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TO THE COMPARATIVE EVALUATION OF THREE-UNIT LORRY CONVOYS OF THE DIFFERENT COMPONENT SYSTEMS BY MANEUVERABILITY

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Summary. The article deals with the maneuverability of three-link road trains with various layout schemes. If a train has more than three links, difficulties arise in that the study of the movement of such a multi-link vehicle is significantly complicated due to the need to take into account the influence of a significant number of factors on the nature of the movement of all links. The interaction of neighboring units in the movement of a train is eventually distributed to the entire vehicle and causes certain deviations of the components of the train (modules) from the direction of movement specified by the driving link (tractor). Considering that a road train as a motor vehicle is a means of increased danger, when solving problems about the possibility of operating three- and multi-link road trains, it is one of the first to take steps towards theoretical studies of their maneuverability, the results of which will be the basis for answering many technical, organizational, and legal questions. Analysis of the calculation results showed that in the established circular path with the selected gear ratios of the control drives, none of the road trains met the requirements of DIRECTIVE 2002/7 / EC. From this, it follows that for three-link road trains, a fundamentally different control drive is needed, which can be a double control drive.

Keywords: car train, maneurability, folding angle, overall traffic band, control drive, trajectory

1. INTRODUCTION

Efficient and stable operation of industry, agriculture, and the normal living conditions of the population are ensured by a complex and extensive transport system, which includes railway, automobile, air, sea, river, and pipeline transport. The general purpose of all types of transport and the existing close relationship between them allow us to consider them as a single transport system for the country. The objective regularities and conditions of functioning of this system depend on the influence of various socio-economic factors that change in a unique way during the development of each individual country. A coordinated and reliable transport system is so important for the state that it receives special attention and is provided with state subsidies, even if certain types of transport are materially unprofitable [1].

In order to increase the efficiency of road transport and reduce fuel consumption and the toxicity of exhaust gases per unit of transported cargo, since 1998, the Scandinavian countries of Sweden and Finland have changed the requirements for the length and total weight of juggernauts up to 25.25 m and 60 t, while maintaining the requirements of the 2002 Directive /7/EC for axial loads [2]. The operation of 2 layout schemes for juggernauts is allowed. The first: the road train is formed from a three-axle tractor + a 5-axle trailer, made on the basis of a serial 3-axle semi-trailer on a two-axle undercarriage. The second is a semi-trailer truck, where a 2-axle trailer, usually with centrally located axles, is attached to a serial semi-trailer. At the same time, the modularity of the rolling stock design is preserved [3].

The appearance of such road trains, the useful body volume of which is about 150 m3, was expected in international transportation, but unfortunately, the road and transport legislation is still not ready for this in the EU, except for Sweden and Finland, of course.

The introduction of long-distance road trains in countries is associated with three groups of restrictions [4], in particular, restrictions on the geometric and mass parameters of motor vehicles, safety requirements for the design of these juggernauts, and the difficulties of intaking them at existing terminals and logistics centers. UNECE Regulations No. 13 for three-link juggernauts also need further development due to the fact that compatibility standards are established only for juggernauts with two transport links, a tractor and a trailer (semi-trailer). In addition, with an increase in the mass of the juggernaut, the traction-coupling devices of the tractor and semi-trailer (trailer) will be more heavily loaded, and, of course, their control regimes must be strengthened. This requirement will indirectly affect the safety of the design of the rolling stock of three-link juggernauts.

Undoubtedly, it is much more difficult for three-link juggernauts to comply with the regulations regarding maneuverability in accordance with Directive 2002/7/EC and GOST R 52302-2004 [5, 6] regarding the controllability and stability of the movement of motor vehicles (MV).

If the juggernaut has more than three links, difficulties arise in that the study of the movement of such a multi-link MV is becoming significantly complicated due to the need to consider the influence of a wide number of factors on the nature of the movement of all links. The interaction of neighboring links during the movement of the juggernaut eventually spreads to the entire vehicle and causes certain deviations of the components of the juggernaut (modules) from the direction of movement set by the leading link (tractor). Taking into account the fact that the juggernaut as an MV is a recipe for increased danger, while solving problems regarding the possibility of operating three- and multi-link juggernauts, one of the first steps should be taken in the direction of theoretical studies of their maneuverability and stability of movement, the results of which will be the basis for answering many questions of a technical, organizational, and legal nature [7].

2. MATERIALS AND METHODS

For the transportation of large consignments of cargo, it is advisable to use three-link road trains of various layout schemes. In order to maximize the compliance of road trains with specific operating conditions, the possibility of forming high-capacity juggernauts from the existing rolling stock without significant changes in its design is used. The modular principle of forming such MVs is used [3]. That is, the single system "juggernaut" can be represented as composed of two or more subsystems, hingedly connected to each other - "tractor vehicle" and "trailer link" = "semi-trailer", "trailer", etc., depending on the layout scheme of the juggernaut. In the design of the links of the juggernaut (tractor, trailer link) - complex technical objects, it is possible to distinguish subsystems of a lower hierarchical level: modules of undercarriages (controlled, uncontrolled), carrier systems, cargo platforms, etc., Fig. 1, from which a road train of a certain layout scheme is formed, Fig. 2.

Studies of long two- and three-link road trains were carried out as early as the 60s of the last century (in particular, in the Scandinavian countries, they became the basis for the legislative approval of the maximum length of road trains of 24 m). However, the development of this topic has resumed with renewed force in the last three years.

As you know, in the Scandinavian countries, road trains with a total length of 24 meters and a total weight of 60 tons were allowed back in the 70s of the last century. Increasing the length limit allows for a "modular" approach. Modular systems, as a rule, consist of the parts shown in Fig. 1: a changeable body 7.82 m, a semi-trailer 13.6 m, a semi-trailer truck (so-called “Dolly”), a tractor, and a trailer [3]. All road trains have a total length of 25.25 m.

For typical long-distance hauling, a long-distance combination can be used for most of the mileage. Near destinations, the trailer can be detached, and the truck can move on its own.

And the semi-trailer can be transported further with the help of a conventional semi-trailer tractor (or, if necessary, a three-axle tractor).

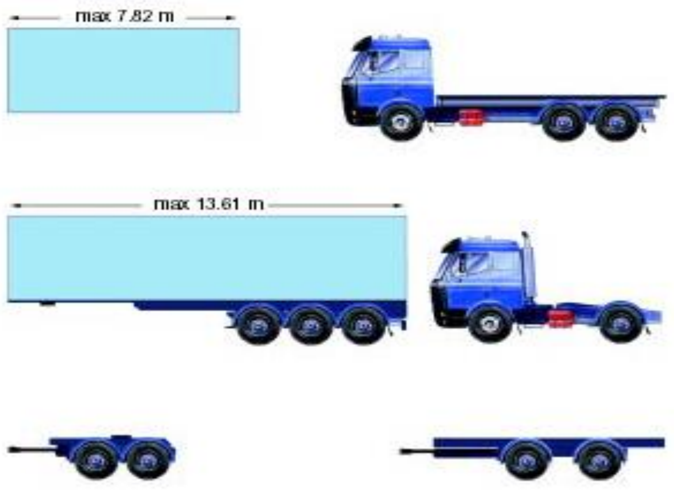


Fig. 1. Components of a "modular" road train

In addition to the use of standard bodies, trailers and semi-trailers, "modular" transportation involves the use of containers that can be transported by both sea and land transport. For such transport, the 25.25m concept is the most efficient, as such a truck transports three containers instead of the two that can be transported by a conventional road train and is thus 30% more efficient [3,12].

Thus, developments in the direction of the development of three-link road trains are the main way to solve the problem of transportation both in Europe and in Ukraine, which does not require significant capital investments and can be implemented in the shortest possible time, provided that the issues of maneuverability and stability of the movement of such road trains are resolved.

Maneuverability of motor vehicles (MV) is a set of such properties that ensure their unhindered movement on a support surface that has limitations both in terms of area and shape [9]. Such restrictions in the movement of MV can be spatial ones related to the length and height of the vehicle, as well as restrictions on the shape and size of the road surface, which serves as a support surface for the rolling of the wheels of its links.

The curvilinear movement of the road train is characterized by such regime parameters as the speed of movement, the turning radius and the turning angles of the steered wheels, which do not remain constant during the operation of the road train. Therefore, both kinematic and dynamic indicators are used to assess the maneuverability of the MV.

Dynamic indicators are provided by a three-axle tractor, which has a sufficient reserve of power and is equipped with power steering.

Among the kinematic indicators, two should be considered the main ones, namely:

- overall traffic lane (OTL), equal to the difference between the outer and inner overall turning radii. Also, worth considering is the fact that the overall turning radii are standardized (R_{zg}=12.5 m, $R_{вг}$=5.3 m), then the overall traffic lane will also be standardized ($B_г$=7.2 m);
- the ability to move in reverse.

The issue the least studied today is the ability to drive a road train in reverse, which was rarely considered theoretically for three-link road trains. The ability to drive in reverse should be checked experimentally during the road tests of the road train.

When determining the OTL, the wheels of the road train are assumed to be both rigid in the lateral direction and elastic.

For wheels rigid in the lateral direction, the issues of maneuverability of a car and a two-track road train were considered in detail by Y. Kh. Zakin in works [8, 9], and for a three-track road train - by Ya. Ye. Farobin [10, 11]. In [12, 13] a simplified analysis of the maneuverability and stability of vehicle combinations, such as a tractor in combination with one or two semitrailers or a truck and a full trailer, was carried out. Vehicle combinations are considered linear dynamic systems with two degrees of freedom for each unit. The motion equations are derived considering the effects of braking and acceleration, and the characteristic equation for motion with constant speed is obtained. They carried out detailed studies on the problems of horizontal stability of road trains and their maneuverability using both analytical and experimental methods.

We should also not forget about the influence of tires on the vehicle's behavior [14].

Significant studies of the maneuverability and stability of the movement of three-link semi-trailer road trains, based on the solution of the system of differential equations of plane-parallel motion of the road train, were conducted by scientists [15]. Mathematical models developed on their basis for studying the turning kinematics of a three-link road train and a road train with a semi-trailer on a dolly on rigid wheels in the lateral direction can also be used for a comparative analysis of the maneuverability of three-link road trains and other layout schemes [16, 17]. It was adapted and improved on existing formulations for the convoy movement problem, and new models and approaches were developed to solve the GCMP more effectively [18]. Also, a robust adaptive size-independent control protocol is designed to assure internal and string stability in the presence of uncertain dynamics by using only relative displacement information [19, 20]. The purpose of the work is a comparative analysis of three-link road trains of different layout schemes according to maneuverability indicators while they perform various turns.

3. DISCUSSION OF THE RESULTS OF THE EXPERIMENT

The basis of the three-link road trains that are in operation today are Scania tractors as well as Krone trailer equipment - three-axle semi-trailers SD-27, two-three-axle trailers with close axles ZZ-18 (ZZ-27), two-three-axle trailers with spread axles with a front pivoting axle AZ-18 (AZ-27), two-axle undercarriage "Dolly".

An analysis of the layout schemes of modern three-link road trains, Fig. 2, which are built according to the modular principle, shows that any layout scheme can be turned into a scheme with a semi-trailer on a dolly (hereinafter a road train). Such a train consists of a tractor, a dolly and a three-axle semi-trailer.

The total weight of such road trains is 60 tons, and the length exceeds 25 m. From the point of view of kinematics, such a road train is transformed into a three-link semi-trailer road train scheme, when the semi-trailer rests on the semi-trailer coupling device of the tractor and the undercarriage turns into a trailer; in the "B-double" scheme, when the dolly is transformed into a semi-trailer; into a scheme with two trailers, when a dolly and a semi-trailer are transformed into trailers (today such a scheme is almost not used due to low traffic stability indicators).

To ensure the necessary maneuverability, each element of the road train must fit into a circle with an inner radius of 5.3 m and an outer radius of 12.5 m. Determining the actual turning radii can be done for a road train with rigid wheels in the lateral direction.

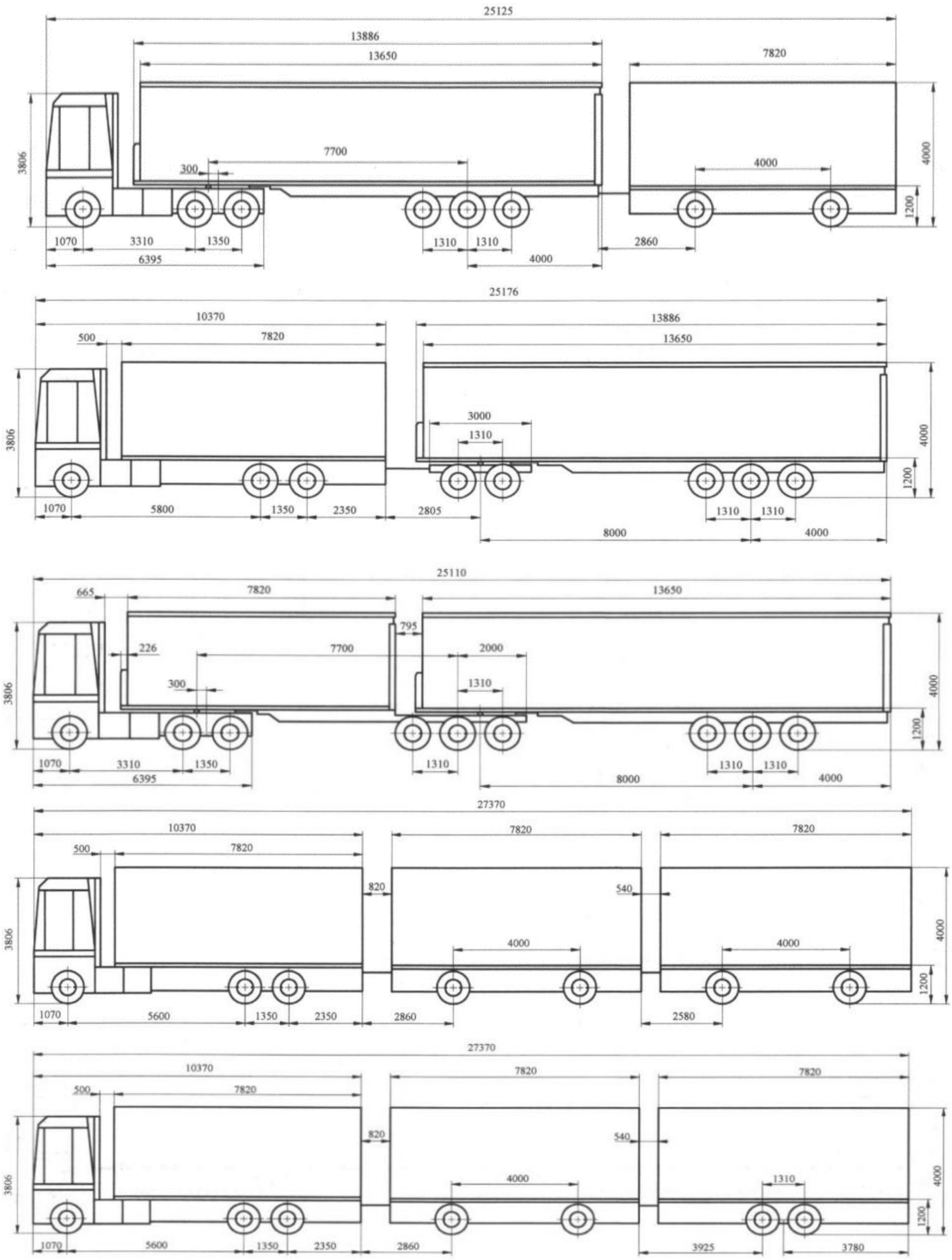


Fig. 2. Layout diagrams of three-link road trains

In the works [8, 9] it is proved that the maneuverability of vehicles at the previous stage can be determined on wheels that are rigid in the lateral direction because of the mistake of the overall traffic lane (OTL) calculations, which does not exceed 10-12%. At the same time, the method of calculating the OTL is based on the determination of the angles of assembly of the links of the road train and the displacement of the trajectories of the driven links relative to the trajectory of the tractor vehicle. This technique can also be used to determine the OTL of three-link road trains with controlled trailer links.

During one-way curvilinear movement, the road train goes through several stages [13]:
- the stage of initial rectilinear movement (before turning);
- stage of entry into the turn;
- circular rotation stage;
- stage of exit from the turn;
- exit of the tractor vehicle on a straight path.

For each turning stage, the differential equations of the folding angles with unguided trailer links were obtained, which were later used in determining the displacement of the links' trajectories relative to the tractor and the OTL of the road train. Analysis of the calculation results showed:
- during a one-way turn, the trajectories of the trailing links are shifted in relation to the trajectory of the leading link towards the center of the turn, thereby increasing the overall traffic lane, and the displacement of the trajectories and OTL increase with the increase in the base of the trailing links;
- the normalized value of the overall traffic lane under real design parameters cannot provide a three-link road train for all the considered layout schemes.

$$\gamma_{K1} = \frac{\gamma_1}{i_0} - \gamma_1, \quad \gamma_{K2} = \frac{\gamma_2}{i_2} - \gamma_2. \tag{1}$$

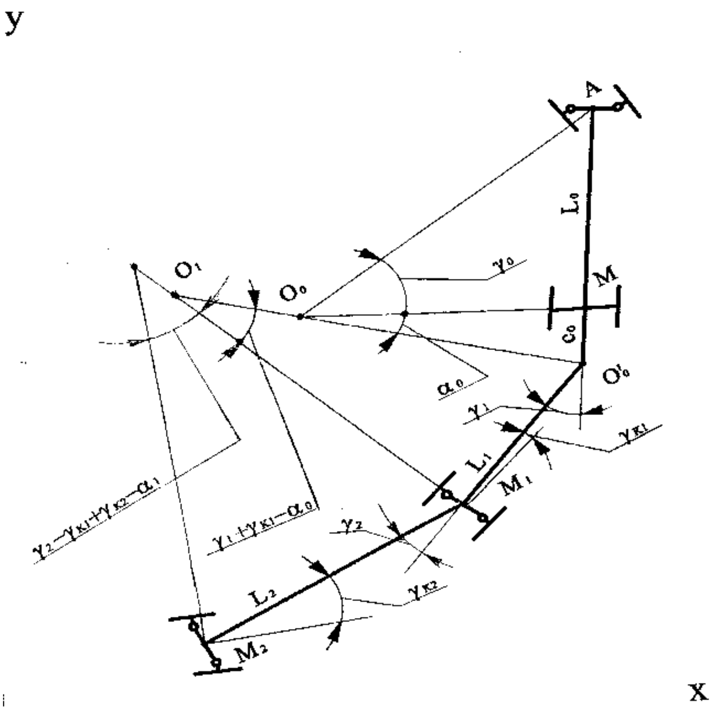


Fig. 3. A turning diagram of a three-link trailer train with controlled trailers

Taking into account the two expressions (1) mentioned above, we get [8]:

$$\frac{d\gamma_1}{d\gamma_0}=\frac{tg(\gamma_0)}{K_{\Pi}\cdot L_0}\cdot\left(1-\frac{L_0}{tg(\gamma_0)\cdot\cos(\alpha_0)}\cdot\frac{\sin\left(\frac{\gamma_1}{i_0}-\alpha_0\right)}{L_1\cdot\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)}\right), \quad (2)$$

$$\frac{d\gamma_2}{d\gamma_0}=\frac{\sin\left(\frac{\gamma_1}{i_0}-\alpha_0\right)}{K_{\Pi}\cdot L_1\cdot\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)\cdot\cos(\alpha_0)}\cdot$$

$$\cdot\left(1-\frac{\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)}{\cos\left(\frac{\gamma_1}{i_0}-\gamma_1+\alpha_1\right)}\cdot\frac{L_1\cdot\cos(\gamma_1-\alpha_0)}{\sin\left(\frac{\gamma_1}{i_0}-\alpha_0\right)}\cdot\frac{\sin\left(-\frac{\gamma_1}{i_0}+\gamma_1+\frac{\gamma_2}{i_2}-\alpha_1\right)}{L_2\cdot\cos\left(\frac{\gamma_2}{i_2}-\gamma_2\right)}\right). \quad (3)$$

Equations (2) and (3) after simple transformations are reduced to the form:

$$\frac{d\gamma_1}{d\gamma_0}=\frac{tg(\gamma_0)}{K_{\Pi}\cdot L_0}\cdot\left(1-\frac{L_0}{tg(\gamma_0)}\cdot\frac{\left(\sin\left(\frac{\gamma_1}{i_0}\right)-\frac{C_0\cdot tg(\gamma_0)}{L_0}\cdot\cos\left(\frac{\gamma_1}{i_0}\right)\right)}{L_1\cdot\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)}\right), \quad (4)$$

$$\frac{d\gamma_2}{d\gamma_0}=\frac{\left(\sin\left(\frac{\gamma_1}{i_0}\right)-\frac{C_0\cdot tg(\gamma_0)}{L_0}\cdot\cos\left(\frac{\gamma_1}{i_0}\right)\right)}{K_{\Pi}\cdot L_1\cdot\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)}-\frac{\left(\cos(\gamma_1)+\frac{C_0\cdot tg(\gamma_0)}{L_0}\cdot\sin(\gamma_1)\right)}{K_{\Pi}\cdot\cos\left(\frac{\gamma_2}{i_2}-\gamma_2\right)}\cdot\frac{\sin\left(-\frac{\gamma_1}{i_0}+\gamma_1+\frac{\gamma_2}{i_2}\right)}{L_2\cdot\cos\left(\frac{\gamma_1}{i_0}-\gamma_1\right)}. \quad (5)$$

It can be seen from expressions (4) and (5) that the resulting equations do not make up a system because the first equation does not depend on the second at all. That is, when there are no feedback links in the road train, the movement of subsequent links does not affect the movement of previous links. Such a scheme is very idealized, but considering that a three-link road train cannot make a turn at high speed, in practice the differences between the calculated and actual values are within acceptable limits [9].

Since, in the general case, during the execution of a turn, the road train goes through four stages (entering the turn, moving in a circle, exiting the turn, and rectilinear movement until the return of all parameters to the initial state), then equations (4) and (5) can be applied only for the first stage of performing a turn.

During movement along a circular trajectory with a radius R_{0MIN} (if there is such a section), the central angle φ_K. becomes the determining parameter. Considering the ratio $d\gamma_0 = R_{0MIN} \cdot K_p \cdot d\varphi_K$, as well as the condition that $\gamma_0 = const = \gamma_{0MAX}$ we obtain [8]:

$$\frac{d\gamma_1}{d\varphi_K} = \left(1 - R_{0MIN} \cdot \frac{\left(\sin\left(\frac{\gamma_1}{i_0}\right) - \frac{C_0}{R_{0MIN}} \cdot \cos\left(\frac{\gamma_1}{i_0}\right)\right)}{L_1 \cdot \cos\left(\frac{\gamma_1}{i_0} - \gamma_1\right)}\right), \tag{6}$$

$$\frac{d\gamma_2}{d\varphi_K} = \frac{\left(\sin\left(\frac{\gamma_1}{i_0}\right) - \frac{C_0}{R_{0MIN}} \cdot \cos\left(\frac{\gamma_1}{i_0}\right)\right) \cdot R_{0MIN}}{L_1 \cdot \cos\left(\frac{\gamma_1}{i_0} - \gamma_1\right)} - \frac{\left(\cos(\gamma_1) + \frac{C_0}{R_{0MIN}} \cdot \sin(\gamma_1)\right) \cdot R_{0MIN}}{L_2 \cdot \cos\left(\frac{\gamma_2}{i_1} - \gamma_2\right)} \cdot \frac{\sin\left(-\frac{\gamma_1}{i_0} + \gamma_1 + \frac{\gamma_2}{i_1} - \alpha_1\right)}{\cos\left(\frac{\gamma_1}{i_0} - \gamma_1 + \alpha_1\right)}. \tag{7}$$

When exiting a turn, equations (4) and (5) are used, but since the steering wheel rotates in the opposite direction, the KP coefficient has a negative value.

The last stage is the rectilinear movement of the tractor until all the initial parameters return to their initial state. Thus, at this stage, the angles of assembly of the links of the road train no longer depend on the position of the steered wheels, but only on the path taken by the tractor. At the same time, $\gamma_0 = 0$.

So we get:

$$\frac{d\gamma_1}{dS_0} = -\frac{\sin\left(\frac{\gamma_1}{i_0}\right)}{L_1 \cdot \cos\left(\frac{\gamma_1}{i_0} - \gamma_1\right)}, \tag{8}$$

$$\frac{d\gamma_2}{dS_0} = \frac{\sin\left(\frac{\gamma_1}{i_0}\right)}{L_1 \cdot \cos\left(\frac{\gamma_1}{i_0} - \gamma_1\right)} - \frac{\cos(\gamma_1)}{\cos\left(\frac{\gamma_1}{i_0} - \gamma_1\right)} \cdot \frac{\sin\left(-\frac{\gamma_1}{i_0} + \gamma_1 + \frac{\gamma_2}{i_1}\right)}{L_2 \cdot \cos\left(\frac{\gamma_2}{i_1} - \gamma_2\right)}. \tag{9}$$

The integration of the folding angle equations for the considered road trains was performed using Mathcad software. The transmission ratio of the direct drive of the control of the trailer links was determined under the condition that the main points of the undercarriage and the semi-trailer move along the trajectory of the main point of the tractor vehicle [9, 15]. Fig. 4 shows the results of the calculation of the angles of assembly of the links of road trains of various layout schemes, provided that the main points of the trailer (roller) and semi-trailer move along the trajectory of the main point of the tractor. The numbers indicate the following variants of road trains: No. 1: road train with steered front axles of the car and a dolly and a steered rear axle of the semi-trailer; No. 2: a road train with a steerable front axle of a car and a steerable front axle of a semi-trailer; No. 3: a road train with a controlled front axle of the car and controlled two extreme axles of the semi-trailer; No. 4: a road train with a steerable front axle of the car and a steerable rear axle of the semi-trailer; No. 5: a road train with a controlled front axle of the car and a controlled rear axle of the trolley.

The analysis of the data, Fig. 4, shows the quite complex dependence of the angles of assembly of the links of the road train on the angle of rotation of the steered wheels of the front axle of the tractor. However, the rotation of the wheels of individual links of the road train can be carried out not only by the angle of rotation of the steered wheels of the front axle of the tractor vehicle but also depending on the assembly angles. In Fig. 5, as an example, the dependencies of the angles of rotation of the wheels of individual axles of the trailer links and the transmission ratios of the control drive to these axes depending on the assembly angles of the road train.

Trajectories of the movement of the characteristic points of the links of the road train were constructed based on the angles of assembly of the towing links and transmission ratios of the control drive, and their displacement relative to the trajectory of the main point of the tractor and the OTL of the road trains was determined, Fig. 3-6 and Tab. 1.

Tab. 1

Dimensional traffic lane of three-link road trains of various layout schemes

Types of the road train				
No1	No2	No3	No4	No5
The gear ratio of the control drive				
i_0= 0,25; i_2= 0,60	i_3= 0,75	i_4= 0,32	i_2= 0,83	i_1= 0,74
Dimensional traffic lane with steady circular traffic, m				
7,38	7,93	7,41	7,53	7,83

Analysis of the calculation results indicates that none of the road trains meets the requirements of DIRECTIVE 2002/7/EC on the established circular trajectory with the selected transmission ratios of the control drives.

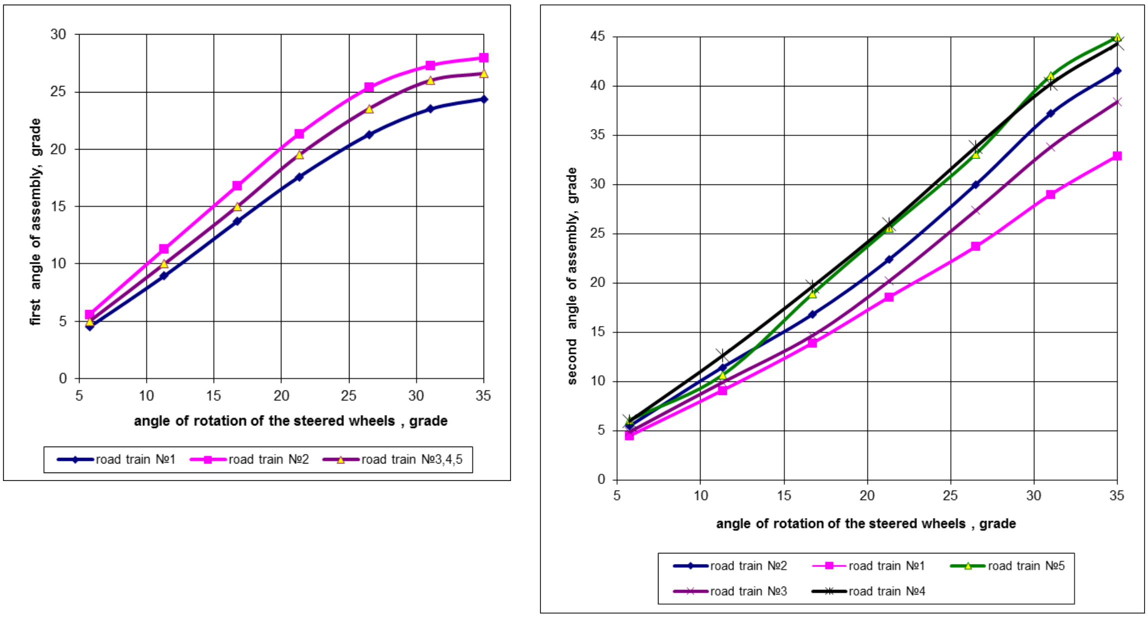
4. CONCLUSIONS

The purpose of the work is a comparative analysis of three-link road trains of various layout schemes in terms of maneuverability while performing various turns.

Studies proved that the maneuverability of vehicles at a preliminary stage can be determined on wheels hard in the lateral direction since the error in calculating the overall traffic lane does not exceed 10-12%.

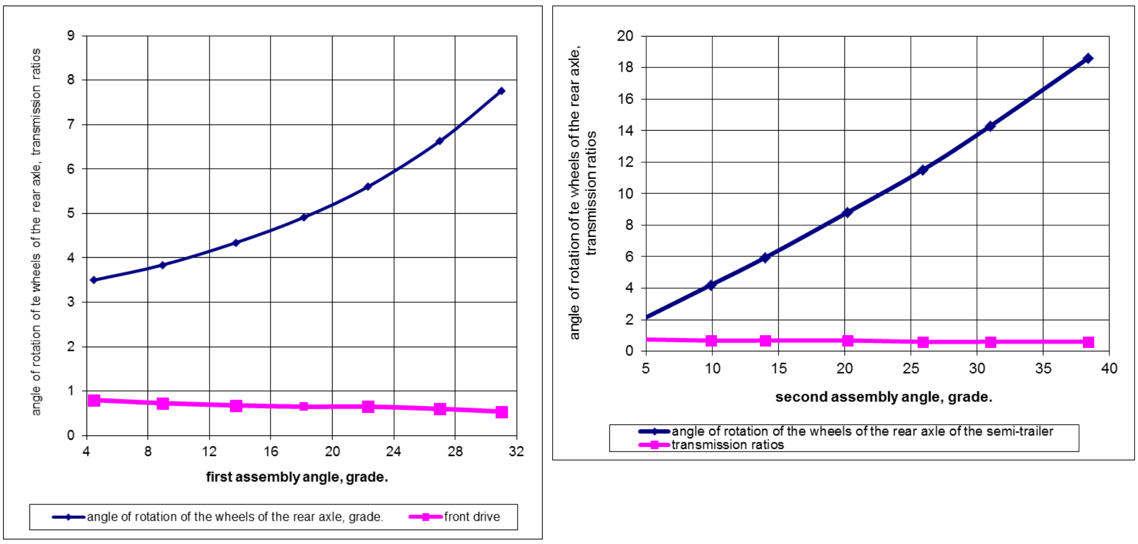
It was established that the angles of folding of the trailing links and the drive ratios of the control drive. The trajectories of the characteristic points of the articulated units were constructed, and their displacement relative to the trajectory of the main point of the tractor and the OTL of the articulated trucks were determined.

Conducted studies of the maneuverability of road trains on wheels rigid in the lateral direction have established that with direct drive control on the axis of the trailer links, none of the road trains meets the requirements of DIRECTIVE 2002/7/EC. It follows that for three-link road trains, a second control drive is fundamentally required, which can be a double control drive.



a) b)

Fig. 4. Dependence of the folding angles of the links on the angle of rotation of the front ones steered tractor wheels for road trains of various layout schemes



a) b)

Fig. 5. Dependence of the angles of rotation of the wheels of the axles of the undercarriage and semi-trailer on the angles' of assembly of links for road trains of various layout schemes

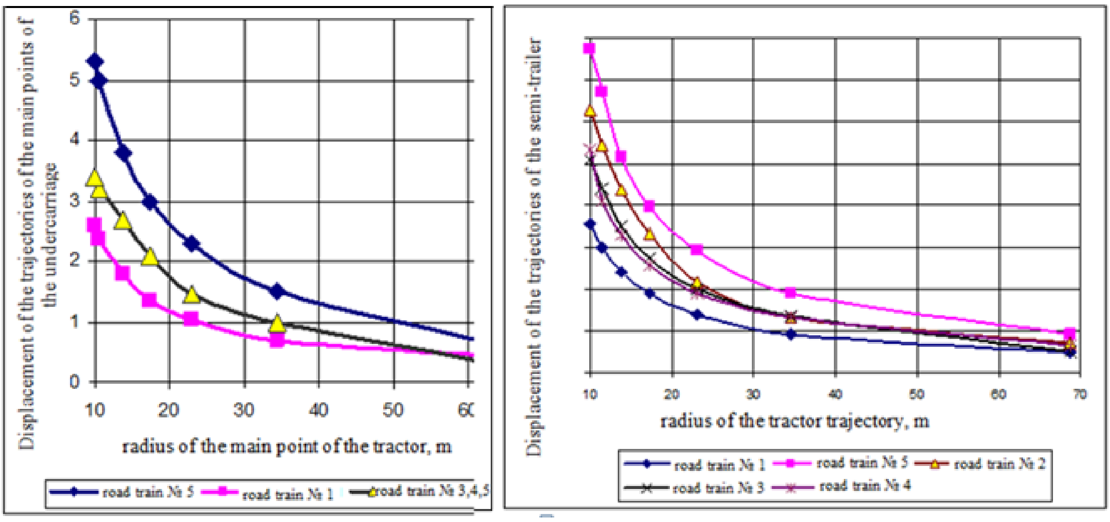


Fig. 6. Displacement of the trajectories of
the main points of the undercarriage (a) and semi-trailer (b)

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