May, 28-29, 2019, Ternopil, Ukraine

**ICCPT 2019: Current Problems of Transport: Proceedings of the 1st International Scientific Conference, May 28-29, 2019, Ternopil, Ukraine**

# Improving of transitway operating properties

**Volodymyr Sakhno [1], Igor Murovanyi [2], Viktor Poliakov [1], Svitlana Sharai [1]**

[1] National Transport University, M. Omelianovycha-Pavlenka str 1, 02000, Kyiv, Ukraine, svp_40@ukr.net
[2] Lutsk National Technical University, Lvivska st 75, 43018, Lutsk, Ukraine, igor_lntu@ukr.net

**Abstract:** Modern public transport systems are increasingly seen as an important means of promoting the safe mobility of the population, especially in urban areas suffering from growing traffic jams. The Transitway or the new bus system “Bus Rapid Transport” (BRT) is the result of the development of a bus public transport network. In comparison with the subway, this project has obvious advantages: lower cost of network creation, lower cost of rolling stock, mobility, etc. These advantages are manifested, first of all, with the maximum use of passenger capacity of transitways, that is, with the application of three-axles transitways and with their motion on the maximum possible speeds. The purpose of this paper is to present the findings of the transitway motion stability research, which was based on the analysis of solutions of motion differential equations. These equations were compiled with respect to the variables of the longitudinal and transverse velocities of the center of the bus mass and the angular velocities of the bus and of two couplings. As a result of the research, the critical velocity of the three-axles transitway has been determined and factors influencing its numerical value have been analyzed. It has been shown that during the operation of the transitway it is necessary to maintain such pressure in the tires so that, for the selected load on the wheels of the axes of the auto-train, the coefficient of resistance to the lateral separation of the wheels of the steered wheels of the bus and the trailer is smaller than the wheels of uncontrolled axes. The practical value of the research is that this finding will be used for increasing the critical speed $v_{cr}$ of the auto-train.

**Keywords:** transitway, auto-train, bus, trailer, speed, stability

## 1. Introduction

Safe public transport systems are increasingly seen as an important means of safe promoting the population mobility, especially in urban areas suffering from growing traffic jams. In many high-income cities, the policy of reducing the use of private transport is particularly emphasized through investments in the development of public transport networks. Investments in safe public transport are also seen as a mechanism that stimulates the growth of physical activity and, therefore, contributes to the health of the population.

The transitway or the new bus system “Bus Rapid Transport” (BRT) is the result of the development of a bus public transport network. In comparison with the subway, this project has obvious advantages: lower cost of network creation, lower cost of rolling stock, mobility, etc. [1].

The BRT system has a number of undeniable advantages [2,3]

- high passenger capacity and efficient payment systems provide low-cost travel;
- high speed of movement allows the transitway to carry a large share of passenger traffic, which contributes to reducing the number of cars on the city roads and, accordingly, reducing emissions of exhaust gases;

**ICCPT 2019: Current Problems of Transport**. https://iccpt.tntu.edu.ua
https://doi.org/10.5281/zenodo.3387522


Peer-review under responsibility of the Scientific Committee of the 1st International Scientific Conference ICCPT 2019: Current Problems of Transport

- an expanded information system informs passengers about bus timetables.

Convenience, safety and improved organization of the traffic are not only items which can give passengers a system of high-speed bus transport. In this system, passenger high-speed buses drive on specially created lanes. They are separated from the carriageway and are equipped with closed passenger stations with platforms on the same level and underground passages [4].

The rolling stock used in the BRT system has two types: the first one is a classic two-axles transitway with an engine operating on both diesel and gas fuels; the second is a three-axles transitway of a new generation with a hybrid electric gas engine. These two variants are inherent in articulated buses, 18 and 24 meters long [5].

Testing hybrid public transport in Gothenburg has showed that the fuel consumption of the Volvo bus is less than 11 liters per 100km. This is much less than an equivalent diesel bus consumes. Hybrids (3 buses were involved in the project) set off on public transit routes, periodically charging the battery at stops. Charging was done by connecting to the charging tire.

Consequently, the main advantages of BRT systems are the relatively small construction cost, the speed of the line construction, the small cost of buses, the ability to flexibly change passenger traffic due to traffic intensity, the possibility of partially using the BRT line for another special transport. It can use separate lanes, or move on existing roads. Bus can drive on a high speed in the city on separate lanes. Bus may have different routes on the same line, unlike the subway. It reduces the use of private vehicles, improves the transport situation and gives the chance to completely abandon small buses in cities [2, 6]. These advantages are manifested, first of all, on the maximum use of passenger capacity of transitways, that is, with the application of tree-axles transitways.

The peculiarity of the functional systems design providing stability and controllability of auto-trains and transitways (further vehicle) is the parallel processes of their design, optimization and modeling of the vehicle dynamics, in general under the multicriteria of sometimes contradictory tasks [7].

The characteristics of stability and handling, as is known, are determined by a combination of operational, mass-geometric and structural parameters of the vehicles modules. In general, it is desirable to combine these parameters in terms of stability and handling even for the same vehicle in the range of operating loads and speeds varying. As a consequence, it is difficult to obtain the exact constructive parameters and quantitative indicators on the criteria of stability and controllability of traffic at the early stages of the vehicle construction [8].

While considering the motion stability of the tree-axles vehicles it has been considered for two control schemes – open and closed. With open control scheme, it has been assessed the vehicle potential stability is assessed, with closed – stability of the driving system - vehicle [8].

The theoretical basis of the analysis is made on the mathematical models of rectilinear and controlled motions of the car and the auto-train designed for automobiles and two-axles auto-trains [9]. On their basis, it has been obtained the differential equations of perturbed traffic of vehicles, the equation of the limits of stability of rectilinear motion of cars and the differential equations of trajectories of characteristic points of parts of auto-trains are obtained, the solutions of which allow to determine the motion critical speed, with the help of which it is possible to predict the behavior of both controlled and uncontrolled vehicles.

## 2. Materials and Methods

In works [8-11], which are considered the issues of maneuverability and durability of three-axles auto-trains, it has been adopted the modular construction of an auto-train was adopted. Under this condition, the auto-train was presented in the form of three modules - a car-tractor and two trailer couplings. In turn, the car-tractor was presented as a single module - a skeleton with front-mounted steering wheels, and in the form of two kinematically independent elements - a skeleton with two (one) rear axes and a steering wheel module. The trailer couplings were also represented in the form of either a single module - a skeleton with non-rotating wheels (axes) or from two kinematically independent elements - a platform and a carriage when each bearing system of a semi-trailer or trailer is based on a carriage, and there is a hinge link between them, and driven by wheels or axes of a semi-trailer and a dual-axes trailer to control them. Thus, the differences in the designs of three-axles auto-trains in most cases are determined by the differences in the design of trailer couplings, since the design of car-tractors remains unchanged.

Motion differential equations for determining the indicators of maneuverability and stability of the auto-trains are either using the method of intersections, or using general theorems of mechanics: about the change of the main vector and the momentum. With the use of the intersection method, the differential motion equations of the car-tractor and trailer couplings can be unified, however, with the increase in the number of auto-train axles, the use of this method becomes problematic due to the need to determine the reactions at the unification points of the auto-train axles. This disadvantage is deprived of the method using general theorems of mechanics, which can be applied to any lay-out scheme of an auto-train, including for a transitway.

Making the motion differential equations for the transitways relative to the variables of the longitudinal v, the transverse u and the angular velocity of the car-tractor ω and the angles of axles assembly of the auto-train φ1 and φ2 will be performed on the following data:

- the auto-train is moving along a flat horizontal surface;
- the unspotted mass is considered to be uncorrected;
- the controlling influence on the parameters of the auto-train is carried out through the steering wheels of the car-tractor;
- do not take into account the presence of gaps in drawbar couplings;
- the distance between the axles of the auto-train does not change because of the small angle of assembly;
- when driving a auto-train on the roads of a real microprofile, the angle of twisting of the frame and its rigidity on torsion are not taken into account;
- the constituent elements of the auto-trains are absolutely solid bodies:
- the passengers in the BRT are located so that the centers of mass axles, as well as the tension-coupling devices connecting them, are located in the vertical plane of axle symmetry;
- the trajectory of the tractor center center is taken as the main trajectory;
- the interaction of the wheels with the bearing surface is expressed through the reaction of the road cloth in the longitudinal and transverse plane, which is a function of the rolling resistance coefficient and the angle of displacement, namely [8]

$$X_i = G_i \times f,$$

$$Y_i = \frac{k_i \delta_i}{\sqrt{1+k_i\,(\varphi^2 G_i^2)^{-1}\,\delta_i^2}},$$

where $G_i$ - vertical load on the wheel;

$f$ - coefficient of rolling resistance;

$\delta_i$, $Y_i$ - angles of discharge and lateral reactions;

$k_i$ - coefficient of resistance to lateral withdrawal;

$\varphi$ - coefficient of adhesion between the tire and the supporting surface in the transverse direction (we consider φ the constant value for the given road conditions).

In addition, the car-tractor will be presented in the form of a single module - a skeleton with front-controlled wheels, the average turning angle of which $\theta_1$. The two rear axes of the tractor are irreversible and located behind the center of the tractor's masses. Both trailers consist of one module - a skeleton with non-rotating wheels (axes).

The work [12] describes a system of equations describing the plane-parallel motion of a three-axles trailer auto-train, which can be applied to the transitway, Fig. 1, in the form of:

$$m(\dot{u} + v\omega) = Y_2 \cos\theta_1 + Y_{21} + YA - YB\cos\gamma_1 + XB\sin\gamma_1;$$

$$I\dot{\omega} = aYA - b(Y_2\cos\theta_1 + X_2\sin\theta_1) - bbY_{21} + c(YB\cos\gamma_1) + M_1 + M_2;$$

$$I_1\dot{\omega}_1 = -YA\lambda\cos\theta + XA\lambda\sin\theta - M_1 = 0; \qquad (1)$$

$$I_2\dot{\omega}_2 = d_1YB - b_1Y_3 - b_{11}Y_{31} + c_1YC - M_3;$$

$$I_3\dot{\omega}_3 = d_2YC - b_{21}Y_{41} - b_{22}(Y_{42}\cos\theta_{32} + X_{42}\sin\theta_{32}) + M_2 - M_3;$$

In the written equations, the following notations are taken:

$V$ – longitudinal component of the speed of the bus mass center;

$\lambda$ (*lambda*) – take-off of the steered wheel of the bus;

$m, J$ – mass and central moment of inertia of the bus;

v, u – longitudinal and transverse projection of the velocity vector of the mass center on the axis associated with the tractor;

$\omega$ (*omega*) – angular velocity of the bus relative to the vertical axis;

$m_1, J_1$ – mass and central moment of inertia of the driving wheel module of the bus;

$v_1, u_1$ – longitudinal and transverse projections of the velocity vector of the masses center of the control wheel module of the bus;

$\omega_1$ – angular velocity of the control wheel module of the bus;

$m_2, J_2$ – weight and central moment of inertia of the wheel trailer module control (second axle);

$v_2$, $u_2$ – longitudinal and transverse projections of the velocity vector of the mass center of the second axle;

$\omega_2$ – angular velocity of the second axle;

$m_3, J_3$ – weight and central moment of inertia of the control wheel of the second trailer (third axle);

$v_3$, $u_3$ – longitudinal and transverse projections of the velocity vector of the center;

$m_3, J_3$ – weight and central moment of inertia of the control wheel of the second trailer (third axle);

$\omega_3$ – angular velocity of the third axle;

$m_4, J_4$ – mass and central moment of inertia of the second trailer (fourth axle);

$v_4$, $u_4$ – longitudinal and transverse projections of the velocity vector of the mass center of the fourth axle;

$V$ – acceleration in the longitudinal direction;

$X_1, X_{2i}, X_{3i}, X_{4i}$ – longitudinal forces on the auto-train axes;

$M_1, M_2, M_3$ – moments of resistance to turning sections of the auto-train;

$a, d_2, d_3$ – distance from the center of the bus mass, the first and second trailers, to the front axis respectively;

$b_{12}$ – distance from the center of mass to the middle axis of transitway;

$b_{13}, b_{22}, b_{42}$ – distance from the center of the bus mass, the first and second trailers, to the rear axis respectively;

$c$ – distance from the rear axis of the bus to the point of coupling with the first trailer;

$l_2, l_3$ – distance from the center of the mass of the first and second trailers to the corresponding points of the coupling.

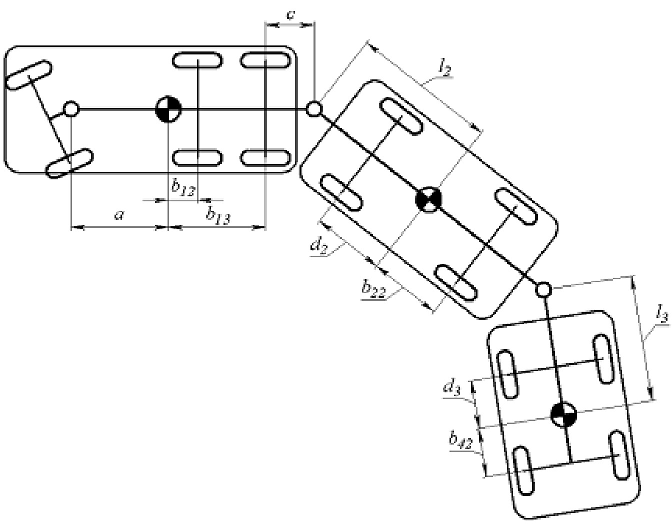


**Figure 1.** Scheme of the BRT tireless turn

After determining the reactions at the coupling points of the bus with the first trailer and the first trailer with the second, the integration of the original system of equations is carried out using the software Maple. At the same time, each of the modes was modeled by one or another law of rotation of the car-tractor steering wheel. For computer simulation of the most typical auto-train rotation on 90 °, which was moving ahead of it straightforwardly, the law of controlling the driving wheels of the car-tractor is given in the form [12]:

$$\theta = \begin{cases} 0 & at\ \ 0 \le t \le t_0 \\ \beta t & at\ \ t_0 < t \le t_1 \\ \beta t & at\ \ t_1 \le t \le t_2 \\ -\beta t & at\ \ t_2 < t \le t_3 \\ 0 & at\ \ t > t_2 \end{cases}, \tag{2}$$

where [0; $t_0$] i [$t_3$; $t_k$] – time of the auto-train movement on a straight line in accordance with the entry into turn and after the turn off;

[$t_0$; $t_1$] – time of entry into turn, controlled wheels of the car-tractor are evenly returned with speed $\beta$ = 0,05 c$^{-1}$;

[$t_1$; $t_2$] – interval of time of the auto-train movement by circle (may be absent);

[$t_2$; $t_3$] – time interval of the exit of the auto-train from a turn (the steering wheels of the car-tractor are evenly returned to the neutral position).

To study the behavior of the auto-train in such a turn the speeds of 5 m / s at the angle of rotation of the controlled wheels of the tractor from $\theta$ = 3,0 ... 35 deg. are taken.

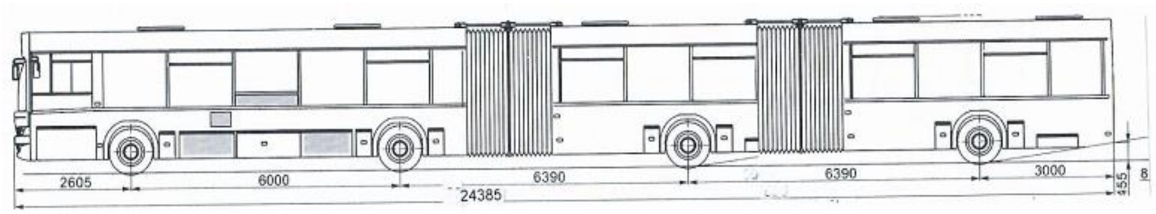


**Figure 2.** The BRT compass scheme

*v =5, $\lambda$ (lambda) =–0,023, a=3,68; b=2,32; c=8,71; d1 =4,17; d2 =4,17;m=18000; J=38500; bus; m1=400 J1=18,5 m2=9500; J2 =31200; m3=400; J3 =11,2; m4=9500; J4 =31200; kf =0; k1=160000; k2=32000; k3=180000; k4=180000; kk1=2600, kk2=1800; h1=30, h3=30; $\varphi$11=0,8; $\varphi$22=0,8; $\varphi$33=0,8; $\varphi$44=0,8; $\theta$0 =0; $\theta$=$\theta$0 +k$\theta\times$n; k$\theta$=0.05; n=1,2...10; $\theta$3 =0,2$\times\theta$; V =0.*

## 3. Results

The overall lane of traffic is determined by the traffic flow of the transitway. At the same time, it was taken the angles of the controlled wheels rotation of the bus, as well as the speed of the auto-trains and trajectories of the mass center of the bus, fig. 3a, on which later the overall dimension of the transitway was constructed, fig. 3b. As it follows from fig. 3b, three-axles BTR with selected parameters for a controlled second-trailer meets the requirements of Regulation 36 on maneuverability.

The obtained system of equations also allows us to investigate the behavior of a three-axles transitway in both stationary and non-stationary movements [13, 14, 15]. In order to determine the stability parameters of the transitway in the general motion case it is necessary to integrate the system of equations (1). This integration was accomplished with the help of the Mathcad 2014 software. As the main estimator of the stability of the transitway a critical speed was chosen.

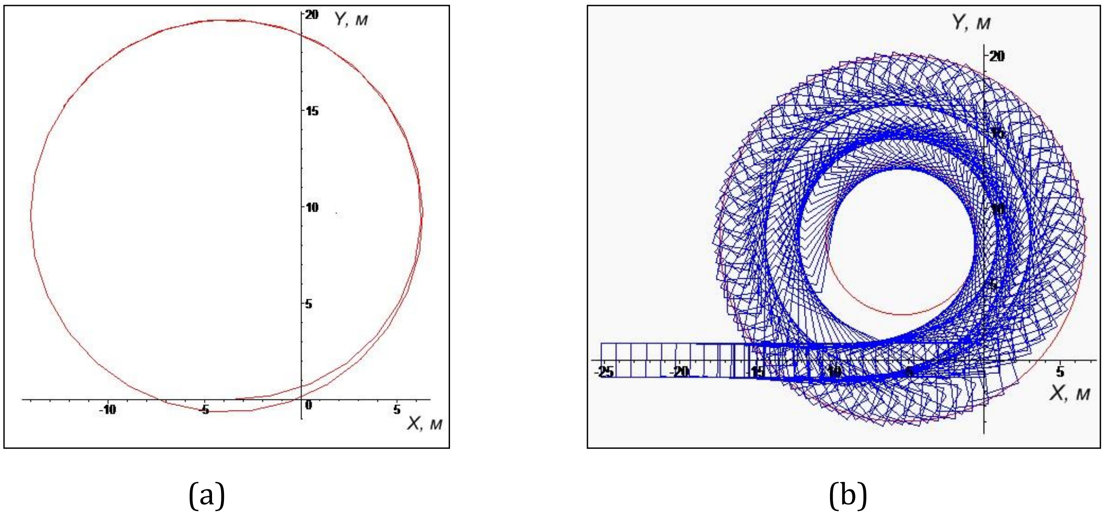


**Figure 3.** Trajectories of the mass center of the bus (**a**) and transitway (**b**) at the speed of 5 m / s

Fig. 4 shows the results of calculations of the BRT critical speed depending on the listed parameters.

The analysis of the above dependencies shows that the increase of the BRT critical speed is positively affected by the decrease of the resistance coefficient of wheels of the driving axes of the bus and the second trailer (for example, by reducing the air pressure in the wheel tires of these axes). Similarly, the increase in the critical speed leads to an increase in the coefficient of resistance of wheels removal of trailer uncontrolled axes, reducing the distance between the mass center of the bus and the coupling point with the first trailer, increasing the mass of the bus and the first trailer, fig. 4a. However, an increase in the resistance coefficient of wheels of the controlled driving axes leads to a decrease in the BRT critical speed, as well as an increase in the mass of the second trailer, fig. 4b.

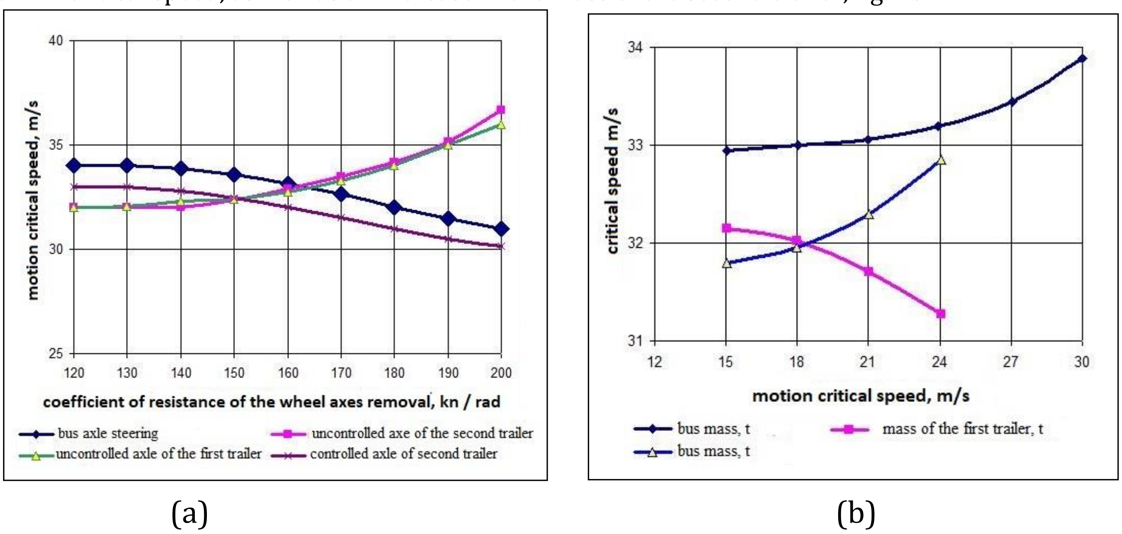


**Figure 4.** Dependence of the BRT critical speed on the resistance of the removal wheels of the BRT axes (**a**) and the masses of the axles (**b**)

## 4. Discussion

Critical speed is one of the main indicators of the BRT stability. The recommendations for its increasing due to the rational choice of mass and layout parameters, in particular increasing the bus mass and the first trailer, reducing the distance between the bus and the first trailer, as well as between the first and second trailers, reducing the resistance ratios of the removal controlled axes wheel and increasing - uncontrolled BRT axes. In view of the fact that the transitway critical speed is lower than the maximum speed for its energy properties, the velocity of the appearance of vibrational instability, which is corresponded to the appearance of the first positive root in the solution of the characteristic equation, was determined further. According to the results of calculations, it has been found that for optimally chosen BRT parameters the critical velocity was 33.5 m / s, while the velocity of oscillatory instability was 30.8 m / s. However, this conclusion needs to be checked also in tensile modes of movement, in particular in such regimes as "twist", "jerk of a steering wheel", movement "snake", S-shaped twist, etc. Each of the following modes can only be considered after integrating the original system of equations. In addition, it is desirable in the future to consider the BRT spatial model, which will enable to take into account the change in load on its axis in dynamics, and accordingly, the change in the parameters of the wheel removal, which may affect the change in critical speed and the rate of appearance of oscillatory instability, which is decisive for the examining transitway.

## 5. Conclusions

The paper deals with the indicators of maneuverability and stability of the three-axles transitway through the solution of the original system of equations. The overall traffic lane, which characterizes the BRT maneuverability, is determined by the circular traffic of the transitway with the selected parameters for the controlled second trailer. It has been established that it meets requirements of Rule 36 regarding maneuverability.

As a result of the research, it has been determined the critical velocity of the three-axles transitway was determined and factors influencing its numerical value have been analyzed. It is shown that during the BRT operating it is necessary to maintain such pressure in the range of the allowable for this tire type, so that for the selected load on the wheels of auto-train axes, the coefficient of resistance of the lateral separation of the wheels removal of the bus steered wheels and the trailer is smaller than one of wheels of uncontrolled axes. It will be used for increasing the auto-train critical speed $v_{kr}$.

## References

1. Sahar Hajeb, Peyman Parvizi, Farzad Norouzi Fard. Safe Lines to Transit in Tehran's BRT. *International Journal of Science and Engineering Investigations* 2012; 1(1), 113-118.
2. [Internet source]– Available online: https://griphon.livejournal. com /222403.
3. David A. Hensher. Sustainable public transport systems: Moving towards a value for money and network-based approach and away from blind commitment, Transport Policy, 2007; Volume 14, Issue 1, 98-102, ISSN 0967-070X, https://doi.org/10.1016/j.tranpol.2006.10.004.
4. Reza Kiani Mavi, Navid Zarbakhshnia, Armin Khazraei. Bus rapid transit (BRT): A simulation and multi criteria decision making (MCDM) approach, *Transport Policy*, 2018; 72, 187-197. ISSN 0967 070X, https://doi.org/10.1016/j.tranpol.2018.03.010.
5. [Internet source] – Available online: https://gre4ark.livejournal.com/52087.
6. T. Satiennam, S. Jaensirisak, W. Satiennam, S. Detdamrong, Potential for modal shift by passenger car and motorcycle users towards Bus Rapid Transit (BRT) in an Asian developing city, IATSS Research, 2016; 39(2), 121-129. https://doi.org/10.1016/j.iatssr.2015.03.002.
7. Sakhno V. Search for ways to increase the stability of the straight-line movement of the auto-train. *Road Transporter and Road Constructor of Ukraine. Bulletin of the Central Scientific Center of the Transport Academy of Ukraine*, 1999; 2, 70-73.
8. Sakhno, V.P.; Marchuk, M.M.; Marchuk, R.M. Study of long haul truck movement along the curvilinear trajectory while steering a carryall semi-trailer – container by braking the wheels of one /INMATEN – Agricultural Engineering, 2016; Volume 49, No.2. National institute of research-development for machines and installations designed to agricculture and food industry – INMA Bucharest.
9. Verbitsky, V.; Sakhno, V.; Kravchenko, A.; Kostenko, A.; Danilenko A. Cars. Sustainability (Monograph). Publishing house "Knowlick": Lugansk, 2013;176 p.
10. Polyakov, V.; Sakhno, V. Three-axles auto-trains. Maneuverability: monograph. Publishing house "Knowledge": Lugansk, 2014; 206 p.
11. Sakhno V., Polyakov V., Shariy S., Bosenko V. Applied Theory of auto-train movement: Training materials. NTU: Kyiv, 2016; 232 p.
12. Sakhno V. Equation of motion of a four-axles trailer auto-train model. Road Transporter and Road Constructor of Ukraine. *Bulletin of North Scientific Center TAU*, 2007; 2, 117-120.

13. Sakhno, V.; Poliakov, V.; Timkov, O.; Kravchenko, O. Lorry convoy stability taking into account the skew of semitrailer axes. Transport Problems. *Wydawnictwo politechniki Slaskiej Gliwice*, 2016; 11(3), 69-76.
14. Volodimir Sakhno, Juraj Gerlici, Victor Poliakov, Alexandr Kravchenko, Oleg Omelnitsky, Tomas Lask. Road train motion stability in BRT system. XXIII Polish-Slovak Scientific Conference Machine Modelling and Simulation. MMS 2018. Book of abstracts, September 4-7, 2018, Rydzyna Poland, 49 p.
15. Sakhno, V.; Poliakov, V.; Murovanyi, I.; Selezniov, V.; Vovk, Y. Analysis of transverse stability parameters of hybrid buses with active trailers. *Scientific Journal of Silesian University of Technology. Series Transport* 2018, 101; 185-201.