

RESEARCH ON THE KINEMATICS OF A SELF-STEERING AXLE USED IN ROAD TRANSPORT SYSTEMS

CERCETĂRI PRIVIND CINEMATICA UNEI AXE AUTODIRECȚIONALE A SISTEMELOR TEHNICE RUTIERE DE TRANSPORT

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ABSTRACT

With the continuous increase in the volume of goods produced, the need to develop high-capacity road transport vehicles that can distribute this volume to various destinations has also increased. The increase in transport capacities involves technical equipment that can take over these capacities. Among the structural components of the mentioned systems, an important role is played by the running system, which at high transport capacities must be equipped with three/four axles. For the most efficient running and with acceptable efforts and wear, especially when entering corners, these running systems must be equipped with one/two self-steering axles, built in such a way as to take over certain additional demands that arise compared to rigid axles. Most of the constructive and functional solutions adopted by established manufacturers for self-steering running system include data resulting from their own research, less widely disseminated, intellectually protected, based on testing, starting from known concepts and previous experience. This paper presents theoretical and experimental research of an alternative way of approaching the concept, by performing an analysis of the kinematics of the self-steering axle when passing over bumps, following which the constructive and functional running parameters will be evaluated, the effects that occur and ways to mitigate or eliminate vertical and transverse oscillations of the axle as well as conclusions and recommendations for manufacturers. The values of the recorded vertical oscillations ranged between 40-80 mm for unevenness between 25-100 mm speeds between 0.5-5 m/s and the transverse ones between 30-10 mm, under the same conditions.

REZUMAT

Odată cu creșterea continuă a volumului de mărfuri produs, a crescut și necesitatea dezvoltării de mijloace tehnice rutiere de transport de mare capacitate care să distribuie acest volum la diverse destinații. Creșterea capacităților de transport implică echipamente tehnice care să poată prelua aceste capacități. Dintre elementele constructive componente ale sistemelor menționate, un rol important îl are sistemul de rulare, care, la capacități mari de transport, trebuie echipate cu trei/patru axe. Pentru o rulare cât mai eficientă și cu eforturi și uzuri acceptabile, mai ales la înscrierea în viraje, aceste sisteme de rulare trebuie echipate cu una/două axe autodirecționale, construite astfel încât să preia anumite solicitări suplimentare care apar față de axele rigide. Majoritatea soluțiilor constructive și funcționale adoptate de către producătorii consacrați, pentru trenurile de rulare autodirecționale, includ date rezultate din cercetările proprii, mai puțin diseminate pe scară largă, protejate intelectual, bazate pe testări, pornind de la concepte cunoscute și experiența anterioară. În această lucrare sunt prezentate cercetări teoretice și experimentale ale unei modalități alternative de abordare a conceptului, prin realizarea unei analize a cinematicii osiei autodirecționale la trecerea peste denivelări, în urma căreia se vor evalua parametrii constructivi și funcționali de rulare, efectele apărute și modalități de atenuare sau eliminare a oscilațiilor verticale și transversale ale axei precum și concluzii și recomandări pentru producători. Valorile oscilațiilor verticale înregistrate s-au încadrat între 40-80 mm pentru denivelări între 25-100 mm și viteze între 0.5-5 m/s iar cele transversale între 30-10mm, în aceleași condiții.

INTRODUCTION

The continuous increase in transport capacities led to the consequent development of road goods transport vehicles by increasing their capacity and dimensions, which required the provision of running trains equipped with either two axles (tandem or bogie type) or three tridem type axles. The creation of these constructive types of running train required that at least one of the axles be directional, in order to achieve a turning radius as small as possible in accordance with the width of certain access roads and with direct implications for reducing the wear of the component elements (tires, bearings or joints) and the running tracks.

Since on goods transport vehicles, the provision of a wheeled axle and the associated steering mechanisms, controlled by the operator, is more difficult to achieve constructively and would also involve significantly higher costs, the system of self-steering wheel axles was developed.

During operation, especially when vehicles are running on less developed roads, often with bumps, self-steering wheels have a classic vertical displacement and a specific oscillatory movement in the transverse plane (shimmy), typical of such wheels, which can lead to instability of the vehicle during running. In order to mitigate these oscillations, both vertical and transverse, as much as possible, the running system has in its structure damping elements whose constructive, functional and positioning parameters in the assembly depend on the characteristics and values of the operating parameters that influence the magnitude of the mentioned oscillations.

Like any steering wheel, the self-steering wheel achieves, in the assembly, the same established steering angles: the wheel convergence angle; the pivot escape angle; the pivot transverse inclination angle; the wheel axis drop angle. Over time, specialists in the field have sought increasingly varied constructive and functional solutions to achieve the greatest possible reduction in the effects of the oscillatory movements of the self-steering wheels above mentioned.

There are many studies on the kinematics of self-steering axles and running systems, as well as achievements of renowned manufacturers of such components.

In one of these studies (*Yang C. et al., 2023*), an idea is proposed to recover the self-steering capacity of a new type of bogie made up of self-steering wheels, using the steering angles. The self-steering performance of the bogie is studied on straight and curved roads, the test results showing that the kinematic system of the new bogie is asymptotically stable, having the ability to correct its direction and automatically return to the centerline of the running track. The return movement is damped exponentially, the bogie having the ability to self-center on straight tracks, the steering angle of the left front wheel obviously decreasing with the decrease of the anti-deviation stiffness on curves.

Another work proposes the use of wheels that rotate independently on a curved track to achieve self-steering capability without any complex bogie structure (*Suda Y., et al., 2012*). The effectiveness of the single-axle, two-bogie vehicle with self-steering wheels that rotate independently on a curved track is proven by the 1/10 scale model experiment. The complete vehicle model is realized by the multibody dynamics software SIMPACKTM. Both the experimental and simulation results show that the running of the analyzed system has good performance. The running stability and the turning and recovery capability on the curved road can be achieved by using a semi-active roll damper.

There are different basic methods to control the direction of a car intentionally (*Trzesniowski, M., 2017*). Cars with pneumatic wheels and tires can have an integrated steering system with sway bar, tilt or pivot-axle steering. The first two types have the disadvantage that their footprint decreases during cornering, and the intervention forces will act on a lever corresponding to half of the tire trajectory. In addition, the steering can be controlled only on the front wheels, the rear wheels or on all wheels together. For high-speed cars, however, a third solution is preferable, namely the steering with pivot-axle on the front axle, a variant that is the subject of this study.

The axis of rotation of the wheel support, or "spindle", on the wheel suspension (e.g. a "pin") is usually constant when the car is steered (pure tire rotation). However, there are now many cars whose suspensions feature a variable ("virtual") axis of rotation.

Although in this paper the subject of study is the self-steering axle, as a component of the running systems on goods vehicles, given that the steering kinematic mechanisms are guided by the same principles, achievements in the field of other types of vehicles can be sources of inspiration for the field addressed in this paper. Therefore, in another paper (*Bonera E., et al., 2020*), the torque steering phenomenon on a fully electric four-wheel drive sports car is analyzed, where a significant part of the torque is transferred to the front axle. The effects of the suspension kinematics and the load variation at the tire contact patch level are taken into account. To evaluate the impact of feedback on steering, the VI-grade® simulation software was adopted and a test campaign was carried out on the professional driving simulator, available at the University of Brescia, to understand the impact of feedback on steering torque on driver perception and performance.

This paper aims to provide an insight into the steering phenomenon in light of the shift towards fully electric vehicles even in the high-performance market segment, in order to understand to which geometric parameters of the car it is directly connected, starting from a comprehensive theoretical background.

Examples of kinematic redesign of the suspension are proposed to minimize the effects of steering torque with the help of specific software. Such a tool was self-developed within the Automotive Engineering

Group of the University of Brescia by the authors of this paper. A thorough validation was performed by comparing the results with commercial tools such as Lotus Suspension Design (Shark®) from Lotus Engineering and with the Adams multi-body package. This tool:

- allows the design and analysis of all types of suspension geometries (from swingarm to full multi-link to typical racing car layouts), including the kinematics of the entire steering line;
- allows any type of user to quickly create a basic design;
- can represent all relevant suspension characteristics;
- can overlay results from developed design stages;
- has a specific configuration mode to simulate the effects of suspension adjustability;
- features direct transfer of suspension kinematics to professional simulation packages such as CarSim® and VI-CarRealTime®.

In another scientific paper (*Alberding M. B., 2013*) two aspects of semi-trailer steering were addressed, firstly, the steering mechanism and secondly, the steering control.

The first part of this paper addresses the steering mechanism. So far, trailer steering offers two uncompromising options, the controlled steering and the self-steering which does not require an actuator, but has a limited performance and cannot be controlled. Controlled steering allows steering control and improved performance, but requires a more expensive actuator. This paper presents a new approach that establishes a balance between these extremes.

In this approach, the steering is influenced by introducing a variable steering geometry into a self-steering system. The steering geometry defines the forces of the tire lever arm in relation to the steering pivot axis, changing the steering geometry thus changing the steering angle.

The literature does not contain empirical studies investigating how driving modes affect vehicle dynamic behavior during regular on-road driving (*Melman T., et al., 2019*).

In a study (*Melman T., et al., 2019*), CAN-bus (Controller Area Network) signals were examined, with the differences between the comfort and sport modes of Renault's Multi-Sense R being the most obvious. Data was collected on a 26.3 km route consisting of a rural section and a motorway section, driven four times in comfort mode and four times in sport mode. By statistically analyzing and ranking 887 CAN-bus signals, major differences were found between the two modes for rear wheel angle, engine torque, longitudinal acceleration and vertical movement, identifying a 3.5 times higher damping coefficient for sport mode compared to comfort mode. Due to the four-wheel steering, compared to comfort mode, sport mode produced a higher lateral acceleration and yaw rate for a given steering angle and driving speed.

In conclusion, this study provides quantitative insight into the extent to which Multi-Sense driving modes impact the lateral, longitudinal, and vertical dynamic behavior of the vehicle.

The results and analysis methods help guide future driving mode designs.

A number of studies have examined the potential of driving modes in areas such as fuel/energy management (*Chau CK., et al., 2017; Si J., et al., 2002; Mohd Tat et al., 2017*), chassis control (*Hilgers C., et al., 2009; Kim W., et al., 2005; Wimmer C. et al., 2014*), and adaptation to personal driving styles (*Jeon Bw, et al., 2016*).

Research on the oscillations of self-steering wheels of running systems on means of transport has also been addressed in scientific works (*Ciupercă R. et al., 2011; Ciupercă R. et al., 2020*).

Some researchers have designed an adaptive ground level control system for use on crawler tractors using the proportional algorithm that can also be adapted for self-steering systems (*Chen X, et al., 2022*).

In other research, the differential steering mechanism of a four-wheel independent drive tractor was analyzed, and a layered control strategy was proposed based on the slip mode control of the yaw torque at the upper level and the optimal torque distribution level based on the average tire load rate based on a difference in vehicle stability at the lower level of the differential dynamics in the direction of the vehicle (*Yuhui A., et al., 2023*). In one article (*Bangyn W., et al., 2024*) systematically analyzes the research progress of key technologies for propulsion chassis for agricultural machinery in hilly and mountainous areas and conducts an analysis of five aspects including the steering system and the automatic navigation and path tracking control system.

In another paper (*Zhanga Z., et al., 2025*) an analytical method is presented to analyze the steering performance of elastically constrained axles under a stationary traction/braking torque in which the impact of traction/braking conditions on steering capacity was analyzed.

The achievements of manufacturers in the field of self-steering drivetrains from established manufacturers have continuously evolved, both from a constructive and functional point of view.

Thus, the BPW company, has remarkable achievements, including a system in which the self-steering axle counteracts and prevents shimmying, thereby maintaining a straight wheel trajectory (<https://www.bpw.co.uk/news-media/bpw-self-steering-axles#:~:text=it%20relies%20on%20corrugated%20washers,to%20the%20straight%20ahead%20position>).

This is accomplished through the use of two overlapping corrugated pressure discs that slide relative to one another, positioned within the pivot-knuckle-axle body assembly. BPW self-steering axles operate without the need for assisted stabilizers (shock absorbers, air bellows), these being automatically controlled depending on the load carried. This system is functional only when driving forward.

For reversing, BPW has created Active Reverse Control, an electro-hydraulic auxiliary system that automatically controls the steering axle consisting of control and hydraulic elements, as well as a steering cylinder with an integrated sensor for steering angle and rotation speed,

When the operator commands reverse, the steering system is automatically engaged via the reversing lights. In addition, the steering can be controlled manually with a remote control for precise movement, accurately positioning a trailer at a specific location. Direction and speed are detected by this revolutionary sensor technology, which is located in the control unit.

BPW also introduced the LST system about ten years ago when it launched a new self-steering axle in the UK for 15.6 m trailers, which allowed 27 degrees of steering.

Another major manufacturer of self-steering systems, Dexter Group (<https://www.dextergroup.com/products/heavy-duty/trailer-steer-axles>), offers a remarkable solution to the self-steering axle system with its exceptional turning radius. A reduced turning radius translates into improved maneuverability, reduced stress on the trailer and reduced tire wear, ultimately leading to lower maintenance costs and an overall improvement in operational efficiency. The self-steering system has an advanced steering damper, centrally placed, providing real tracking and turning stability. For reversing, a pneumatic bellows system is provided for straight-line return and locking. It also has adjustable steering stops to maximize steering angles of up to 30°.

The ADR Group has successfully launched its new “Dual Function” axles with the innovative “EasyDrive” electronic system, combining the advantages of self-steering and steered axles in a simple design (<https://www.adraxles.com › news › simple-and-efficient>).

Since the implementation of European Regulation 167/2013 in 2016, the agricultural industry has seen a gradual increase in the use of heavy-duty trailers. These vehicles are capable of carrying loads exceeding 40 tons and are based on chassis equipped with three or four axles, often with large-section tires operating at low pressures. In order to support such heavy loads on tandem or tridem axles, chassis manufacturers have had to completely re-evaluate their offerings, developing products specifically adapted for heavy-duty trailers.

Self-steering axles allow the steering of one or more axles by adjusting the position of the wheel pivot in relation to the axle. The resulting friction between the tire and the ground generates torque, changing the angles of the wheels to align with the desired trajectory of the tractor. Controlled steering axles achieve the same goal using hydraulic systems operated either hydraulically or electro-hydraulically. The first solution is the simplest, most cost-effective and most reliable; however, it faces challenges in reversing maneuvers, as the tensions between the tire and the ground can steer the axle in the opposite direction.

GIGANT from Dinklage is a member of the Krone Group and one of the leading manufacturers of axles and suspensions for the commercial vehicle trailer market and has developed the robust and low-maintenance GIGANT self-steering axle, designed for axle loads of 9 to 12 tons (<https://www.gigant.com/en/products/axles/self-steering-axles/>).

Thanks to the compact design, steering angles of up to 22° can be achieved, depending on the tire size and track width, steering rod adjustment and therefore the steering can be adjusted simply and precisely via an eccentric screw. In addition, the axle has a stabilizing bellows, which allows for optimum steering with minimal resistance, depending on the load.

MATERIALS AND METHODS

The variation in intensity of the two oscillatory movements, vertical and transverse, of the self-steering wheels, mentioned in the introduction chapter, depends mainly on functional operating parameters such as: the load carried, the speed of travel; the size of the unevenness of the roadway; the air pressure in the tires. Since in the bibliography of the various studies, few researches were identified regarding the impact of the mentioned parameters on the kinematics of the self-steering wheel, in the present paper it was proposed as the final objective to determine the variation of the two oscillatory movements following the tests carried out

on a two-axle bogie-type running system, with self-steering wheels, mounted on an agricultural semi-trailer, when passing over uneven surfaces, at different values of the mentioned functional operating parameters.

- **Self-steering axle kinematics when passing over an obstacle**

To ensure good rolling stability of the self-steering undercarriage, it is essential to understand in detail the kinematics of the self-steering wheels, which generate oscillatory movements: a vertical oscillation characterized by angle β , and a transverse oscillation characterized by angle θ . The variation of these movements depends on the constructive characteristics and functional parameters of the axle system.

The angular displacements β and θ are determined from the self-steering wheel kinematics relations written in the context of considering the wheel-obstacle impact, as an oblique collision between an elastic body, the wheel with tire and a wall, the obstacle, according to relations (1;2), using the kinematic schemes in Fig. 1 and Fig. 2.

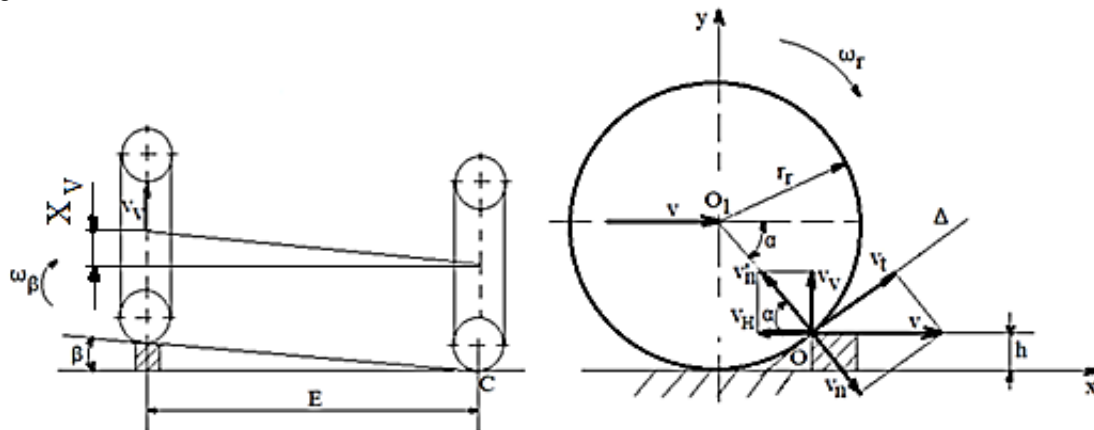


Fig. 1 - Self-steering axis kinematics in the vertical plane

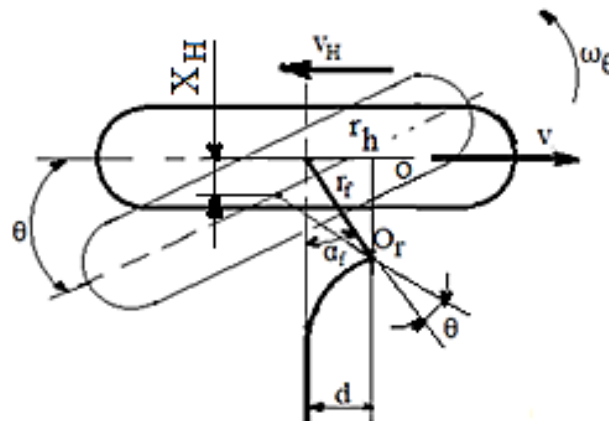


Fig. 2 - Self-steering wheel kinematics in the transverse plane

$$\beta = \omega_{\beta} \cdot t \quad (1)$$

$$\theta = \omega_{\theta} \cdot t \quad (2)$$

where:

ω_β – angular speed of the wheel in the vertical plane, [rad/s];

ω_θ - angular speed of the wheel in the transverse plane, [rad/s];

t – time in which the wheel-obstacle collision occurs, [s].

The angular speeds ω_β , ω_θ are expressed as a function of the vertical components v_v and transverse v_H of the linear velocity of movement of the wheel v , according to relations (3-6):

$$\omega_\beta = \frac{v_v}{F} \quad (3)$$

$$\omega_\theta = \frac{v_H}{r_f \cos \alpha} \quad (4)$$

$$v_p = v_n' \cdot \sin \alpha \quad (5)$$

$$v_H = v'_n \cdot \cos \alpha \quad (6)$$

where:

- v'_n – normal component of the speed after the collision, [m/s];
- v_v – vertical component of the speed v'_n after the collision with the obstacle, [m/s];
- v_H – transverse component of the speed after the collision with the obstacle, [m/s];
- E – axle gauge, [m];
- r_f – axle stub arm length, [m];
- α – attack angle of the obstacle by the wheel, [degrees].

According to the theory of oblique collision of two spheres, from classical mechanics, the speed before collision and the speed after collision are decomposed into their components in the normal direction of collision and tangent to the wheel (Fig. 1). For simplification reasons, frictionless motion is considered at the moment of collision so that the two tangential components of the speeds before and after collision do not change, having the same value.

According to the theory of elastic collision, the relations of interest are written between the normal components of the speeds before and after collision and the linear displacement speed, according to relations (7) for vertical displacement and relations (8) for transverse displacement after collision, using the kinematic schemes in Fig. 1, 2:

$$\begin{aligned}
 v'_n &= k \cdot v_n = k \cdot v \cdot \cos \alpha \\
 v_v &= k \cdot v \cdot \cos \alpha \cdot \sin \alpha \\
 \omega_\beta &= \frac{k \cdot v \cdot \cos \alpha \cdot \sin \alpha}{E} \\
 \beta &= \frac{k \cdot v \cdot \cos \alpha \cdot \sin \alpha}{E} \cdot t \\
 v_H &= k \cdot v \cdot \cos \alpha \cdot \cos \alpha = k \cdot v \cdot \cos^2 \alpha \\
 \omega_\theta &= \frac{v_H}{r_f \cdot \sin \alpha_f} = \frac{k \cdot v \cdot \cos^2 \alpha}{r_f \cdot \sin \alpha_f} \\
 \theta &= \frac{k \cdot v \cdot \cos^2 \alpha}{r_f \cdot \sin \alpha_f} \cdot t
 \end{aligned}
 \tag{7}$$

$$\tag{8}$$

where:

- k – tire restitution coefficient;
- α_f – steering arm angle to the axle center, [degrees].

To perform the tests of the self-steering axle, it was mounted on a biaxial wheel train, of the bogie type with leaf spring suspensions, a component part of an agricultural semi-trailer, symbolized RTC which was towed during the tests by an agricultural tractor symbolized U 650, Fig.3.a. The self-steering axle has incorporated in its construction two telescopic shock absorbers, mounted face to face, to attenuate transverse oscillations. To simulate the obstacles, four types of square metal pipes were mounted on a concrete track, Fig. 3.b, of dimensions and arrangement according to table 1, mounted in the same direction so that one of the self-steering wheels passes over the respective obstacles under the same conditions

Table 1

Type and arrangement of obstacles on the test track			
No.	No. of obstacles	Obstacle dimensions (square pipes), [mm]	Distance between obstacles, [m]
1	2	25x25	5
2	2	50x50	5
3	2	80x80	5
4	2	100x100	5

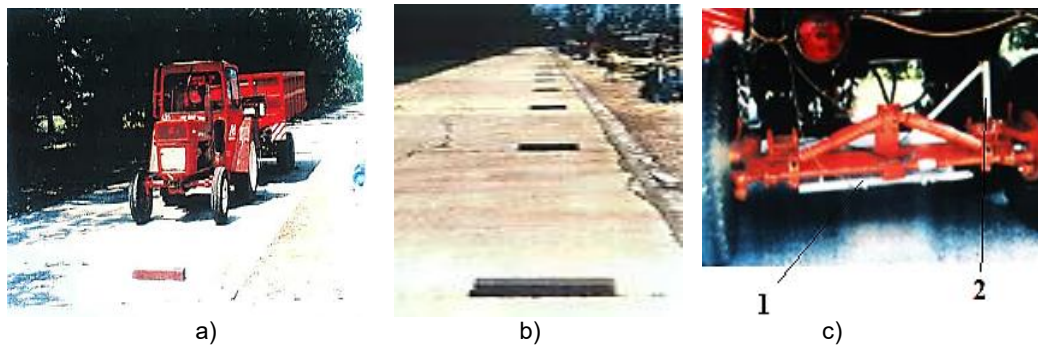


Fig. 3 a, b, c - Images from the self-steering axle tests

• **The constructive characteristics of the self-steering axle used in the tests are:**

- E – axle gauge, 1.700 m;
- α – angle of attack of the obstacle by the wheel, depending on the height of the obstacle: 70° for $h=25$ mm; 62° for $h=50$ mm; 54° for $h=80$ mm; 50° for $h=100$ mm;
- r_f – length of the axle knuckle arm, 0.254 m;
- k – tire restitution coefficient, depending on the air pressure: 0.8525 at 2.5 bar; 0.8555 at 3.0 bar; 0.8605 at 3.5 bar;
- α_f – angle of the knuckle arm relative to the axle center, 45° ;
- d – pivot axis misalignment, 0.100 m.

• **Equipment used in the tests** (Fig. 4)

- To record the angular displacements θ and β of the self-steering wheel/axle, they were indirectly recorded by two inductive displacement transducers, type W 100 and W 200, mounted in its kinematic system so that the recordings of each transducer are not influenced by other disturbing movements, Fig. 3.c, pos.1 for recording displacements in the transverse direction X_H and pos. 2 for vertical recordings X_V . Also, two 120 Ohm and 8 mm long strain gauges were used to measure the voltages in the connection bar.
- MGCplus (HBM) acquisition system, equipped with modules specific to each type of sensor:
 - modules for inductive displacement transducers (ML38B);
 - modules for strain gauges (ML801B for unipolar extensometry), ensuring synchronized data acquisition.
- The acquired data was saved in ASCII format, using the catman Easy software (HBM), and subsequent processing was performed in the GlyphWorks platform (HBM).

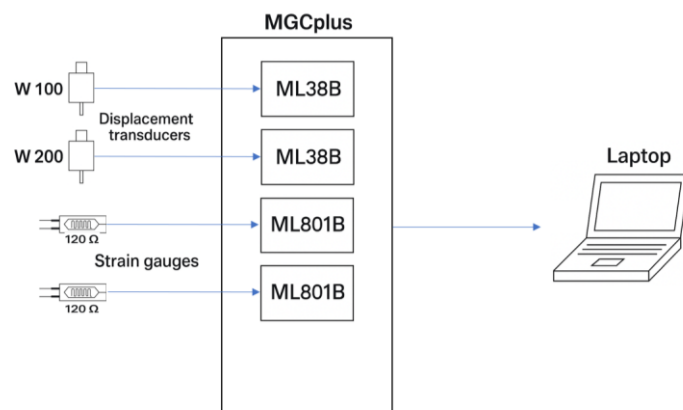


Fig. 4 - Block diagram of the equipment used in testing

The purpose of the tests performed was to determine the variation of the displacements of the self-steering wheel/axle in the transverse direction X_H and vertical direction X_V , when passing over obstacles, as a result of the manifestation of β and θ oscillations, with the variable working parameters of the running system, such as: mass to be transported, travel speed, obstacle height, tire type and air pressure in it, in order to determine the influence of each parameter on the kinematics of the self-steering axle. The test parameters are specified in table 2 and the tests performed included multiple combinations between them.

Table 2

Test parameters										
Parameter name										
Average speed, v [m/s]	Obstacle height, h [mm]				The load on the wheel, m [kg]			Tire air pressure, p [bar]		
0.62	25	50	80	100	500	1000	1500	3.5	3.0	2.5
1.88										
2.92										
4.50										

It was taken into account that the height of the chosen obstacles should be in accordance with the estimated parameters of the main road categories (Draghici I., 1980; Untaru M., Stoicescu A., 1981), according to table 3.

Table 3

Estimated parameters of the main road categories			
No.	Road category	Height of irregularity h [mm]	Length of irregularity L [m]
1	Hiway	10...20	10...15
2	Asphalt road	10...20	1...2
3	Paved road	30...40	0.15...0.30
4	Dirt road	50...70	0.10...0.15

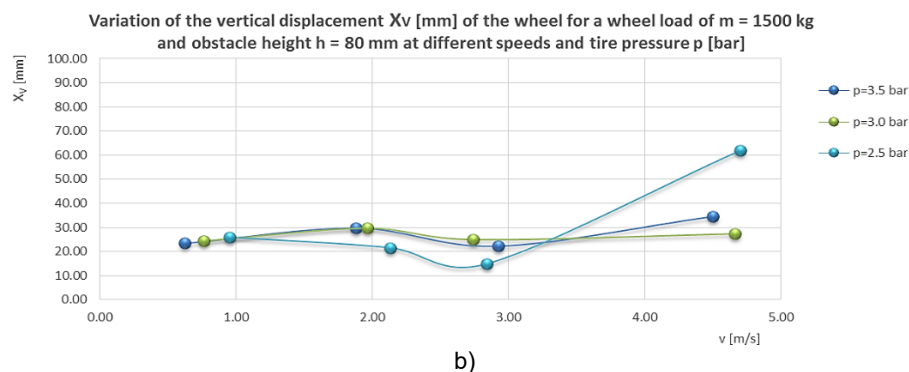
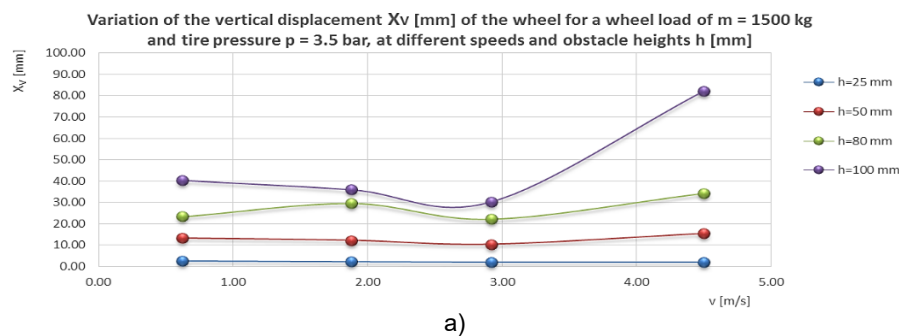
RESULTS

The experiments were carried out with variable working parameter values from table 2.

In the case of the experiments carried out for the 1500 kg mass on the wheel, the installation of the transducers in the system and their calibration allowed only the recording of the vertical oscillations of the axle in one direction, when climbing the unevenness (the values being only positive), and for the transverse oscillations on one side (left) compared to the direction of travel, the system allowing the mechanical locking of the wheel on one of the sides (right).

Under these conditions, the variations of the vertical oscillations, embodied in linear displacements X_V , are presented graphically in Fig. 5a, b, c, and of the transverse oscillations X_H , according to Fig. 6a, b.

In the case of experiments carried out for a mass of 1000 kg on the wheel, the placement and calibration of the transducers also allowed the recording of vertical oscillations when the wheel climbing the bump (positive values) and descended from the bump (negative values) and of the transverse ones on the left (positive values) and on the right (negative values), according to the graphs in Fig. 5.d, respectively Fig. 6.c.



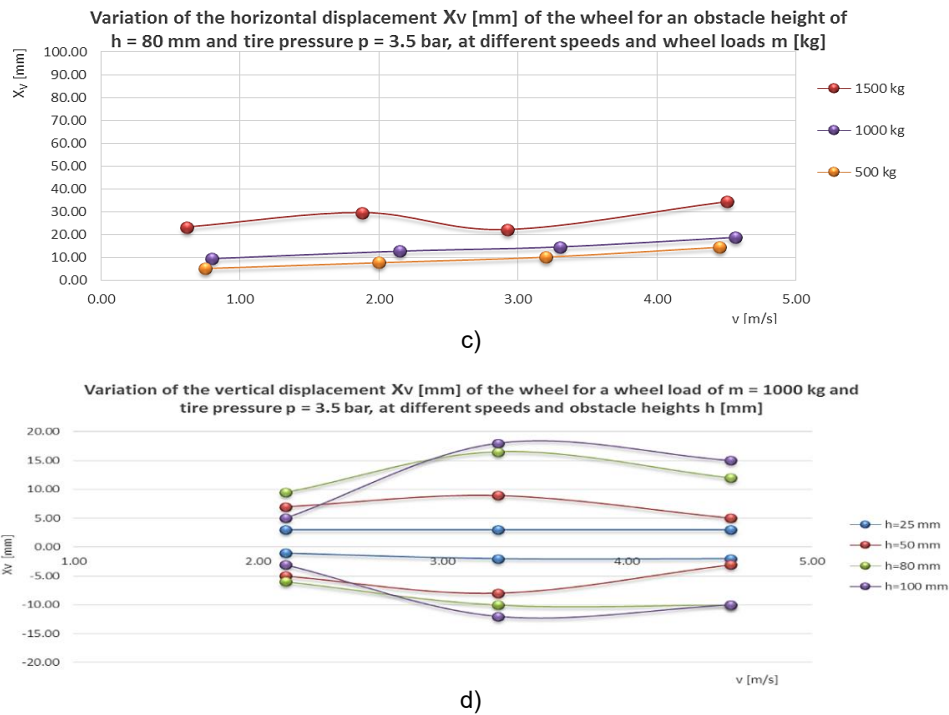


Fig. 5 - Variations of vertical axis oscillations, β , with working parameters, v , h , p , m

The vertical wheel displacement X_V and therefore the oscillation β , increases with the increase in the speed of movement and the air pressure in the tire when passing over bumps, the increase being more pronounced at high bumps and tire pressures, Fig. 5a. b.

Increasing the load on the wheel does not imply significant changes in the value of the displacements X_V , especially at small bumps, Fig. 5c.

The values of the vertical displacements are higher with the increase in the height of the bump and are significantly higher when the wheel moves upwards (lifts), Fig. 5d.

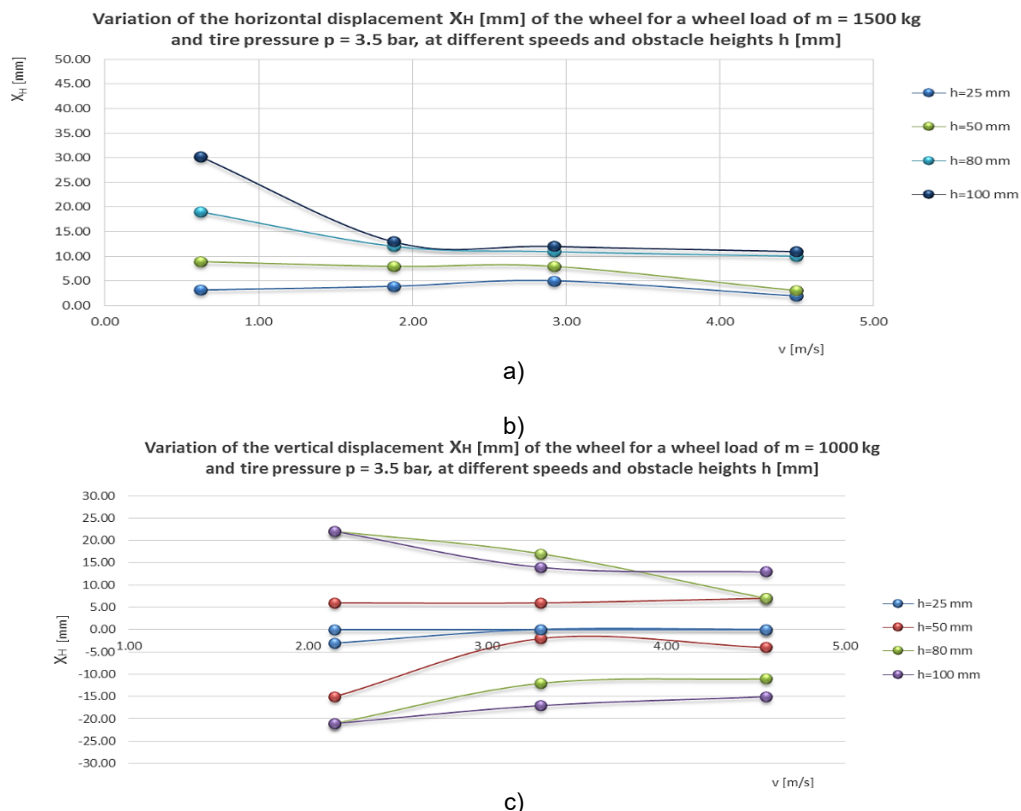


Fig. 6 - Variations in transverse wheel oscillations, θ , with working parameters, v , h , p , m

The displacements of the self-directional wheel in the horizontal-transverse plane “shimmy” (oscillation θ) do not manifest themselves when moving on a smooth road or on small bumps, below 25 mm, Fig. 6.a

On larger bumps and with increasing speed, a decrease in the amplitude of the oscillations θ is observed because the forces in the telescopic shock absorbers also increase with the speed of movement, Fig. 6.a. The transverse oscillations do not change significantly with the variation of the air pressure in the tire, Fig. 6.b.

The transverse oscillations show only small variations in the left-right movement of the self-steering wheel Fig. 6c. Figure 7 illustrates the time evolution of the oscillations of the self-steering axle β and the wheel θ , from the moment the wheel encounters the bump until the oscillations are damped and return to steady state.

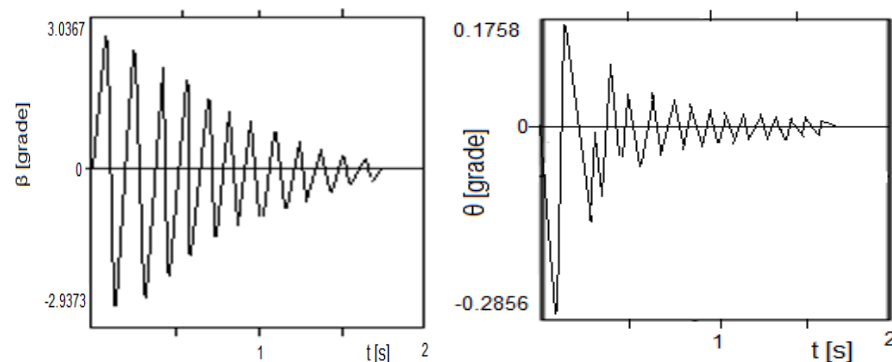


Fig. 7 - Variation of self-steering axle β /wheel θ oscillations over time, when passing over bumps

As shown in Fig. 7, the oscillations exhibit an initial moderate damping immediately after contact with the irregularity, after which the attenuation becomes progressively more pronounced, leading to complete cancellation of the oscillatory motion by the end of the observed period.

CONCLUSIONS

Based on the experimental research, the following conclusions can be drawn:

- ✓ The vertical displacement of the wheel X_V , and consequently the oscillation angle β , increases with vehicle speed and tire inflation pressure when passing over road irregularities Fig. 5 a, b;
- ✓ Increasing the wheel load does not significantly affect vertical displacements X_V on small bumps, as higher loads result in greater tire deformation which partially absorbs the disturbance;
- ✓ Transverse oscillations of the self-steering wheel (“shimmy” angle θ) do not manifest on smooth roads or when encountering small irregularities below 25 mm; the resulting disturbances are sufficiently damped by the telescopic shock absorbers in the steering assembly;
- ✓ For larger bump heights and higher travel speeds, a decrease in the oscillation amplitude θ is observed. This occurs because the damping force of the shock absorbers increases with piston velocity, counteracting the higher excitation forces. Under these conditions (bump heights 25-100 mm and speeds 0.5-5 m/s), transverse displacements fall within 30-10 mm (Fig. 6a);
- ✓ When wheel load increases, oscillation damping becomes more pronounced, even over larger irregularities, due to higher inertial stability moments within the system;
- ✓ On large surface irregularities (80-100 mm) at speeds above 10 km/h, the amplitude of transverse oscillations remains nearly constant, as increased tire lateral stiffness and shock absorber forces provide greater damping;
- ✓ Although the lateral tire adhesion force opposing “shimmy” decreases with speed, the damping force of the shock absorbers increases with piston velocity, resulting in a net reduction in shimmy oscillation effects as travel speed increases;
- ✓ As shown in Fig. 7, oscillations exhibit moderate initial damping immediately after encountering the irregularity, followed by a more pronounced attenuation phase, culminating in complete decay of the oscillatory motion.

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