COMPARATIVE ESTIMATION OF MANEUVERABILITY OF THE MULTI-TRACK ROAD TRAINS OF DIFFERENT LAYOUT SCHEMES

Volodymyr Sakhno[1], Igor Murovanyi[2], Oleksandr Razboinikov[1], Olekcii Palamarchyk[1], Valerii Dembitskyi[2,*]

[1]National Transport University, Kyiv, Ukraine
[2]Lutsk National Technical University, Lutsk, Ukraine

*E-mail of corresponding author: dvm2@meta.ua

Valerii Dembitskyi 0000-0002-1006-9218,
Igor Murovanyi 0000-0002-9749-980X,
Olekcii Palamarchyk 0009-0003-9782-1015
Volodymyr Sakhno 0000-0002-5144-7131,
Oleksandr Razboinikov 0000-0003-3024-0999

Resume

Today, in the constructions of multi-link road trains, two main layout schemes are used, as a rule - trailer (car + n trailers) and semi-trailer (tractor car + n semi-trailers).

Previously conducted studies established that the maneuverability indicators of the road trains can be determined on wheels rigid in the lateral direction, that is, according to kinematic models, which are based on the angles of assembly of the road train links. These angles are defined for both a three-link trailer and a semi-trailer vehicle train, for different locations of the extended link.

For the semi-trailer road trains, the requirements for maneuverability are not met, and therefore the trailer links must be equipped with more or less complex control systems. With a direct control drive on the front axles of the second and third semi-trailers, when turning at 90º and 180º, only the first layout scheme satisfies the requirements for maneuverability.

Available online: https://doi.org/10.26552/com.C.2025.005

Article info

Received 20 June 2024
Accepted 30 September 2024
Online 6 November 2024

Keywords:

maneuverability
road train
three-link trailer
semi-trailer
folding angles
turning angles

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Issue

Ensuring sustainable and stable development of the state's economy necessitates putting into operation the intermodal transport systems. One of the most promising and widespread among them is container transportation. To maintain the competitiveness of container transportation, it is important to put into operation the modern designs of containers, designed for the transportation of a wide range of goods. That can be achieved by putting into operation the multi-modal vehicles [1-4]. A container is the most perspective and widespread multi-modal vehicle. A container delivery is ordered, not only by big trade companies, but by the enterprises of middle and little range that make import and export of goods, as well, [5]. Most customers choose exactly the container transportation due to the clear advantages, namely a goods preservation; a reduction of terms for cargo-handling works due to what the goods delivery time is reduced; a possibility of transporting of any goods, including dangerous, perishable, bulked, heavy-weight and off-clearance loads; a universality as a container can be transported by a car, train and sea transport that allows to reduce the expenses of time and money for a load delivery into the final destination; a possibility of the prefabricated loads delivery; a computerization of the delivery process operation [6]. The choice depends on the load peculiarities and a distance where this load should be delivered. A load transportation price depends on this, as well. Container freight transportation by the two-track, and in recent years, three-track road trains are the most popular. This is due to a number of advantages of three-track road trains compared to two-track trains [7-8] - less specific weight, that is a weight that is equal to a unity of carrying capacity; a lower cost price of the industrial mass production of the trailers and semi-trailers then the vehicles that correspond to them by the carrying capacity; a bigger specific body area (approximately half as much again), that makes the significant operation advantages; the less investments into the building of storage areas as the trailers and semi-trailers do not need the covered

Figure 1 *Road train with two trailers [9]*

lodgings; a possibility to quickly plan the transportation with different structure of road train depending on the operating conditions; the less specific charges (per a single unit of carrying capacity) of labor force and materials for maintenance and repair works. It is not strange that in Europe there are 35-meter road trains with two trailers that can carry three containers [9]. It is explained by the fact that the Cargo transportation rules, as a traffic code, have a tendency to change from time to time. So recently in Denmark there was a thought about a necessity of using the long road trains of 34 meters on the general usage roads. Such an innovation is related to an intention to reduce the number of the exhaust gas emissions (Figure 1).

If the local politicians support this initiative, Denmark can become the second country in Europe where it would be allowed to drive the road trains more than 30 meters long, namely the wagons with double trailers (34.5 m), after such initiative on its roads was supported by Sweden, where such road trains have been operated for five last years already. An idea of using the long-dimension vehicles on its roads is also investigated in Poland. It is worth saying that in USA and Australia the length of road trains is not restricted, that is why one can meet there the real champions, for example, in Australia a general length of road train can become approximately 50 meters.

It is necessary to notice that the full masses, dimensions and permissible loads for the trucks in Europe are regulated by DIRECTIVE 2002/7/EC [10], where the maximum full mass of a two-track road train with a semi-trailer on a pneumatic support can not exceed 44 t. When using a three-track road trains, a general mass of a road train G_{an} is increasing up to 60 t, and of a multi-track ones - up to 100 t. Along with that for a two-track road train, it is possible to use a double-axle vehicle-tractor (at a load on a driving axle $G_2 = 0.25 \times G_{an} = 11.0$ t), for the three-track road train - a three-axle vehicle-tractor with a wheel formula 6x4 ($G_2 = 0.25 \times G_{an} = 15.0$ t), for a multi-track road train - a three-axle vehicle-tractor. A further increase of a mass of a multi-track road train up to 90to 100 t needs using of a multi-axle vehicle-tractor or a hybrid power drive of road train.

A base of multi-track road trains, together with vehicles-tractors, consists of trailers and semi-trailers. Along with that, at a great variety of layout schemes of multi-track road trains, a construction of the last-mentioned ones can be composed from a comparatively little number of constructively completed functional elements - modules [11]. This is a unique system “road train” can be represented as a composed of two or more sub-systems, articulated between them - “vehicle-tractor” and “trailer tracks (trailer, semitrailer)” depending on a layout scheme of a road train. Today, in the constructions of multi-track road trains, as a rule are used the two main layout schemes - trailer (vehicle + *n* trailers) and semi-trailer (vehicle-tractor + *n* semitrailers). That is why it is reasonable to compare two these layout schemes at a transportation of three containers.

2 Literature sources analysis

Modern development of public and truck transport leads to increasing f the vehicles demand for passenger and cargo carrying. This tendency proves the arguments of power economy and decreasing of environmental pollution level that is caused but a restricted number of the vehicles and drivers necessary to carry a great number of loads and passengers. As a consequence, the trucks and city buses manufacturers today design the constructions of high capacity in the form of joint and multi-track vehicles. [12-15]. The swing joints make the long vehicles to be unique in use and admit a quick maneuverability even in dense urban conditions. However, the maneuverability of the long-articulated vehicles can be dangerous even for experienced drivers. So, the researcher Altafini [16] showed that the tracks with a great number of trailers (MTAHV) demonstrate the unstable operation modes at high speeds, including an assembly of tracks, a swinging of trailer and turning over. These unstable, unfavorable operation modes, can lead to the traffic accidents. On the other side, these vehicles have bad maneuverability at low speeds.

To increase a safety of the multi-track road trains operating, the numerous investigations were conducted, for example, Latif, Chalhoub and Pilipchuk [17] was examined a using of a slide mode controller, as well as a controller with feedback with an integral state at different driving situations and the pavement conditions.

In a research work [18] was shown that the interconnections between the axles and the tracks of the vehicles with some trailers can create a specific oscillating behavior of the trailers during the vehicle's maneuvers. These oscillations are a direct consequence of a vehicle kinematic feature, related with a construction of a traction and towed device. At an example of one pair of tracks of the vehicles there are accepted the regularities of its turning that are expanded in future on a road train with a free number of trailers. Numerous results obtained for a kinematic of three trailers approve the theoretical thoughts that give some cardinal view on a problem.

That is why the typical kinematic models of the multi-track road trains will be useful while solving such problems as: a formal analysis of the kinematic features, a quick planning of the nominal maneuvers, a prediction of the operation modes etc., [19-21].

For a kinematic vehicle model with n trailers was offered an adaptive control scheme based on a neural network of a radial-basis function (RBFNN), [22].

As a conducted analysis has shown, a lot of research works are dedicated to the problem of improving of the operating indices of the multi-track vehicles [23-27].

The development of compact and easy to use mathematic models of the articulated vehicles for planning, controlling and localization of driving, becomes increasingly important in a time of intellectual transport systems, especially when there is a need for effective predictions of driving for the multi-track vehicles of different kinematic structures [28-33]. In a reference [34] a module algorithm approach to the kinematic modeling of non-holonomic (multiple-unit) articulated buses was offered, including the trucks with n-trailers (as a separate case), that consists of traction vehicle passively joined to a free number of guided and unguided trailers and with different placement of controlled axles in a kinematic chain. Kinematic models are valid at a condition of absolute rolling of all wheels of a vehicle (without sliding/sliding) that is practically approved for the conditions of maneuverability at low speed. In a research work [21] it is presented a conception and an analysis of stability of a feedback control system to track a trajectory of a road train with free number of articulated trailers. Thanks to the use of a cascade management structure, the proposed solution is modular and easily scalable depending on the number of trailers. A formal analysis of the closed system assures the sufficient conditions for an asymptotic tracking of a totality of the so-called sample trajectories with trajectory curvature both invariable and variable in time. The cascade law of trajectory control, investigated in the article, solves a problem of tracking the kinematics of a multi-track road train.

At the same time, considerably less attention in the literature is given to the issues of kinematic modeling and analysis of semi-trailer road trains (such as B-double and B-triple), which differ in design from more common trailer road trains, as well as to the study of their maneuverability. In a scientific article [35] was shown that for the road trains of semi-trailer scheme a kinematic model is more complicated than in a standard case of a road train with some trailers concerning its controllability. Along with that, the more complicated equations can be interpreted as the virtual steering control of the wheels situated on the semi-trailers, whose turning angles are found by the non-linear feedback from an output state of a system configuration.

A curvilinear motion of a road train is characterized by such mode parameters as running speed, turning radius and turning angles of controlled wheels, that during the road train operation do not stay constant. That is why to estimate the maneuverability of the vehicles, both kinematic and dynamic indices are used.

The dynamic indices are assured by a system "engine-transmission" of a traction vehicle or vehicle-tractor.

The kinematic indices should assure:

- an overall traffic lane (OTL), that is equal to a difference of external and internal overall turning radii. Taking into consideration that the overall turning radii are fixed (R_{eo}=12.5 m, R_{io}=5.3 m), an overall traffic lane would be also fixed (B_0 = 7.2 m);
- a possibility of backward running.

The least studied until today is a question of possibility of a road train backward running that was not almost theoretically considered for the multi-track road trains. However, for the multi-track road trains that run as a rule between terminals situated at the city entrance, a problem of backward running is not actual.

The authors examine a maneuverability of the three-track road trains of different layout schemes [36], as though if a train has more than three tracks, the difficulties concern the fact that an investigation of running of such a multi-track vehicle is rather complicated because of the necessity to take into consideration an influence of many factors on the running character.

As is known, the characteristics of maneuverability and running stability of a vehicle are determined by a combination of operating, mass-geometric and construction parameters of its modules and their control systems. In general case, the desirable combinations of named parameters from the point of view of maneuverability and stability in a range of operating loadings and running speeds, even for the same vehicle can be different. As a consequence, on the early phases of vehicle creation, it is difficult to get the precise construction parameters and quantity indices by the criterion of maneuverability and its running stability. The success in solving such problems depends on the

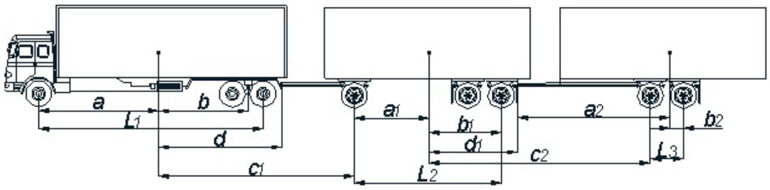


Figure 2 *Layout scheme of a trailer road train*

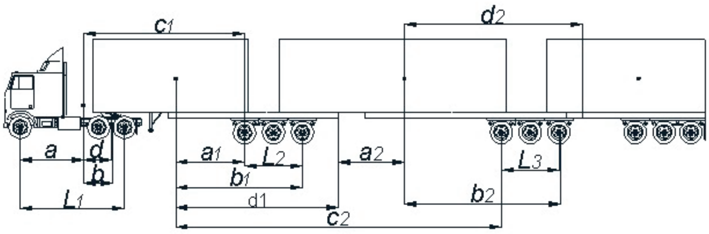


Figure 3 *Layout scheme of a semi-trailer road train*

fact how successfully a mathematical model and its substantial parameters, which describe a behavior of a dynamic system in different running modes, are chosen. For maneuverability it is an equation in a plane-parallel movement, for stability - in spatial one. So, in a research work [36] the differential equations were derived of plane-parallel movement to find the parameters of maneuverability and running stability of the two-track semi-trailer and three-track trailer road trains, however, the using of these equations to comparatively estimate the multi-track road trains - container carriers can lead to a substantial fault. Because of this, the aim of a given research work is a comparative estimation of multi-track road trains - container carriers of different layout schemes by the maneuverability parameters.

3 Research requirements

The overall lane of curvilinear movement of a multi-track road train, in contrast to a rectilinear movement lane, has a difficult form, restricted by the projections of trajectories on a horizontal plane of external wing, concerning a turning center of a vehicle-tractor and rear end of trailer or semi-trailer. The overall traffic lane (OTL) of a road train at turning is determined by a main trajectory of a vehicle-tractor and a displacement of trajectory of trailer or semi-trailer from the main trajectory to the turning center. The overall traffic lane and the overall passage (a part of space taken by a road train at turning) get their maximum at the stable curvilinear, that is circular, trajectory. That is especially valid on that trajectory that the overall traffic lane of a multi-track road train should be determined. In a research work [36] was shown that the indices of the road trains maneuverability (at a movement with the speeds that do not exceed 10 m/s) it is possible to determine on the rigid in lateral direction wheels, that is by the kinematic models.

The next layout schemes of the multi-track road trains are examined - container carriers with the uncontrollable trailer tracks:

- a road train-container carrier composed of three trailers, Figure 2;
- a road train-container carrier composed of three semi-trailers (road train of type B-triple), Figure 3.

Each of these layout schemes was examined in two variants that were characterized by a location of a 40-foot container - inside or at the end of a road train.

All the indices of maneuverability are determined by the parameters of a curvilinear movement of a road train, the main of them are the assembly angles of a road train. So, for a trailer road train these would be two assembly angles: the first one between a tractor

$$\begin{aligned}
&\frac{d\varphi_1}{dt} + \frac{\nu_A}{L_1 \dfrac{\sin(\pi/2 - \varphi_2 - \alpha_1)}{\sin(\varphi_1 + \varphi_2 + \alpha_1)}} - \frac{\nu_{C1} tg\theta}{a + b - d} = 0 \\
&\frac{d\varphi_2}{dt} - \frac{\nu_{C1}\sin(\pi/2 - \varphi_1)}{\dfrac{a_1 + b_1}{tg\varphi_1}\sin(\pi/2\varphi_2 - \alpha_1) \times \sqrt{1 + \left(\dfrac{d_1 - c_1}{a_1 + b_1} tg\varphi_2\right)^2}} - \frac{\nu_A \sin(\varphi_1 + \varphi_2 + \alpha_1)}{L_2 \sin(\pi/2 - \varphi_1 - \alpha_1)} = 0, \\
&\frac{d\varphi_3}{dt} - \frac{\nu_{C1}\sin(\varphi_1 + \varphi_2 + \alpha_1) \times L_1^2 \sin(\gamma_1 + \varphi_3 + \alpha_2)}{L_2 L_3 \sin\varphi_2 \sin(\pi/2 - \varphi_3 - \alpha_2)} \times \\
&\times \frac{\sin(2/\pi - \varphi_2 - \alpha_1) ctg\gamma_1}{\dfrac{a_2 + b_2}{tg\varphi_2} \times \sqrt{1 + \left(\dfrac{d_2 - c_2}{a_2 + b_2} tg\varphi_2\right)^2} + L_2 \dfrac{\cos\varphi_1}{\sin(\varphi_1 + \varphi_2 + \alpha_1)} - L_3 \sin(\pi/2 - \varphi_2 - \alpha_1) ctg\gamma_1} - \\
&- \frac{\nu_{C1} L_1 \sin(\varphi_1 + \varphi_2 + \alpha_2)}{L_2 L_3 \sin(\pi/2 - \varphi_2 - \alpha_2)} = 0.
\end{aligned} \tag{1}$$

$$
\begin{aligned}
&\alpha_1 = \operatorname{arctg}\left(\frac{d_1 - c_1}{a_1 + b_1}\operatorname{tg}\varphi_1\right),\\
&\alpha_2 = \operatorname{arctg}\left(\frac{d_2 - c_2}{a_2 + b_2}\operatorname{tg}\varphi_2\right),\\
&\gamma_1 = \operatorname{arctg}\left(\frac{l_1 \sin(\varphi + \varphi_1 + \alpha_1)}{L_1 \sin(\pi/2\varphi_2 - \alpha_1)} \times \frac{1}{\sqrt{1 - \left\{\frac{\left[\frac{\sin(\pi/2 - \varphi_2 - \alpha_1)}{\sin(\varphi_2 + \varphi_1 + \alpha_1)}\right]^2 + 1 - \left[\frac{\sin(\pi/2 - \varphi_1)}{\sin(\varphi_2 + \varphi_1 + \alpha_1)}\right]^2 \Big]^2}{2 \times \frac{\sin(\pi/2 - \varphi_2 - \alpha_1)}{\sin(\varphi_2 + \varphi_1 + \alpha_1)}}\right\}}}\right),\\
&\gamma_2 = \operatorname{arctg}\left(\frac{L_2 \sin(\varphi_3 + \alpha_2)}{L_3 \sin(\pi/2 - \alpha_2)} + \frac{1}{\sqrt{1 - \left\{\frac{\left[\frac{\sin(\pi/2 - \alpha_2)}{\sin(\varphi_3 + \alpha_1)}\right]^2 + 1 - \left[\frac{\sin(\pi/2 - \varphi_3)}{\sin(\varphi_3 + \alpha_2)}\right]^2}{2 \times \frac{\sin(\pi/2 - \alpha_1)}{\sin(\varphi_3 + \alpha_1)}}\right\}}}\right).
\end{aligned}
\tag{2}
$$

In Equations (1), (2) the following notations are adopted:
L_1, L_2, L_3 - a base of tracks of a road train, m;
v_A - a road train running speed, m/s;
v_C - a vehicle-tractor mass center speed, m/s;
θ - a turning angle of the controlled wheels of a vehicle-tractor, rad;
a - a distance from a mass center of a vehicle-tractor to a front axle;
b - a distance from a mass center of a vehicle-tractor to an axle of balance beam of rear axles;
d - a distance from a mass center of a vehicle-tractor to a point of joining of first trailer track;
φ_1 - an assembly angle between the vehicle-tractor and a first trailer track;
φ_2 - an assembly angle between the first and second trailer track;
φ_3 - an assembly angle between the second and third trailer track;
a_1, a_2 - a distance from a mass center of the first (second) trailer track to a front axle of trailer and a point of joining with a previous track (of semi-trailer);
b_1, b_2 - a distance from a mass center of the first (second) trailer track to a rear axle of trailer (semi-trailer);
c_1 - a distance from a mass center of vehicle-tractor to a front axle of the first trailer track;
d_1- a distance from a mass center of the first trailer track to a point of joining with the second trailer track;
c_2 - a distance from a mass center of the first trailer track to a front axle of the second trailer track;
d_2- a distance from a mass center of the second trailer track to a point of joining with the third trailer track.

and the first trailer track, and the second one - between the second and third trailer track, and for a road train of type B-triple - these would be three assembly angles: the first one between the vehicle-tractor and the first semi-trailer, the second one - it is an angle between the first and second semi-trailers, and the third one is between the second and third semi-trailer. Since the most common case is a road train of type B-triple, the assembly angles were determined for it, as it is shown in [36].

In given system of equations (2), the additional angles are determined by the dependences.

For a trailer road train, it is necessary to adopt $\varphi_1 = 0$.

Since the road train comes through different phases of turning, these are namely - an entry in turning, a movement in a circle, an exit of turning, a linear movement of a road train, so the assembly angles should be determined exactly for these phases.

Figure 4 shows an example of the assembly angles of the road trains tracks of a semi-trailer scheme. For the road trains of trailer scheme the assembly angles are for 17 and 21 % smaller than the second and third assembly angles of the semi-trailer road train for different turning phases.

By the found assembly angles of the road train tracks, the overall turning radii of a road train and a presumptive maneuverability index - an overall traffic lane - are determined.

In Tables 1 and 2 are given the layout schemes of typical road trains that are constructed thanks to a software of Scania company, and t an overall lane of these road trains is determined, using the Equations (1) - (6), at circular movement and entry in turning.

As it follows from the data of Table 1, none of the layout schemes of three-track road train satisfies the requirements of DIRECTIVE 2002/7/EC concerning maneuverability. Taking into account a character of such road trains operation (running between terminals at the city entrance), more important are the parameters of maneuverability of a road train at the turning of 90° and 180°.

In Table 2 there are given the values of overall radii and of overall traffic lane of the road trains that are investigated, at the named turnings.

As it follows from Table 2, almost all the trailer road trains, in contrast to the semi-trailer ones, at turning of 90° and 180°, satisfy the requirements of DIRECTIVE

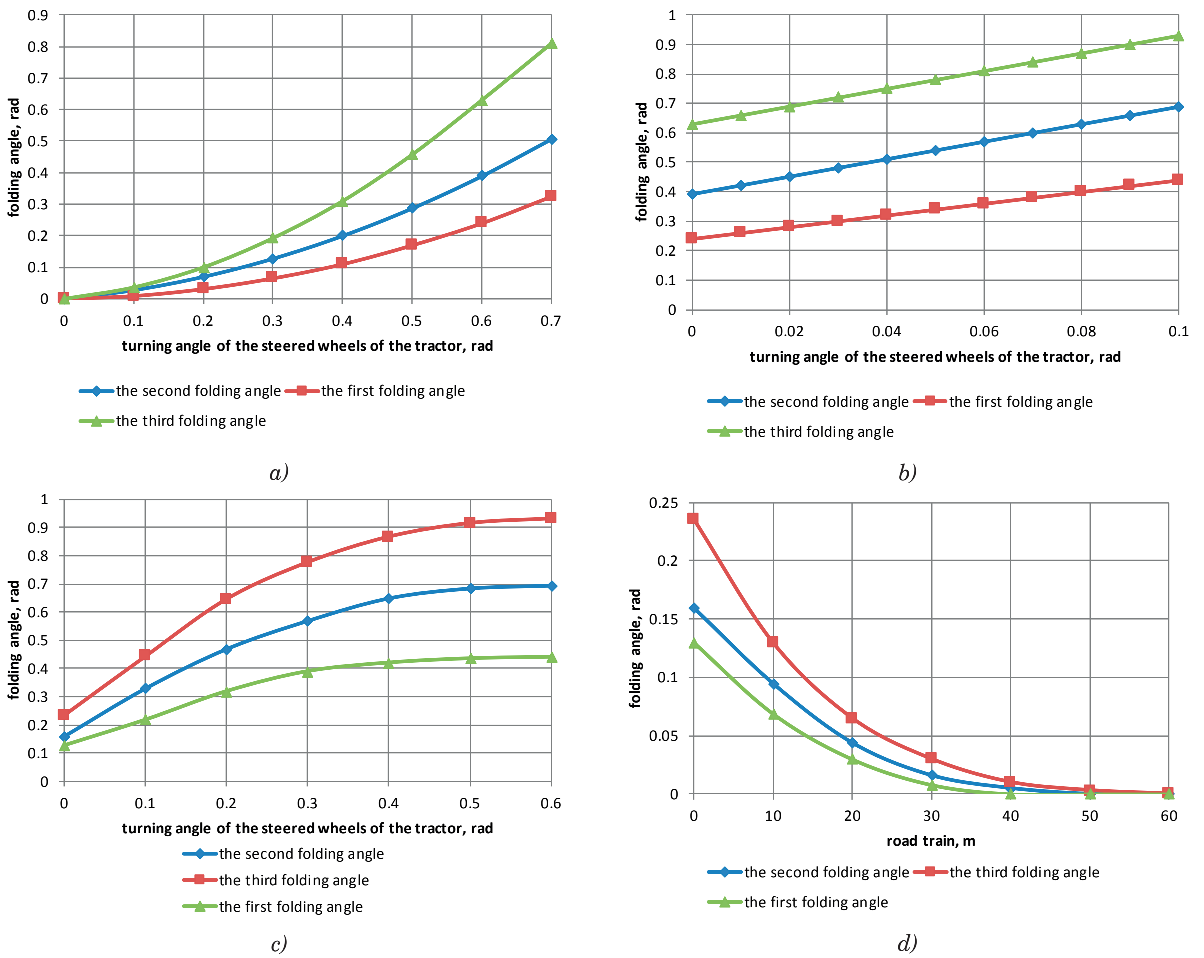


Figure 4 *Change of assembly angles of the road train for different turning phases:a) entry in turning; b) movement in a circle; c) exit of turning; d) tractor movement on a linear trajectory*

2002/7/EC concerning maneuverability. Because of that, the semi-trailer road trains should be equipped with the control systems.

In a research work [36] is shown that for the trailer and semi-trailer road trains, the most distributed are the systems of direct control when a turning angle of the controlled wheels (axle) of trailer track is determined as a function of assembly angle. Since the second and third trailer tracks should be, first of all, equipped with the control systems, so exactly these tracks should have the controlled wheels (axles) whose turning is made correspondingly to an assembly angle.

While having the controlled trailer tracks, the assembly angles for different turning phases are written like [36]:

- at entry in turning:

$$\frac{d\varphi_2}{d\theta}=\frac{tg(\theta)}{K_n\cdot L_2}\times \times\left(\begin{array}{l}1-\dfrac{L_2}{tg(0)}\times\\ \times\dfrac{\left(\sin\left(\dfrac{\varphi_2}{i_0}\right)-\dfrac{C\cdot tg(\theta)}{L_2}\cdot\cos\left(\dfrac{\varphi_2}{i_0}\right)\right)}{L_2\cdot\left(\dfrac{\varphi_2}{i_0}-\varphi_2\right)}\end{array}\right), \tag{3}$$

$$\frac{d\varphi_3}{d\theta}=\frac{\left(\sin\left(\dfrac{\varphi_2}{i_0}\right)-\dfrac{C\cdot tg(\theta)}{L_2}\cdot\cos\left(\dfrac{\varphi_2}{i_0}\right)\right)}{K_n\cdot L_2\cdot\cos\left(\dfrac{\varphi_2}{i_0}-\varphi_2\right)}- -\frac{\left(\cos(\varphi_2)+\dfrac{C\cdot tg(\theta)}{L_1}\cdot\sin(\varphi_2)\right)}{K_n\cdot\cos\left(\dfrac{\varphi_3}{i_1}-\varphi_3\right)}\times \times\frac{\sin\left(-\dfrac{\varphi_2}{i_0}+\varphi_2+\dfrac{\varphi_3}{i_1}-\alpha_1\right)}{L_3\cdot\cos\left(\dfrac{\varphi_2}{i_0}-\varphi_2+\alpha_1\right)}, \tag{4}$$

where K_n - a mode turning coefficient;
θ - a turning angle of the controlled wheels of a vehicle-tractor, rad;

- at movement in a circle:

$$\frac{d\varphi_2}{d\varphi_K}=\left(\begin{array}{l}1-R_{0MIN}\times\\ \times\dfrac{\left(\sin\left(\dfrac{\varphi_2}{i_0}\right)-\dfrac{C}{R_{0MIN}}\cdot\cos\left(\dfrac{\varphi_2}{i_0}\right)\right)}{L_2\cdot\cos\left(\dfrac{\varphi_2}{i_0}-\varphi_2\right)}\end{array}\right), \tag{5}$$

***Table 1** Turning parameters of three-link road trains*

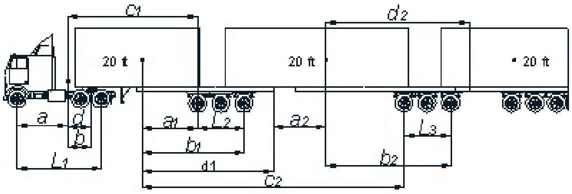
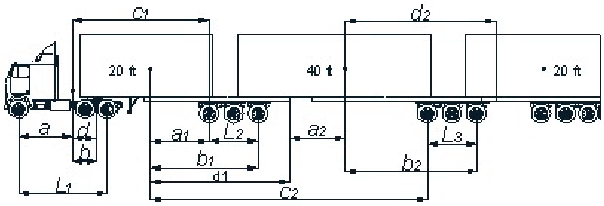
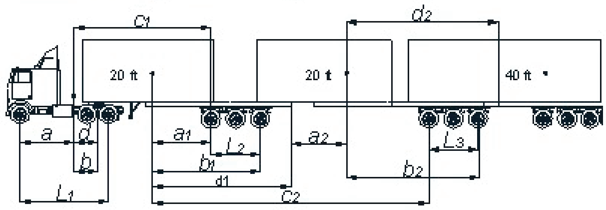
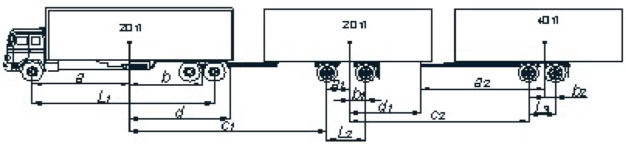
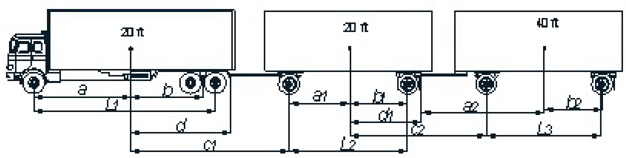
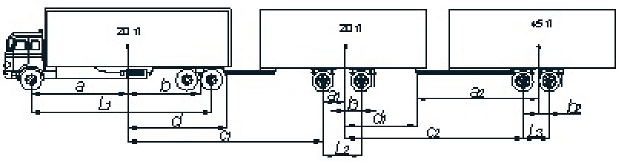
Road train type		Turning parameters, m		
		R_{eo}	R_{io}	B_o
1		5.3	13.925	8.625
2		5.3	14.401	9.101
3		5.3	14.625	9.325
4		5.3	12.433	7.133
5		5.3	12.053	6.753
6		5.3	14.723	9.101

***Table 2** Overall radii and overall traffic lane of the road trains*

Road train type	Turning parameters, m					
	180º			90º		
	R_{eo}	R_{io}	B_0	R_{eo}	R_{io}	B_0
1	13.925	5.731	8.194	13.925	6.143	7.782
2	14.401	5.750	8.651	14.401	6.183	8.218
3	14.625	5.766	8.859	14.625	6.209	8.416
4	12.433	5.353	7.080	12.433	5.707	6.726
5*	12.053	5.638	6.415	12.053	5.959	6.094
6	14.723	7.058	7.665	14.723	7.521	7.202

*Note: trailers with the separated axles with controlled front axles

$$\frac{d\varphi_3}{d\varphi_K} = \frac{\left(\sin\left(\frac{\varphi_2}{i_0}\right) - \frac{C}{R_{0MIN}} \cdot \cos\left(\frac{\varphi_2}{i_0}\right)\right)}{L_2 \cdot \cos\left(\frac{\varphi_2}{i_0} - \varphi_2\right)} - \frac{\left(\cos(\varphi_2) + \frac{C}{R_{0MIN}} \cdot \sin(\varphi_2)\right)}{L_3 \cdot \cos\left(\frac{\varphi_3}{i_0} - \varphi_3\right)} \times \frac{\sin\left(-\frac{\varphi_2}{i_0} + \varphi_2 + \frac{\varphi_3}{i_1} - \alpha_1\right)}{\cos\left(\frac{\varphi_2}{i_0} - \varphi_2 + \alpha_1\right)}, \tag{6}$$

where φ_K - an angle of inclination of the road train, rad;

- at exit of turning are used the same Equations (3) and (4), but a mode coefficient of turning K_n should be taken with negative sign;
- at a linear movement of tractor-vehicle (at this phase the assembly angles do not depend anymore on a position of driving wheels but only on a distance that is passed by a vehicle-tractor, then $d\theta = K_n \cdot dS_0$, where S_0 - the initial value of the path, at $\theta = 0$ one will get:

$$\frac{d\varphi_2}{dS_0} = -\frac{\sin\left(\frac{\varphi_2}{i_0}\right)}{L_2 \cdot \cos\left(\frac{\varphi_2}{i_0} - \varphi_2\right)}, \tag{7}$$

$$\frac{d\varphi_3}{dS_0} = \frac{\sin\left(\frac{\varphi_2}{i_0}\right)}{L_2 \cdot \cos\left(\frac{\varphi_2}{i_0} - \varphi_2\right)} - \frac{\cos(\varphi_2)}{\cos\left(\frac{\varphi_2}{i_0} - \varphi_2 + \alpha_1\right)} \times \frac{\sin\left(-\frac{\varphi_1}{i_0} + \varphi_1 + \frac{\varphi_2}{i_1} - \alpha_1\right)}{L_3 \cdot \cos\left(\frac{\varphi_3}{i_1} - \varphi_3\right)}, \tag{8}$$

where C - a distance from a rear axle of a first semi-trailer to a point of joining with the second semi-trailer;
α_1 - an angle between a perpendicular to a rear axle of tractor and a ray that joins a point of joining of the first semi-trailer with the second one and an immediate turning center of a road train;
K_n - a mode turning coefficient;
i_o, i_1 - correspondingly the speed ratio of the front wheels control linkage of the second and third semi-trailers (according to the data from [15] we take as equal i_o = 0.5 and i_2=0.6).

Introduction of the trailers tracks control leads to a reducing of first and second assembly angles, correspondingly for 18 to 20% and 27 to 32%. It leads to a decreasing of an overall track lane of a road train, while making different turning by it, Table 3.

Analysis of the data of Table 3 shows that the three-track semi-trailer road trains even with the controlled second and third semi-trailers, while carrying one 40- or 45-feet container and two 20-feet containers, do not satisfy the requirements concerning a maneuverability and at turning of both 90° and 180°, taking into account their significant length (about 36 m). Issuing from a presented analysis, one can make a conclusion that for the multi-track road trains there is actual a choice of type of the wheels (axles) control linkage of the semi-trailer tracks and their location in the road train compound.

4 Results discussion

While carrying three containers - two 20-feet and one 40 or 45-feet, there is important not only a choice of layout scheme of road train (trailer, semi-trailer one), but a location of the elongated track (for carrying 40- and 45-feet containers) in a road train compound, as well. This choice is possible to do based on the analysis of maneuverability indices of trailer and semi-trailer road trains.

Previously conducted studies established that the maneuverability indices of the road trains (when moving at speeds not exceeding 10 m/s) can be determined on wheels rigid in the lateral direction, that is, according to kinematic models, which are based on the assembly angles of the road train tracks. These angles are defined for both a three-track trailer and a semi-trailer road train for different locations of the extended track.

Based on the found assembly angles of the tracks, the overall turning radii of the road train and the overall maneuverability index - the overall traffic lane - are determined. At the same time, it is shown that none of the layout schemes of the three-link road train, except for the road train with separated and controlled axles of the trailer tracks (scheme 5), does not satisfy the requirements of DIRECTIVE 2002/7/EC concerning maneuverability. Taking into account the kind of the

***Table 3** Overall radii and overall traffic lane of road trains with guided trailers*

Road train type	Turning parameters, m								
	Movement in a circle			Turning 180º			Turning 90º		
	R_{eo}	R_{io}	B_o	R_{eo}	R_{io}	B_o	R_{eo}	R_{io}	B_o
1	5.3	13.063	7.763	12.925	6.405	6.520	12.925	6.731	6.194
2	5.3	13.491	8.191	14.401	6.615	7.786	14.401	7.005	7.396
3	5.3	13.693	8.393	14.625	6.832	7.793	14.625	6.209	8.416

operation of such road trains (running between terminals at the entrance to the city), the maneuverability parameters of the road train at typical turns 90° and 180° are more important. For such turns, the trailer road trains are more promising, for which the requirements of the DIRECTIVE concerning maneuverability are met at turnings of 90° and are almost fulfilled when turning at 180°. For semi-trailer road trains, the requirements for maneuverability are not met, and therefore the trailer tracks must be equipped with more or less complex control systems. With a direct control drive on the front axles of the second and third semi-trailers, when turning at 90° and 180°, only the first layout scheme satisfies the requirements for maneuverability. Therefore, for the semi-trailer scheme, it is necessary to develop a more advanced control system in comparison to the direct control drive.

5 Conclusions

1. The maneuverability indices of the three-track road trains on wheels rigid in the lateral direction were determined, that is, according to kinematic models, which are based on the assembly angles of the road train tracks. These angles are defined for both a three-track trailer and a semi-trailer road train for different locations of the extended track. Thus, while entering a turning the first and second assembly angles of a trailer road train are for 12 and 15 % smaller than the second and third assembly angles of a semi-trailer road train. This correlation is valid with a little deviation (5-7 %) for other turning phases, as well.
2. It was shown that none of the layout schemes of the three-track road train, except for the road train with separated and controlled axles of the trailer tracks (scheme 5, Table 1), does not satisfy the requirements of DIRECTIVE 2002/7/EC concerning maneuverability. When turning at 90° and 180°, almost all the trailer road trains of all the layout schemes, in contrast to semi-trailer schemes, satisfy the requirements of DIRECTIVE 2002/7/EC.
3. There was found that at the controlled first axles of the second and third semi-trailers, an overall traffic lane of such road train, while comparing to an uncontrolled road train, at a movement in a circle is reducing for 10 to 12 %, but all the road trains do not satisfy the requirements concerning maneuverability.

Acknowledgment

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] LOVSKA, A, GERLICI, J., DIZO, J., KRAVCHENKO, O. Analysis of the strength of a hopper-typecontainer when transported by a semi-trailer. *Transport and Logistics: the International Journal*. 2023, **23**(55), p. 1-12. ISSN 2406-1069.
[2] WOODCOCK, A., TOVEY, M. (2020) Designing whole journey, multimodal transport provision. *The Design Journal* [online]. 2020, **23**(1), p. 91-112. eISSN 1756-3062. Available from: https://doi.org/10.1080/14606925.2019.1693210
[3] PORTAPAS, V., ZAIDI, Y., BAKUNOWICZ, J., PADDEU, D., VALERA-MEDINA, A., DIDEY, A. Targeting global environmental challenges by the means of novel multimodal transport: concept of operations. In: 2021 5th World Conference on Smart Trends in Systems Security and Sustainability WorldS4: proceedings [online]. IEEE. 2021. eISBN 978-1-6654-0096-1, p. 101-106. Available from: https://doi.org/10.1109/WorldS451998.2021.9514048
[4] CORNELL, A. Improving interconnectivity with multimodal transportation [online]. In: *Sustainable mega city communities*. WOODROW, W. C. (Ed.). Butterworth-Heinemann, 2021, ISBN 9780128187937, p. 191-202. Available from: https://doi.org/10.1016/B978-0-12-818793-7.00011-1
[5] PENCHEVA, V., ASENOV, A., SLADKOWSKI, A., IVANOV, B., GEORGIEV, I. Current issues of multimodal and intermodal cargo transportation [online]. In: *Modern trends and research in intermodal transportation. studies in systems, decision and control. Vol. 400.* SLADKOWSKI, A. (Ed.). Cham: Springer, 2022. ISBN 978-3-030-87119-2, eISBN 978-3-030-87120-8. Available from: https://doi.org/10.1007/978-3-030-87120-8_2
[6] FENG, X., SONG, R., YIN, W., YIN, X., ZHANG, R. Multimodal transportation network with cargo containerization technology: advantages and challenges. *Transport Policy* [online]. 2023, **132**, p. 128-143. ISSN 0967-070X. Available from: https://doi.org/10.1016/j.tranpol.2022.12.006
[7] TOPALIDS, V. A. Promising heavy-duty road trains for Eurasian transportation (in Russian) [online]. Available from: www.iru-cis.ru/iru-moscow/ 2007/02_sr/doc/21/ Topalidi_Uzbekistan_- Rus.pdf/

[8] TSCHOKE, M., BOYSEN, N. Container supply with multi-trailer trucks: parking strategies to speed up the gantry crane-based loading of freight trains in rail yards. *OR Spectrum* [online]. 2018, **40**, p. 319-339. ISSN 0171-6468, eISSN 1436-6304. Available from: https://doi.org/10.1007/s00291-017-0491-1

[9] 35-meter trucks with three trailers will appear in Europe [online]. Available from: inform@newsyou.info

[10] DIRECTIVE 2002/7/EC of European parliament and of the council of 18 February 2002 amending Council Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic. Official Journal of the European Communities. 2002. No L67/47-49.

[11] SHKVARKO, K. V. Long-term three-link road trains - a new stage in the development of road transport in Ukraine on the way to Europe. *System Management Methods, Technology and Organization of Production, Repair and Operation of Cars: Scientific Journal*. 2003, **17**, p. 146-152. ISBN 978-966-632-215-2.

[12] LEDUC, G. *Longer and heavier vehicles. An overview of technical aspects* [online]. Technical Report EUR 23949 EN. Luxembourg: Joint Research Centre, Institute for Prospective Technological Studies, 2009. ISSN 1018-5593, ISBN 978-92-79-12983-4. Available from: https://doi.org/10.2790/12649

[13] ISLAM, M. Parallel design optimization of multi-trailer articulated heavy vehicles with active safety systems. Ontario, Canada: University of Ontario Institute of Technology Oshawa, 2013.

[14] HUANG, W., AHMADIAN, M., RAHIMI, A., STEIGINGA, L. Dynamics performance of long combination vehicles with active control systems. *Vehicle System Dynamics* [online]. 2023, **61**(7), p. 1831-1880. ISSN 0042-3114, eISSN 1744-5159. Available from: https://doi.org/10.1080/00423114.2023.2194545

[15] ZHU, S., HE, Y. A Coordinated control scheme for active safety systems of multi-trailer articulated heavy vehicles. In: The 28th IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks: proceedings. 2023.

[16] ALTAFINI, C. Some properties of the general n-trailer. *International Journal of Control* [online]. 2001, **74**(4), p. 409-424. eISSN 1366-5820. Available from: https://doi.org/10.1080/00207170010010579

[17] LATIF, A., CHALHOUB, N., PILIPCHUK, V. Control of the nonlinear dynamics of a truck and trailer combination. *Nonlinear Dynamics* [online]. 2020, **99**, p. 2505-2526. ISSN 0924-090X, eISSN 1573-269X. Available from: https://doi.org/10.1007/s11071-019-05452-1

[18] GOTTMANN, F., WIND, H., SAWODNY, O. On the influence of rear axle steering and modeling depth on a model based racing line generation for autonomous racing. In: 2018 IEEE Conference on Control Technology and Applications CCTA: proceedings [online]. 2018. eISBN 978-1-5386-7698-1, p. 846-852. Available from: https://doi.org/10.1109/CCTA.2018.8511508

[19] LJUNGQVIST, O., EVESTEDT, N., AXEHILL, D., CIRILLO, M., PETTERSSON, H. A path planning and path-following control framework for a general 2-trailer with a car-like tractor. *Journal of Field Robotics* [online]. 2019, **36**(8), p. 1345-1377. ISSN 1556-4959, eISSN 1556-4967. Available from: https://doi.org/10.1002/rob.21908

[20] GONZALEZ, D., PEREZ, J., MILANES, V., NASHASHIBI, F. A review of motion planning techniques for automated vehicles. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2016, **17**(4), p. 1135-1145. ISSN 1524-9050, eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2015.2498841

[21] TIAN, X., HE, R., SUN, X., CAI, Y., XU, Y. An ANFIS-based ECMS for energy optimization of parallel hybrid electric bus. *IEEE Transactions on Vehicular Technology* [online]. 2019, **69**(2), p. 1473-1483. ISSN 0018-9545, eISSN 1939-9359. Available from: https://doi.org/10.1109/TVT.2019.2960593

[22] CHENG, J., WANG, B., ZHANG, Y., WANG, Z. Backward orientation tracking control of mobile robot with N trailers. *International Journal of Control, Automation and Systems* [online]. 2017, **15**, p. 867-874. ISSN 1598-6446, eISSN 2005-4092. Available from: https://doi.org/10.1007/s12555-015-0382-7

[23] DULEBA, I. Kinematic models of doubly generalized N-trailer systems. *Journal of Intelligent and Robotic System* [online]. 2019, **94**, p. 135-142. ISSN 0921-0296, eISSN 1573-0409. Available from: https://doi.org/10.1007/s10846-018-0817-5

[24] GUEVARA, L., MICHALEK, M. M., CHEEIN, F. A. Collision risk reduction of N-trailer agricultural machinery by off-track minimization. *Computers and Electronics in Agriculture* [online]. 2020, **178**, 105757. ISSN 0168-1699. Available from: https://doi.org/10.1016/j.compag.2020.105757

[25] SHOJAEI, K., ABDOLMALEKI, M. Output feedback control of a tractor with N-trailer with a guaranteed performance. *Mechanical Systems and Signal Processing* [online]. 2020, **142**, 106746. ISSN 0888-3270. Available from: https://doi.org/10.1016/j.ymssp.2020.106746

[26] MICHALEK, M. M., PAZDERSKI, D. Forward tracking of complex trajectories with non-standard N-trailers of non-minimum-phase kinematics avoiding a jackknife effect. *International Journal of Control* [online]. 2019, **92**(11), p. 2547-2560. ISSN 0020-7179, eISSN 1366-5820. Available from: https://doi.org/10.1080/00207179.2018.1448117

[27] GAO, Y., CAO, D., SHEN, Y. Path-following control by dynamic virtual terrain field for articulated steer vehicles. *Vehicle System Dynamics* [online]. 2020, **58**(10), p. 1528-1552. ISSN 0042-3114, eISSN 1744-5159. Available from: https://doi.org/10.1080/00423114.2019.1648837

[28] KEYMASI, K. A., MOOSAVIAN, S. A. A. Dynamic modeling and tracking control of a car with trailers. *Multibody System Dynamics* [online]. 2016, **37**, p. 211-225. ISSN 1384-5640, eISSN 1573-272X. Available from: https://doi.org/10.1007/s11044-015-9472-9

[29] WONG, J. Y. *Theory of ground vehicles*. New York: Wiley, 2008. ISBN 9780470170380.

[30] JAZAR, R. *Truck dynamics: theory and applications*. New York: Springer, 2008. ISBN 978-0-387-74243-4, eISBN 978-0-387-74244-1.

[31] QUINGYUN, W., PENG, W., NING, C. Dynamics modeling and simulation of trailer with compliance steering system. *MATEC Web of Conferences* [online]. 2017, **139**, 00001. eISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201713900001

[32] LJUNGQVIST, O., BERGMAN, K., AXEHILL, D. Optimization-based motion planning for multi-steered articulated vehicles. *IFAC-PapersOnLine* [online]. 2020, **53**(2), p. 15580-15587. ISSN 2405-8971, eISSN 2405-8963. Available from: https://doi.org/10.1016/j.ifacol.2020.12.2403

[33] SAKHNO, V. Maneuverability, movement stability of buses of the especially large size class. *Periodica Polytechnica Transportation Engineering* [online]. 2024, **52**(1), p. 104-112. ISSN 0303-7800, eISSN 0303-7800. Available from: https://doi.org/10.3311/PPtr.21856

[34] MICHALEK, M. M. Modular tracking controller for N-trailers with non-zero hitching offsets. In: 2015 American Control Conference: proceedings. 2015. p. 5371-5376.

[35] SAKHNO, V., POLIAKOV, V., LYASHUK, O., MUROVANYI, I., STELMASHCHUK, V., ONYSCHUK, V., TSON, O., ROZHKO, N. To the comparative evaluation of three-unit lorry convoys of the different component systems by maneuverability. *Scientific Journal of Silesian University of Technology. Series Transport / Zeszyty Naukowe Politechniki Slaskiej. Seria Transport* [online]. 2023, **121**, p. 189-201. ISSN 0209-3324, eISSN 2450-1549. Available from: https://doi.org/10.20858/sjsutst.2023.121.12

[36] POLYAKOV, V. M., SAKHNO, V. P. *Three-lane road trains. Maneuverability*. Luhansk: Knowledge, 2014. ISBN 978-617-579-918-5.