153-163). Cham: Springer. doi: 10.1007/978-3-031-63504-5_15.

[9] Chi, Y., Mao, L., Wang, X., Pang, S., & Yang, Y. (2024). Three-dimensional numerical simulation and experimental validation of airborne ground-penetrating radar based on CNCS-FDTD method under undulating terrain conditions. *Scientific Reports*, 14(1), article number 22156. doi: 10.1038/s41598-024-73375-y.

[10] Dai, D., Chen, D., Mao, X., Zhang, Y., Li, Y., Wang, S., & Zhang, B. (2023). Design and performance analysis of indoor calibration device for the force-measuring system of the tractor three-point hitch. *International Journal of Agricultural and Biological Engineering*, 16(3), 47-54. doi: 10.25165/j.ijabe.20231603.7455.

[11] Dong, Y., Yan, D., & Feng, X. (2023). Stability of tracked vehicles on soft grounds under multidirectional loading conditions. *Canadian Geotechnical Journal*, 60(11), 1743-1755. doi: 10.1139/cgj-2022-0532.

[12] Duan, L., Kang, K., Chen, S., Du, Z., Zhang, L., Liu, Z., Yang, F., & Wang, Z. (2025). Analysis and verification of a slope steering model of TRVs in hilly and mountainous environments. *Agronomy*, 15(1), article number 147. doi: 10.3390/agronomy15010147.

[13] García, J.M., Yánez, P., & Martínez, J.E. (2023). Evaluation of navigability in skid-steer mobile robots with passive trailers moving on sloping terrain. *Revista Iberoamericana de Automática e Informática Industrial*, 20(1), 13-24. doi: 10.4995/riai.2022.17161.

[14] Gong, X., Tao, G., Qiu, R., Zang, Z., Zhang, S., & Gong, J. (2024). Terrain-aware spatio-temporal trajectory planning for ground vehicles in off-road environment. In *Proceedings of the 10th international conference on electrical engineering, control and robotics* (pp. 200-207). Guangzhou: IEEE. doi: 10.1109/EECR60807.2024.10607329.

[15] Hamersma, H.A., van Aswegen, J.C., Guthrie, A.G., & Els, P.S. (2024). UAV-based three-dimensional rough terrain modelling. In *Proceedings of the 21st international and 12th Asia-Pacific regional conference of the international society for terrain-vehicle systems* (pp. 163-169). Ferrara: ISTVS. doi: 10.56884/TK3ZX342.

[16] Han, S., Yoon, K., Park, G., & Huh, K. (2024). Robust lane keeping control for tractor with multi-unit trailer under parametric uncertainty. *IEEE Transactions on Intelligent Vehicles*, 9(1), 2333-2347. doi: 10.1109/TIV.2023.3272655.
[17] Hassan, H., Sahib, B., Krehel, R., & Kočiško, M. (2017). Increase of accuracy of geometric forms of surfaces ground by a grinding wheel of various grain sizes. *Advances in Mechanical Engineering*, 9(8). doi: 10.1177/1687814017726006.
[18] Hrushetskyi, S., Oleksiyko, S., & Tykhy, M. (2024). Modern running system of management of agricultural machinery. *International Science Journal of Engineering & Agriculture*, 3(6), 61-74. doi: 10.46299/j.isjea.20240306.06.
[19] Huseynov, H. (2024). New trends in mechanical engineering technology. *Advances in Science and Technology*, 148, 257-263. doi: 10.4028/p-XvVNq0.
[20] Ismayilzada, M., Safarova, T., Novruzova, U., & Abbasova, S. (2025). Innovative technologies in the production of agricultural machinery to improve the efficiency of agribusinesses. *Scientific Horizons*, 28(5), 78-89. doi: 10.48077/scihor5.2025.79.
[21] Kolahi, P.M., & Nazemizadeh, M. (2023). Nonlinear dynamic modeling of tractor-trailer mobile robots with consideration of wheels inertia and their optimal point-to-point path planning. *Meccanica*, 58(1), 245-253. doi: 10.1007/s11012-022-01578-6.
[22] Li, Q., & Zhu, H. (2024). Performance evaluation of 2D LiDAR SLAM algorithms in simulated orchard environments. *Computers and Electronics in Agriculture*, 221, article number 108994. doi: 10.1016/j.compag.2024.108994.
[23] Li, Z., Yin, C., Peng, Z., Zhou, C., & Jalanezhad, M. (2024). Designing a time path tracking stabilizing controller for a tractor-trailer robot in the presence of uncertainties. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. doi: 10.1177/09544070241238048.
[24] Liu, X., Wang, G., Suo, X., Du, T., Wang, W., & Zhang, C. (2025). Modeling and performance analysis of a hydraulically interconnected suspension for tri-axle mining dump trucks considering pitch-roll resistance. *Journal of Mechanical Science and Technology*, 39(2), 483-495. doi: 10.1007/s12206-025-0101-0.
[25] Ma, X., Xu, J., & Zhang, X. (2023). Bilateral constrained control for prosthesis walking on stochastically uneven terrain. *International Journal of Mechanical Sciences*, 239, article number 107896. doi: 10.1016/j.ijmecsci.2022.107896.
[26] Manoharan, A., Sharma, A., Belsare, H., Pal, K., Krishna, K.M., & Singh, A.K. (2024*). Bi-level trajectory optimization on uneven terrains with differentiable wheel-terrain interaction model*. doi: 10.48550/arXiv.2404.03307.
[27] Meng, Q., Huai, Y., Wang, X., Li, Z., Zhang, R., & Nie, X. (2025). Three dimensional forest dynamic evolution based on hydraulic erosion and forest fire disturbance. *Computers and Graphics*, 126, article number 104152. doi: 10.1016/j.cag.2024.104152.
[28] Nadykto, V., Golub, G., Tsyvenkova, N., Kyurchev, V., Skliar, O., Skliar, R., Golub, V., & Shubenko, V. (2025). Modeling movement stability of machine-tractor units based on modular type tractor. *Applied Sciences*, 15(5), article number 2822. doi: 10.3390/app15052822.
[29] Puras, B., Raush, G., Freire, J., Filippini, G., Roquet, P., Tirado, M., Casadesús, O., & Codina, E. (2024). Development of a virtual telehandler model using a bond graph. *Machines*, 12(12), article number 878. doi: 10.3390/machines12120878.
[30] Qi, G., Yue, M., Xu, M., Zhang, L., & Liu, Y. (2025). Integrated NMPC-based vehicle stability and tracking control strategy for heavy-duty truck with road bank angle estimation. *Journal of Vibration and Control*. doi: 10.1177/10775463251337514.
[31] Rebrov, O.Y., Malko, M.M., Rebrova, A.O., & Yakunin, M.Ye. (2023). Method of determining reasonable tire sizes for wheeled agricultural tractors. *Technical Service of Agricultural, Forestry and Transport Systems*, 1, 117-125. doi: 10.20998/2078-6840.2023.1.14.
[32] Ruetenik, G.A., Jansen, J.D., Val, P., & Ylä-Mella, L. (2023). Optimising global landscape evolution models with $^{10}$Be. *Earth Surface Dynamics*, 11(5), 865-880. doi: 10.5194/esurf-11-865-2023.
[33] Sah, D.K., & Selekwa, M.F. (2024). Advancing autonomous backing of tractor-trailer systems: A dynamic model approach. In *Proceedings of the ASME 2024 international mechanical engineering congress and exposition* (article number IMECE2024-146070). Portland: American Society of Mechanical Engineers. doi: 10.1115/IMECE2024-146070.
[34] Sharma, T., & He, Y. (2024). On trade-off relationship between static and dynamic lateral stabilities of articulated heavy vehicles. *Designs*, 8(5), article number 103. doi: 10.3390/designs8050103.
[35] Singh, H., & Mehta, M. (2024). Development of dynamic model of tractor for vibration analysis of operator's seat. *AIP Conference Proceedings*, 2962, article number 020066. doi: 10.1063/5.0192395.
[36] Tao, W., Chen, B., Zhou, L., Zheng, Z., Wu, J., & Duan, M. (2025). Design of a magnetorheological (MR) suspension damper for an agricultural tractor seat based on an adaptive neuro-fuzzy inference system (ANFIS) and active disturbance rejection control (ADRC). *Mechanical Sciences*, 16(1), 113-124. doi: 10.5194/ms-16-113-2025.
[37] Tong, W., Liao, K., Li, L., Gao, Z., Chen, F., & Luo, H. (2024). Optimization of the *Camellia oleifera* fruit harvester engine compartment heat dissipation based on temperature experiments and airflow field simulation. *Agriculture*, 14(9), article number 1640. doi: 10.3390/agriculture14091640.
[38] Vintoniak, V. (2024). Innovations in electronics for detecting objects in surface layers of soil: A review of methods and directions for further improvement. *Technologies and Engineering*, 25(3), 9-20. doi: 10.30857/2786-5371.2024.3.1.

[39] Wang, B., Gong, B., Xu, W., & Shi, X. (2024). An efficient method for modeling and evaluating the bench terrain of open-pit mines. *Frontiers in Earth Science*, 12, article number 1351352. doi: 10.3389/feart.2024.1351352.
[40] Wang, W.-H., Zou, T.-A., Xu, X.-J., & Xu, H.-J. (2023). Enhancing the tractive performance of unmanned vehicles using an optimised wheel-step driving system. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 237(5), 958-977. doi: 10.1177/09544070221087002.
[41] Yang, Y.-J., Jang, M.-K., & Nam, J.-S. (2024). Dynamic simulation model of miniature tracked forestry tractor for overturning and rollover safety evaluation. *Agriculture*, 14(11), article number 1991. doi: 10.3390/agriculture14111991.
[42] Zhou, B., Chen, S., Hu, J., You, Y., Wang, D., & Zhang, Q. (2023). Multi-body dynamics modeling and test of an articulated steering half-track tractor. *International Journal of Agricultural and Biological Engineering*, 16(6), 124-133. doi: 10.25165/j.ijabe.20231606.8165.

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## Моделювання динамічних характеристик тракторних систем для підвищення стійкості при роботі на нерівних полях

**Анотація.** Метою дослідження було з'ясування впливу зміщення центра мас, кута нахилу рельєфу та локальних збурень на просторову стійкість транспортної системи з подальшим визначенням граничних режимів її рівноваги. Методологія базувалась на поєднанні теоретичного моделювання, адаптивного керування та багаторівневої валідації в умовах змінного середовища. Було встановлено критичне вертикальне зміщення корпусу до 0,15 м при нахилі 18° через асиметричне проходження перешкод, що підтверджувало необхідність точного прогнозування динаміки. Аналіз стійкості встановив безпечні кути крену 25-30° для чорноземів України (коефіцієнт тертя 0,6-0,8). Нерівномірне навантаження й вологість ґрунту (20-30 %) впливало на стабільність, що вимагала калібрування моделей. Гібридні методи дозволили компенсували вібрації сидіння шляхом адаптивного керування демпфером. Система адаптивного контакту з поверхнею покращила прохідність на м'яких ґрунтах, а нелінійне предиктивне керування оптимізувало траєкторію руху на схилах. Встановлено доцільність урахування геометрії опорної площини й положення центра мас при розробці алгоритмів стабілізації агротехніки з огляду на вплив на стійкість у змінному рельєфі. Стохастичне моделювання збурень ґрунту дозволило прогнозувати вплив випадкових змін середовища на траєкторію й стабільність техніки. Запропонована теоретична модель придатна для проєктування та систем динамічного контролю корпусу, особливо для роботи на схилах і складній геометрії. Інтеграція сенсорних систем із моделями забезпечувала адаптацію до умов реального часу. Практична цінність результатів полягала у підвищенні безпеки роботи аграрної техніки та оптимізації її просторової орієнтації на схилах інженерами-технологами та розробниками систем активного вирівнювання під час проєктування техніки нового покоління

**Ключові слова**: прискорення; коефіцієнт зчеплення; випробування в польових умовах; стабілізація; адаптивне керування