V. Sakhno[1], I. Murovanyi[2], V. Polyakov[1], S. Sharai[1], O. Razboinikov[1], M. Roi[1]
[1]*National Transport University, Kyiv, Ukraine*
[2]*Lutsk National Technical University, Lutsk, Ukraine*

ON THE QUESTION REGARDING THE USE OF THREE-LINK ROAD TRAINS IN UKRAINE

Carrying out cargo transportation in intercity and international transportation by three-link road trains, compared to single vehicles, has a number of advantages, which ensure an increase in the productivity of rolling stock, a decrease in the cost of road transportation, a decrease in the total cost of cargo transportation, etc. Ukraine does not have its own production of tractor vehicles that can be used to work with trailers or semi-trailers with a large load capacity. Therefore, when choosing rolling stock for three-link road trains, its necessery to focusation on the products of leading automobile companies.

It was established by researches that the generalizing indicator of traction-speed properties of a motor vehicle is the average speed of movement, because it affects its productivity and determines the efficiency of its use. In the work, this speed is determined according to the developed algorithm. It was established that the average speeds of road trains consisting of tractors of the N3 category (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and O4 trailers of the KRONE brand in given road conditions differ little from each other. The maximum deviation of the average speed of movement, which has the largest value 22.99 m/s (for Volvo FH16+KRONE SDP-27), from the smallest value 21.05 m/s (for DAF XF 105+KRONE SDP-27), does not exceed 8.5%, i.e. further comparison of road trains should be fulfilled according to other criteria, in particular according to maneuverability when moving on a route.

It is shown that the considered three-link road trains do not satisfy the requirements of Directive 2002/7/EC regarding maneuverability. For three-link road trains with unguided trailing links, the minimum external overall turning radius with an internal overall radius of 5.3 m varies from 12.63 m for a trailed road train to 14.9 m for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of road trains, in particular, the introduction of controlled trailer links into their structure and the determination of their placement in the road train.

Keywords: transport system, technical and operational indicators, load capacity, three-link road train, tractor vehicle, semi-trailer, trailer, average speed, maneuverability.

INTRODUCTION

An integral part of the functioning of the country's transport system is the cargo delivery by rolling stock of the road transport, in particular, by three-link road trains of increased load capacity. These road trains are widely application in the countries of the European Union, the USA and Canada, where they are used to execution of transportation of industrial, agricultural and construction cargo.

The using of three-link road trains in intercity freight transportation has a number of advantages compared to single vehicles, which affect to increase mileage utilization rate, to reduce of idle time during load-unload operations, to increase the speed and decrease of cargo delivery time, to decrease the number of trips and the total mileage of vehicles, and, as a result, to increase of the productivity of the rolling stock, to reduce the cost price of road transportation, to decrease of the total cost of cargo transportation, and reducing the number of harmful emissions into the environment. This gives reason to believe that for Ukraine in the conditions of martial law, with the increase in the volume of road freight transportation and the presence of an almost unchanged road network, the issue of the use of three-link road trains becomes relevant.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The use of road trains is an effective method of increasing productivity and reducing the cost price of transportation [1]. Ukraine, unfortunately, does not have its own production of tractor vehicles that can be used to work with trailers or semi-trailers with a large load capacity. It is obvious that the purchase of foreign-made wheeled vehicles (tractors, trailers and semi-trailers) for the purpose of creating a new type of rolling stock must be preceded by a detailed comparative analysis of their technical characteristics in order to ensure of meeting to requirements, which established by national and international legislation, as well as customers (consumers) of these products regarding such technical and operational properties of road trains as active and passive safety, traction-speed properties, fuel efficiency, environmental indicators, controllability, stability. The choice of the type of tractor and its towing links for execution of cargo transportation must be carried out taking into account the safety of their constructions, compliance of their operational characteristics with the conditions under which transportation is planned and the goals set by the organizers of transportation.

Increasing of the quality of vehicles, including improving traction-speed properties, should be carried out at the expense of market competition. Thus, EU legislation, in particular EU Directive 92/6/EEC [2], provides requirements for the construction of vehicles in relation to only one indicator - the maximum speed. The implementation of Directive 92/6/EEC into the national legislation of Ukraine is provided for by the Ukraine-EU Association Agreement. In addition, Ukraine joined the UN Regulations No. 89 [2] regarding the limitation of the maximum speed of vehicles, which are also included in the list of mandatory requirements that apply to vehicles put into circulation, according to the "Procedure for approval of the design of vehicles, their parts and equipment" [2].

The mentioned measures to limit the maximum speed of vehicles are introduced with the aim of increasing road safety. They do not change the potential maximum speed, but only artificially limit the speed by adjusting the fuel supply to the engine when the vehicle is reached the given speed. Therefore, the average speed of traffic, as well as the quality of vehicles in general, should not "suffer" from the implementation of such regulatory measures.

Since the average speed of a freight vehicle is a factor that, together with the load capacity, determines its productivity and provides the most complete idea concerning traction-speed properties, this evaluation indicator is undoubtedly gaining weight among the criteria by which it is advisable to conduct comparative analyzes of road trains [1]. The average speed of movement depends on the interaction of the main elements of the "Vehicle - road - driver - environment" system. The first two elements are defining, the last two are limiting, since their influence always reduces the speed of movement, which could be developed by this or that road train at full use of its technical capabilities on the given path of its movement [1,2].

Increasing the operational characteristics of the road network and its development is, without a doubt, one of the powerful measures for solving the problem of road safety. At the same time, reducing the number of vehicles and drivers on the road network when putting the three-link road trains into operation will significantly improve the situation with accidents [3-6]. Therefore, simultaneously with the development of the transport infrastructure, it is advisable to focus attention on measures to possibilities of unloading the road network due to process improving of cargo transportation organizing.

In the modern automobile industry, when creating three-link road trains, the issue of choosing towing links is relevant and is actively discussed in the scientific literature. There are two main schemes of three-link road trains - trailer and semi-trailer. In the trailing scheme, each link rests on its axles, and in the semi-trailer - as on its axles and on the axis of the previous link.

In Ukraine, intercity and international cargo transportation is carried out by road trains consisting of MAN, DAF, IVECO, VOLVO and other similar tractors, and of Krone, Schmitz, Fliegle and other similar semi-trailers. The selection of the best combination of the road train in the composition with the specified tractors and semi-trailers (trailers) are carried out according to the indicators of traction-speed properties (high-speed driving mode) and maneuverability (road restrictions).

If a road train has more than three links, difficulties arise in that the study of the movement of such a multi-link vehicles is significantly complicated due to the need to take into account the influence of a considerable amount of factors on the nature of the movement of all links. The interaction of neighboring links during the movement of the road train eventually spreads to the entire vehicle and causes certain deviations of the components of the road train (modules) from the direction of movement set by the leading link (tractor). Taking into account the fact that the road train as an vehicle is a means of increased danger, when solving problems regarding the possibility of operating three- and multi-link road trains, the first steps should be taken in the direction of theoretical studiying of their maneuverability and stability of movement, the results of which will be the basis for answering many questions of technical, of an organizational and legal nature [7-9]. Thus, in [10], a simplified analysis of the maneuverability and stability of combinations of vehicles, such as a tractor in combination with one or two semi-trailers, or a truck and a full trailer, was carried out. Combinations of tractor vehicles with trailers and semi-trailers are considered as linear dynamic systems with two degrees of freedom for each module. The model of the road train with 31 degrees of freedom is built using the AutoSim package. At the same time, it is shown that the maneuverability and stability of the road train can be significantly improved with the help of an inerter, which is considered effective for increasing the stability and productivity of multi-track road trains. However, as practice shows, determining the nature of the behavior of the system in the area of instability and identifying the causes of its occurrence has not lost its relevance until now.

Since the curvilinear movement of the vehicle determines the construction of the control systems of the towing links, at the first stage it is necessary to decide with parameters of vehicle during circular movement and its execution of various maneuvers [7]. At the second stage, the previously obtained parameters are checked for the satisfaction of stability indicators both in a rectilinear movement and when execution various maneuvers. Selection and optimization of vehicle parameters for the entire range of operational speeds and loads requires availability of differential equations of motion. Such equations of varying degrees of complexity for two- and three-link road trains are given in works [7,10,11] and others. Combinations of vehicle are considered as linear dynamic systems with two degrees of freedom for each block. In work [12], the equations of vertical and lateral dynamics of a road vehicle with 6 degrees of freedom are reduced to matrix form. The movement of such vehicle in the vertical and lateral planes was studied. It is shown that the developed method can be applied to the analysis of traffic stability, in particular passenger road trains. In [13], a multivariate extension of the D2-IBC (Data Driven - Inversion Based Control) method is considered and its application to control the stability of the traffic of road trains is discussed in detail. Work [14] shows that freight vehicles with lots of trailers (MTAHV: multi-trailer articulated heavy vehicle) exhibit unstable modes of movement at high speeds, including folding of links, swinging of the trailer, and overturning. These unstable, adverse traffic modes can lead to traffic accidents.On the other hand, these vehicles have poor maneuverability at low speeds. This requires research and their analysis in order to find a compromise between the maneuverability of the vehicles at low speeds and its lateral stability at high speeds.

PURPOSE AND OBJECTIVES OF THE STUDY

The characteristics of maneuverability and stability of the vehicle movement, as is known, are determined by a combination of operational, mass-geometric and constructural parameters of its modules and their control systems. In general, the desired combination of the specified parameters from the point of view of maneuverability and stability even for the same vehicle in the range of operating loads and speeds are different. As a result, it is difficult to obtain accurate constructural parameters and quantitative indicators in the early stages of the creation of vehicle based on the criteria of maneuverability and stability of its movement. Success in solving such problems depends on how successfully the mathematical model and its essential parameters describing the behavior of the dynamic system in different modes of motion will be chosen. In work [10], differential equations of plane-parallel motion were compiled to determine the motion stability indicators. However, these equations can characterize the stability of vehicle only in rectilinear motion. Using them to assess maneuverability can lead to significant errors. In this regard, the aim of the work is a comparative evaluation of three-link road trains of different layout schemes according to the indicators of traction-speed properties and maneuverability.

To achieve the goal of the research, the following tasks are solved:

- the comparative evaluation of three-link road trains of different layout schemes according to traction-speed properties, selection of the best option;
- the comparative analysis of three-link road trains of different layout schemes in terms of maneuverability, selection of the best option.

The materials of the research are the technical characteristics and constructual features of tractors MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16, and Krone semi-trailers and trailers.

By methods of research of traction-speed properties and maneuverability of three-link road trains of various layout schemes was expected:

- development of a methodology for determining the traction-speed properties of three-link road trains consisting of MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16 tractors with Krone semi-trailers and trailers for choosing the best option;
- simulation of the movement of road trains along curves of highways to assess the influence of the layout scheme of a three-link road train on maneuverability indicators and its compliance with the requirements of regulatory documents.

RESEARCH RESULT

By previously conducted studies [1,2,15] it were established that the general indicator of the traction-speed properties of a single car and road train is the average speed of movement, as it determines its productivity and efficiency of use.

The average speed is determined by the driving conditions of the road train and the capabilities of the tractor in each of the gears [15]. In this regard, the solution to the task of determining the average speed of the vehicle can be sought on the basis of the comparison of the forces of movement resistance and the traction forces that the vehicle can develop on the drive wheels.

Depending on the initial data on the road resistance coefficient of vehicle [16], it is possible to use discrete or probabilistic methods of calculating the average speed of the vehicle.

Considering the traffic conditions of three-link road trains, preference should be given to the probabilistic method. At the same time, movement resistance values are determined on the basis of data about route and described by the normal law of the distribution of the road resistance coefficient along the length of the route [15], i.e

$$f(\psi) = \frac{1}{\sigma_{\psi} \times \sqrt{2\pi}} \times e^{-\frac{(\psi - m_{\psi})^2}{2\sigma_{\psi}^2}}, \quad (1)$$

where m_{ψ} and σ_{ψ} - the mathematical expectation and average square deviation of the road resistance coefficient ψ.

The average speed of vehicle under the probabilistic distribution of road resistance on a given route was determined by the algorithm presented in the table 1 [15].

Table 1

Basic calculation formulas for determining indicators of traction-speed properties of a vehicle

Parameter	Calculation formula
1	2
Equation of motion during acceleration	$$\frac{dV}{dt} \times m_a \times \delta_i = a \times V^2 + b \times V + c\,, \quad (2)$$ where V - the speed of the road train, m/s; m_a - the mass of the road train, kg; a, b, c - the coefficients of the polynomial that approximates the external speed characteristics of the tractor engine; δ_i - the coefficient that takes into account the increase in the inertia forces of the rolling masses of the road train due to its rotating masses, which is defined as $$\delta_i = 1 + \sigma_1 \times u_{ki}^2 + \sigma_2; \quad (3)$$ σ_1 - the coefficient that takes into account the rotating masses of the engine and transmission of the tractor; σ_2 - the coefficient that takes into account the rotating masses of the wheels of the tractor and the towing links; u_{ki} - the transmission ratio of the tractor gearbox on the i-th gear.
Acceleration time on the i-th gear, s	$$\tau_i = m_a \times \delta_i \times \int_{V_{Hi}}^{V_{Ki}} \frac{dV}{a \times V^2 + b \times V + c}, \quad (4)$$ where V_{Hi} - the initial speed on the i-th gear in the acceleration process, s; V_{Ki} - the final speed on the i-th gear in the acceleration process, s.
The time of acceleration of the road train, s	$$T = \Sigma \tau_i. \quad (5)$$
Acceleration path on the i-th gear, m	$$S_i = m_a \times \delta_i \times \times \left\{ \frac{1}{2 \times a_i} \times ln\left|a \times V^2 + b \times V + c\right|\Big|_{V_{Hi}}^{V_{Ki}} - \frac{b}{2 \times a} \times \times \int_{V_{Hi}}^{V_{Ki}} \frac{dV}{a \times V^2 + b \times V + c} \right\}. \quad (6)$$

Continuation of table 1

1	2
Dispersal path of the road train, m	$$S = \Sigma S_i. \qquad (7)$$
Equation of motion when running out	$$\frac{dV}{dt}\times m_a\times\delta_0' = -m_a\times g\times\left(f_0\times K_f\times V\right) - K_B\times F\times V^2 - P_{fx}, \qquad (8)$$ where δ_0' - the coefficient that takes into account the increase in the inertia forces of the translational masses of the road train due to the rotating masses of only the wheels; g - the acceleration of free fall, m/s^2; f_0 - the coefficient of rolling resistance at a speed of 1 m/s; K_f - the coefficient that takes into account the increase in the rolling resistance coefficient f from the speed of movement; K_B - the coefficient of air resistance of the road train, N×s^2/ m^4; F - the Midel area, m^2 (taken to be equal to the area of the projection of the road train on the plane perpendicular to its longitudinal axis) and is defined as $$F = B\times H; \qquad (9)$$ B - the tractor track, m; H - the height of the road train, m; P_{fx} - the force of resistance to motion when the engine is idling, N, which is defined as $$P_{fx} = (2 + 0{,}025\times V)\times m_a\times g\times 10^{-3}. \qquad (10)$$
Minimum steady speed, m/s	$$Vmin_y = -\frac{m_a\times g\times f_0\times A_i - K_B\times F\times C_i}{m_a\times g\times K_f\times A_i - K_B\times F\times B_i} + \sqrt{\left(\frac{m_a\times g\times f_0\times A_i - K_B\times F\times C_i}{m_a\times g\times K_f\times A_i - K_B\times F\times B_i}\right)^2 - \frac{m_a\times g\times(f_0\times B_i - K_f\times C_i)}{m_a\times g\times K_f\times A_i - K_B\times F\times B_i}}, \qquad (11)$$ where A_i, B_i, C_i - the constant coefficients determined by the car's engine and transmission parameters.
Maximum speed, m/s	$$V_{max} = \frac{-b_i - \sqrt{b_i^2 - 4\times a_i\times c_i}}{2\times a_i}. \qquad (12)$$
Maximum acceleration during acceleration, m/s^2	$$j_{max} = \frac{1}{G_a\times\delta_i}\times\left(c_i - \frac{b_i^2}{4\times a_i}\right), \qquad (13)$$ where G_a - the gravitational force from the full mass of the road train, N.
Average acceleration during acceleration, m/s^2	$$j_{cp} = \frac{1}{G_a\times\delta_i}\times\left[\frac{a_i}{3}\times(V_K^2 + V_K\times V_H + V_H^2) + \frac{b_i}{2}\times(V_K + V_H) + +c_i\right]. \qquad (14)$$
The maximum climb that can be overcome	$$\sin\alpha_{max} = \frac{1}{G_a\times\delta}\times \times\left(C_i - G_a\times g\times f_0\times\cos\alpha - \frac{(B_i - G_a\times g\times K_f\times\cos\alpha)^2}{4\times A_i}\right), \qquad (15)$$ where α - the angle of elevation of the road.
Speed on rise, m/s	$$V_{\text{уст}} = \frac{-b_i - \sqrt{b_i^2 - 4\times a_i\times c_i}}{2\times a_i}. \qquad (16)$$

Continuation of table 1

1	2
Maximum traction force on the hook, N	$$P_{KPmax} = \frac{b_i^2}{4 \times a_i}. \quad (17)$$
Average speed on the route, m/s	$$V_c = \frac{0{,}27 \times N_{уд} \times \eta_m \sum_{i=1}^{n} K_i \times d_i}{\frac{\gamma_{piN} \times \sum K_i \times d_i}{l_i}}, \quad (18)$$ where $N_{уд}$ - the specific power of the road train, kW/t; η_m - the efficiency factor of the transmission of the tractor; K_i - the relative path of the road train in the i-th gear; γ_{piN} - the specific traction force of the road train in the i-th gear when the engine is operating in the maximum power mode; l_i - the coefficient that takes into account the type of speed distribution law on the transmission; d_i - the calculation coefficient, which is defined as $$d_i = \frac{V_i}{V_{i-1}}; \quad (19)$$ V_i, V_{i-1} - the maximum speeds on i-th and i -1 gears, m/s.
Coefficients of equations	$$a_i = A_i - K_B \times F. \quad b_i = B_i - K_f \times m_a \times g. \quad c_i = C_i - f_a \times m_a \times g \quad (20)$$ $$A_i = a \times \frac{U_i^3 \times \eta_м}{r_д \times r_к^2}, \quad B_i = b \times \frac{U_i^2 \times \eta_м}{r_д \times r_к}, \quad C_i = c \times \frac{U_i \times \eta_м}{r_д} \quad (21)$$ where U_i - the gear ratio of the transmission of the tractor in the i-th gear; $r_д$ - the dynamic radius of the wheel, m; $r_к$ - the rolling radius of the wheel, m.

In accordance with the given algorithm, the average speed of road trains carrying out intercity and international transportation on paved roads in flat terrain is determined. For such roads, the parameters of the normal distribution law of the road resistance coefficient along the length of the path are [14]: m_ψ=0.022, σ_ψ=0.012.

In the table 2 shows the results of calculating the average speed of road trains consisting of tractors MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105 and Volvo FH16 with Krone semi-trailers and trailers.

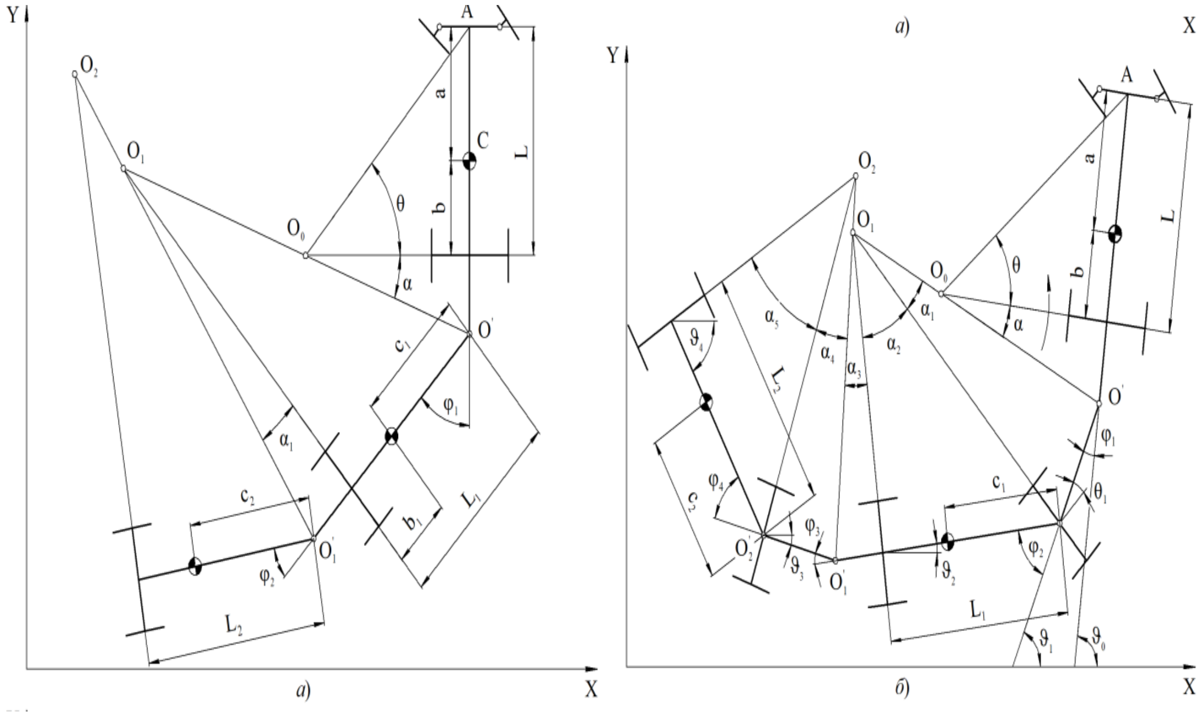
Table 2

The average speed of a road train consisting of different tractors

Tractor	MAN TGA	Iveco Magirus	Scania R-series	DAF XF 105	Volvo FH16
Average speed, m/s	22.13	21.57	22.68	21.05	22.99

As follows from the table 2, the average speeds of road trains consisting of tractors of category N3 (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers of category O4 in given road conditions differ little from each other. The maximum deviation of the average speed of movement, which has the largest value (for Volvo FH16+KRONE SDP-27 – 22.99 m/s), from the smallest value (for DAF XF105+KRONE SDP-27 – 21.05 m/s) does not exceed 8.5%, that is, further comparison of road trains should be executed according to other criteria, in particular, according to maneuverability when moving on a given route.

In the paper [7], in which the issues of maneuverability of three-link vehicles trailed and semi-trailer layout schemes were considered, the modular construction of the road train was adopted. Under this condition, the road train was presented in the form of three modules - a tractor and two towing links (Fig. 1).



а) - according to the semi-trailer scheme; *б)* - according to the trailer scheme.
Figure 1. Calculation scheme of a three-link road train

With the modular construction of the road train, the tractor is presented in the form of one module - a skeleton with front steerable wheels and one or two axles with non-rotating wheels (axles). For further calculations, it was assumed that the turning angles of the left $\theta_л$ and right $\theta_п$ of the steered wheels of the tractor are equal to their average turning angle θ, i.e. $\theta_л=\theta_п=\theta$. The towing links were also presented in the form of either one module - a skeleton with non-rotating wheels (axles) under the semi-trailer layout scheme, or from two kinematically independent elements - a platform with a non-rotating rear axle and a rotating axle with a drawbar, in which the angles of rotation of the first and second trailers - θ_1 and θ_2, moreover, there is a hinge connection between them.

Determining the maneuverability indicators of the road train with sufficient accuracy for practical calculations can be carried out on rigid in the lateral direction wheels at the angles of assembly and rotation of the links of the road train.

These angles for a towed road train (Fig. 1) are defined as follows [7]:

$$\frac{d\varphi_1}{dt} + \frac{v_A}{L \times \frac{\sin(\pi/2-\varphi_2-\alpha_1)}{\sin(\varphi_1+\varphi_2+\alpha_1)}} - \frac{v_C \times tg\theta}{a+b-d} = 0, \qquad (22)$$

where φ_1 - the first folding angle (the angle between the longitudinal axis of the tractor and the drawbar of the first trailer);

φ_2 - the second folding angle (the angle between the longitudinal axis of the first trailer and its drawbar);

v_A - the speed of point A (the middle of the steered axle of the tractor);

v_C - the speed of point C (center of mass of the tractor);

L - tractor base;

a - the distance from the center of mass to the front axle of the tractor;

b - the distance from the center of mass to the rear axle of the tractor (to the middle of the paired axles of a three-axle vehicle);

d - the distance from the center of mass of the tractor to the point of towd with the first towing link;

α_1 - the auxiliary angle, which is defined as

$$\alpha_1 = arctg\left(\frac{d_1-c_1}{a_1+b_1} \times tg\theta\right), \qquad (23)$$

c_1 - the distance from the center of mass of the first trailer to the point of towd with the tractor;
a_1 - the distance from the center of mass of the first trailer to its front axle;
b_1 - the distance from the center of mass of the first trailer to its rear axle;
d_1 - the distance from the center of mass of the first towing link to the point of towd with the second towing link;

$$\frac{d\varphi_2}{dt} - \frac{v_{C1} \times sin(\pi/2 - \varphi_1)}{\frac{a_1+b_1}{tg\theta_0} \times sin(\pi/2 - \varphi_2 - \alpha_1) \times \sqrt{1 + \left(\frac{L_1 - c_1}{a_1 + b_1} \times tg\theta_1\right)^2}} - \frac{v_A \times sin(\varphi_1 + \varphi_2 + \alpha_1)}{L_1 \times sin(\pi/2 - \varphi_1 - \alpha_1)} = 0, \quad (24)$$

where L_1 - base of the first trailer.

$$\frac{d\varphi_1}{dt} - \frac{v_{C1} \times sin(\varphi_1 + \varphi_2 + \alpha_1) \times L^2{}_1 \times sin(\gamma_1 + \varphi_3 + \alpha_2)}{L_2 \times L_3 \times sin\varphi_2\, sin(\pi/2 - \varphi_3 - \alpha_2)} \times$$
$$\times \frac{sin\left(\frac{\pi}{2} - \varphi_2 - \alpha_1\right) \times ctg\gamma_1}{\frac{a_2+b_2}{tg\varphi_2} \times \sqrt{1 + \left(\frac{d_2 - c_2}{a_2 + b_2} \times tg\varphi_2\right)^2} + L_2 \times \frac{cos\varphi_1}{sin(\varphi_1 + \varphi_2 + \alpha_1)} - L_3 \times sin(\pi/2 - \varphi_2 - \alpha_1) \times ctg\gamma_1} -$$
$$- \frac{v_{C1} \times L_1 \times sin(\varphi_1 + \varphi_2 + \alpha_2)}{L_2 \times L_3 \times sin(\pi/2 - \varphi_2 - \alpha_2)} = 0, \quad (25)$$

where φ_3 , φ_4 - the third and fourth folding angles;
α_2 - the auxiliary angle, which is defined as

$$\alpha_2 = arctg\left(\frac{d_2 - c_2}{a_2 + b_2} \times tg\varphi_2\right), \quad (26)$$

where d_2 - the distance from the center of mass of the second towing link to the point of towd with the third towing link;
c_2 - the distance from the center of mass of the second trailer to the point of its towd with the first trailer;
a_2 - the distance from the center of mass of the second trailer to its front axle;
b_2 - the distance from the center of mass of the second trailer to its rear axle;
ϕ_1, ϕ_2 - the auxiliary angles, which are defined as

$$\phi_1 = arctg\left[\frac{l_1 \times sin(\varphi_2 + \varphi_1 + \alpha_1)}{L_1 \times sin(\pi/2 - \varphi_2 - \alpha_1)} \times \frac{1}{\sqrt{1 - \left\{\frac{\left[\frac{sin(\pi/2 - \varphi_2 - \alpha_1)}{sin(\varphi_2 + \varphi_1 + \alpha_1)}\right]^2 + 1 - \left[\frac{sin(\pi/2 - \varphi_1)}{sin(\varphi_2 + \varphi_1 + \alpha_1)}\right]^2}{2 \times \frac{sin(\pi/2 - \varphi_2 - \alpha_1)}{sin(\varphi_2 + \varphi_1 + \alpha_1)}}\right\}^2}}\right], \quad (27)$$

$$\phi_2 = arctg\left[\frac{L_2 \times sin(\varphi_4 + \varphi_3 + \alpha_2)}{d_2 \times sin(\pi/2 - \varphi_4 - \alpha_2)} \times \frac{1}{\sqrt{1 - \left\{\frac{\left[\frac{sin(\pi/2 - \varphi_4 - \alpha_2)}{sin(\varphi_4 + \varphi_3 + \alpha_2)}\right]^2 + 1 - \left[\frac{sin(\pi/2 - \varphi_3)}{sin(\varphi_4 + \varphi_3 + \alpha_2)}\right]^2}{2 \times \frac{sin(\pi/2 - \varphi_4 - \alpha_2)}{sin(\varphi_4 + \varphi_3 + \alpha_2)}}\right\}^2}}\right] \quad (28)$$

where L_2 - base of the second trailer.

$$\frac{d\varphi_4}{dt} - \frac{v_{C1} \times tg\phi_1 \times sin(\varphi_1 + \varphi_2 + \alpha_1)}{\frac{a_2+b_2}{tg\theta_2} \times sin(\pi/2 - \varphi_2 - \alpha_2) \times \sqrt{1 + \left(\frac{l_2 - c_2}{a_2 + b_2} \times tg\theta_2\right)^2}} - \frac{v_{C1} \times sin(\varphi_1 + \varphi_2 + \alpha_1) \times sin(\phi_1 + \varphi_4 + \alpha_2)}{d_2 \times sin\,\varphi_2 \times sin(\pi/2 - \varphi_4 - \alpha_2)} = 0. \quad (29)$$

In the case of a semi-trailer truck, the first and second folding angles are marked as γ_1 and γ_2 (Fig. 1, a).

It is advisable to determine the angles of assembly of the links and rotation of the steered axles of the trailers during the circular motion of the road train. In this case, the calculation formulas for determining the folding angles and angles of rotation of the steered axles of the second and third trailers are determined by the geometric parameters of the links and the setting parameter - the angle of rotation of the steered wheels of the tractor. So, if the turning angle of the steered wheels of the tractor is taken as a defining parameter for the road train, then the turning angles and folding angles are determined as follows:

$$\varphi_1 = arcsin\frac{L_1^2+c_1^2-b^2}{2\times L_1\times\sqrt{L_1^2\times ctg^2\theta\ \ +c_1^2}} - arctg\frac{c_1}{L_1\times ctg\theta}, \quad (30)$$

$$\varphi_2 = arcsin\frac{L_1^2-c_1^2+b^2}{2\times L_1\times\sqrt{L_2^2\times ctg^2\theta\ \ +b^2}} + arctg\frac{b}{L_2\times ctg\theta}, \quad (31)$$

$$\varphi_3 = arcsin\frac{L_2^2+c_2^2-{b_1}^2}{2\times L_2\times\sqrt{L_1^2\times ctg^2\theta_1+c_2^2}} - arctg\frac{c_2}{L_1\times ctg\theta_1}, \quad (32)$$

$$\varphi_4 = arcsin\frac{L_2^2-c_1^2+{b_1}^2}{2\times L_2\times\sqrt{L_1^2\times ctg^2\theta_2+{b_1}^2}} + arctg\frac{b_1}{L_1\times ctg\theta_2}, \quad (33)$$

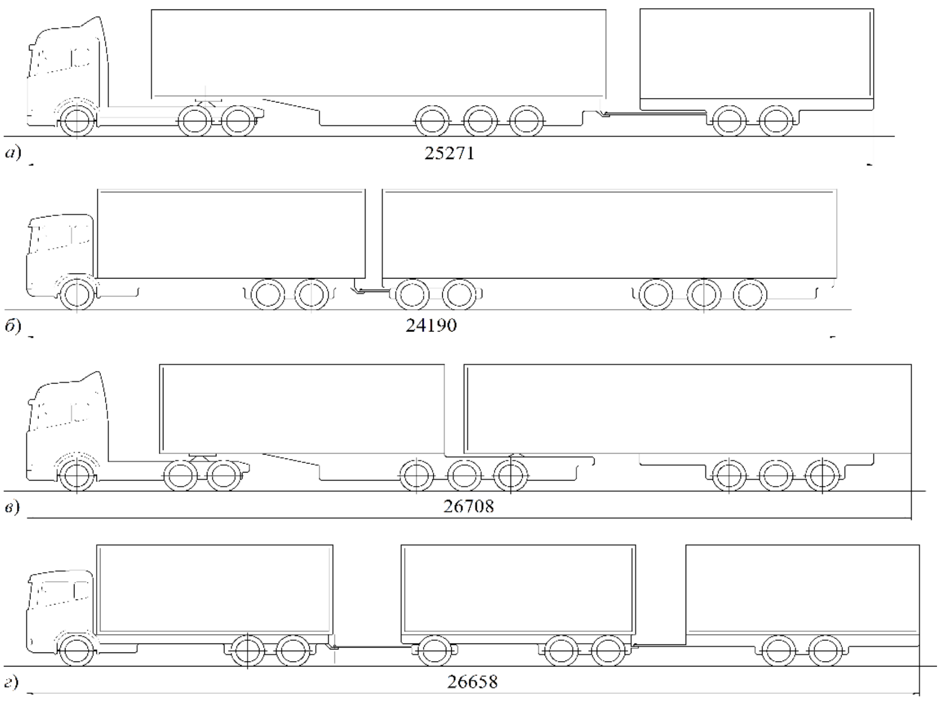
$$\theta_1 = arctg\frac{L_1}{L_2\times ctg\theta_1}, \quad (34)$$

$$\theta_2 = arctg\frac{L_2}{L_1\times ctg\theta_2}. \quad (35)$$

The constructural differences of freight trains are determined by the number of axles of the driving link (tractor) and trailing links (trailer or semi-trailer), by the number of controlled axles and their location. At the same time, from the proposed general scheme of a three-link road train (Fig. 1, b), it is possible to obtain any other one by equating to zero either the mass and the moment of inertia of the axis, or the angle of rotation of the axis, or the corresponding composition parameters.

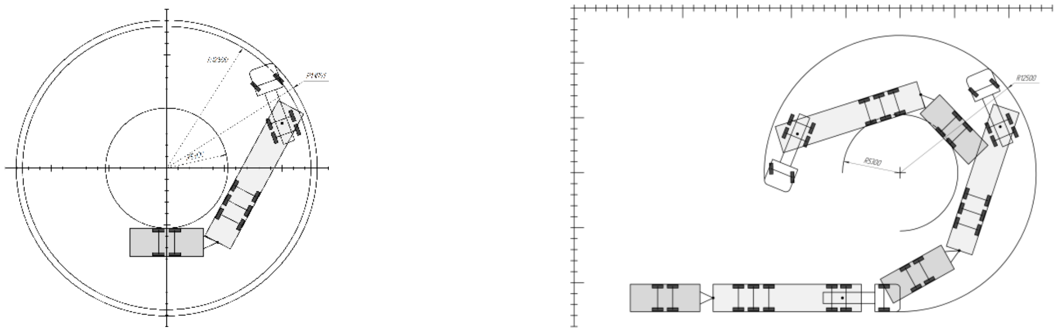
The overall turning radii of the road train and the generalizing indicator of maneuverability - the dimensional traffic lane - are determined by the found angles of assembly of the links of the road train.

In fig. 2 shows the layout schemes of typical road trains.



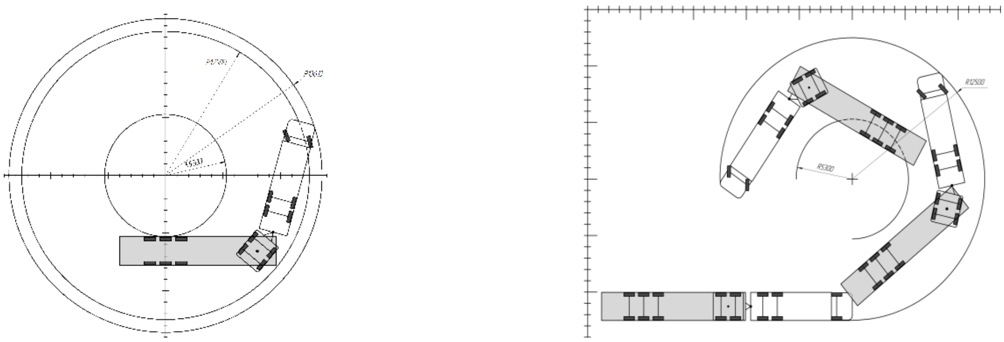
а) - a saddle-coupled three-link road train; *б)* - a three-link road train on a “Dolly” trolley;
в) - "B-Double" type three-link road train; *г)* - trailer three-link road train.
Figure 2. Layout schemes of typical road trains

In fig. 3-6 it is shows a graphic representation of the determination of the dimensional traffic lane of typical road trains during circular motion and when entering a turn.



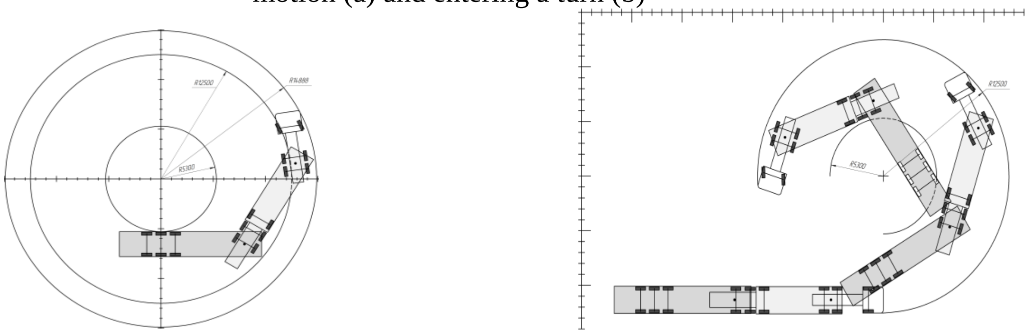
а) б)

Figure 3. The dimensional traffic lane of a saddle-coupled three-link road train at circular motion (a) and entering a turn (b)



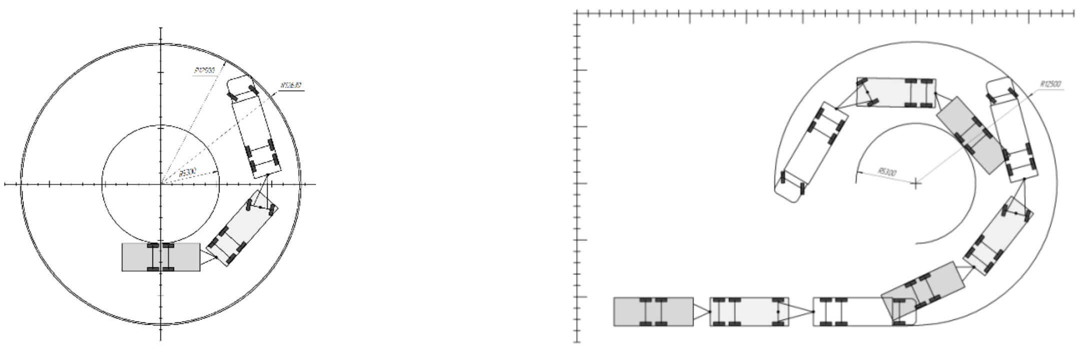
а) б)

Figure 4. The dimensional traffic lane of the trailer three-link road train on a “Dolly” trolley at circular motion (a) and entering a turn (b)



а) б)

Figure 5. The dimensional traffic lane of a three-link road train of the "B-Double" type at circular motion (a) and entering a turn (b)



а) б)

Figure. 6. The dimensional traffic lane of the trailer three-link road train at circular motion (a) and entering a turn (b)

Data analysis of fig. 3-6 shows that three-link road trains do not saticfy the requirements of Directive 2002/7/EC on maneuverability [17]. For three-link road trains with unguided towing links, the minimum external overall turning radius with an internal overall radius of 5.3 m changes within from 12.63 m for a trailed road train to 14.9 m - for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of tractor and in the construction of towing links, in particular, the introduction of controlled towing links into their composition and the determination of their placement in the composition of road train.

DISCUSSION OF THE RESULTS OF THE STUDY

As shown by the calculations of the generalizing indicator of traction-speed properties, the average speed of a road train consisting of tractors of category N3 (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and trailers of category O4 of the KRONE brand in given road conditions differ little from each other, despite the fact that the power of the Volvo FH16 tractor engine (Ne=449 kW) exceeds the power of the DAF XF 105 engine (Ne=375 kW) by 16.5%. From this, it can be concluded that choosing a tractor for a three-link road train based on the power of the engine of the tractor is not appropriate. The selection of the layout scheme of a three-link road train should be based on such indicators as maneuverability and stability of movement.

Conducted studies of the maneuverability of road trains of various layout schemes showed that none of them not saticfy the requirements of Directive 2002/7/EC on maneuverability [17]. Therefore, the issues of maneuverability and stability of three-link road trains with controlled towing links can become directions of further research.

SUMMARY

1. It was established that the average speeds of road trains consisting of tractors of the N3 category (MAN TGA, Iveco Magirus, Scania R-series, DAF XF 105, Volvo FH16) with semi-trailers and trailers of the KRONE brand of the O4 category differ little from each other in the given road conditions. The maximum deviation of the average speed of movement, which has the largest value (for Volvo FH16+ KRONE SDP-27) 22.99 m/s, from the smallest value (for DAF XF 105+KRONE SDP-27) 21.05 m/s, do not exceed 8,5%, i.e. further comparison of road trains should be execute according to other criteria, in particular, according to maneuverability, when moving on a given route.

2. It is shown that the considered three-link road trains do not saticfy the requirements of Directive 2002/7/EC regarding maneuverability. For three-link road trains with unguided towing links, the minimum external dimensional turning radius with an internal dimensional radius of 5.3 m varies from 12.63 m for a trailer road train to 14.9 m for a "B-Double" type road train. This is explained by the fact that the length of the three-link road train lies within 26.0...27.0 m. Therefore, for the practical use of three-link road trains in Ukraine, changes should be made both in the transport legislation and in the construction of tractor, in particular, the introduction of controlled towing links into their composition and the determination of their placement in the composition of road train.

DECLARATION OF COMPETING 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.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

1. Sakhno, V. P., Poliakov, V. M., Murovaniy, I. S., Sharay, S. M. (2019). To choose the type of tractor for a high-capacity road train. Bulletin of Machine Building and Transport: scientific journal. Vinnytsia National Technical University, 2 (10), 120-125. doi: https://doi.org/10.31649/2413-4503-2019-10-2-120-125

2. Zharov, K. S. (2014). Selection and justification of the type of truck-tractor of a large-capacity train. Kyiv: National Transport University, 166.

3. Organisation WHO, Global Status Report on Road Safety, WHO, Geneva, Switzerland, 2018. URL: https://www.who.int/publications/i/item/9789241565684

4. Road Traffic Injuries and Related Safety Measures: A Multicentre Analysis at Military Hospitals in Tabuk, Saudi Arabia. URL: https://www.hindawi.com/journals/emi/2021/6617381/

5. Vranes, A. J., (2018). Road traffic safety as a public health problem: evidence from Serbia. Journal of Transport & Health, 8, 55–62. URL: https://www.sciencedirect.com/science/article/abs/pii/S2214140517305820

6. Viscusi, W. Kip (2015). The Role of Publication Selection Bias in Estimates of the Value of a Statistical Life. American Journal of Health Economics, 1(1), 27–52. URL: https://www.journals.uchicago.edu/doi/epdfplus/10.1162/ajhe_a_00002

7. Poliakov, V. M., Sakhno, V. P. (2013). Three-lane road trains. Maneuverability: monograph. Luhansk: Noulidzh, 206. ISBN 978-617-579-918-5

8. Sakhno, V. P., Poliakov, V. M., Sharay, S. M., Murovaniy, I. S., O. Ye. Omelnytskii. (2019). Articulated buses. Maneuverability and stability: monograph. Lutsk: Lutsk National Technical University, 288. ISBN 978-617-672-243-4

9. Sakhno, V., Polyakov, V., Murovanyi, I., Timkov, O., Mialkovska, L., Popovych, P., Poberezhnyi, L. (2023) Influence of the technical condition of the running system of articulated buses on stability of their straight-line motion. Communications - Scientific Letters of the University of Žilina.Volume 25, Issue 1, Pages B52 - B61. https://www.scopus.com/record/display.uri?eid=2-s2.0-85148281167&origin=resultslist

10. Hsueh-Ju Chen, Wei-Jiun Su, Fu-ChengWang. (2017). Modeling and analyses of a connected multi-car train system employing the inerter.Special Issue Article. Advances in Mechanical Engineering, 9(8), 1–13. https://doi.org/10.1177/1687814017701703

11. Zhang, Y., Khajepour, A., Huang, Y. (2018). Multi-axle/articulated bus dynamics modeling: a reconfigurable approach. Vehicle System Dynamics International Journal of Vehicle Mechanics and Mobility, 56(9). https://www.tandfonline.com/doi/full/10.1080/00423114.2017.1420205

12. Hales, F. D. (1972). The vertical motion lateral stability of road vehicle trains. Technology University / UK, Transport and Road Research Laboratory (TRRL). 79. https://trid.trb.org/view/112747

13. Galluppi, O., Formentin, S., Novara, C., Savaresi, S. M. (2017). Nonlinear stability control of autonomous vehicles: a MIMO D^2-IBC solution. IFAC-PapersOnLine, 50(1), 3691-3696. https://doi.org/10.1016/j.ifacol.2017.08.563

14. Islam, M. M. (2013). Parallel design optimization of multi-trailer articulated heavy vehicles with active safety systems. University of Ontario Institute of Technology Oshawa, Ontario, 171. URL: https://hdl.handle.net/10155/309

15. Sakhno, V. P., Bezborodova, H. B., Maiak, M. M., Sharay, S. M. (2004). Cars. Traction-speed properties and fuel efficiency. Kyiv: KPIC, 174. ISBN 966-7192-55-5.

16. Beshun, O. A., Melanchenko, Ya. V. (2018). Analysis of factors affecting the force and coefficient of rolling resistance of the wheel. Machinery & Energetics. Journal of Rural Production Research. Kyiv, 9(4), 123-131. http://journals.nubip.edu.ua/index.php/Tekhnica/article/view/12362/10736%3E

17. 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. (2002). Official Journal of the European Communities, L 67/47-49. https://www.legislation.gov.uk/eudr/2002/7/resources

.*Volodymyr SAKHNO*, Doctor of Technical Science, Professor, Head of the Automobile Department, National Transport University, Kyiv, Ukraine, e-mail: sakhno@ntu.edu.ua
https://orcid.org/0000-0002-5144-7131

*Igor MUROVANYI**, Ph.D. in Engineering, Associate Professor, Dean of the Faculty of Transport and Mechanical Engineering, Lutsk National Technical University, e-mail: igor_lntu@ukr.net
https://orcid.org/0000-0002-9749-980X

Victor POLYAKOV, Ph.D. in Engineering, Associate Professor, Professor of the Automobile Department, National Transport University, e-mail: poljakov_2006@ukr.net
http://orcid.org/0000-0001-7042-3066

Svitlana SHARAI, Ph.D. in Engineering, Associate Professor, Professor of the International Transport and Customs Control Department, National Transport University, e-mail: Svetasharai@gmail.com
http://orcid.org/0000-0001-6568-4990

Oleksandr RAZBOINIKOV – Ph.D. in Engineering, Associate Professor of the Automobile Department, National Transport University, Kyiv, e-mail: razboyn1k@ukr.net
https://orcid.org/0000-0003-3024-0999

Maksym ROI - Doctor of Philosophy, Associate Professor of the International Transport and Customs Control Department, National Transport University, e-mail: 7569027@ukr.net
http://orcid.org/0000-0001-5788-4220

* Corresponding author.

Received 24 March 2024;
Accepted 10 May 2024
Available online 28 May 2024

DOI 10.36910/conf_avto.v1i1.1390