MOBILITY OF THE METROBUS. WAYS OF IMPROVEMENT

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Abstract

In this article it is offered the ways to improve the maneuverability of three-link metrobuses by choosing a rational layout scheme and design parameters of its trailer units. Considering that the movement of the metrobus is carried out on direct routes, that is, the maneuverability of the metrobus is appropriate to determine by the overall traffic lane (OTL) size. OTL equal to the difference of the radii of rotation of the points of the train, the farthest and closest to the center, that is, the difference of the overall radii of rotation - the outer (R_z = 12.5 m) and internal (R_v = 5.3 m). The methodology for calculating OTL is based on determining the angles of assembly of the road train links and the offset of the driven links trajectories relative to the trajectory of the master. Maneuverability indicators of the three-link metrobus are defined on elastic in the lateral direction wheels. Studies were performed for one-way rotation and ISO maneuvering with the obtained trajectories of links and the overall traffic lane of a metrobus with guided and unmanaged trailer links.

Keywords: metrobus; mobility; trajectory; traffic lane; trailer

1. Introduction

The metrobus or the new Bus Rapid Transport (BRT) bus system is the result of the development of the public transit bus network.

The BRT system has several distinct advantages [2, 12]:

- high passenger capacity and efficient payment systems ensure low-cost travel;
- high speed of movement allows the metrobus to carry a significant share of passenger traffic, which helps to reduce the number of cars on the city roads and, accordingly, to reduce exhaust emissions;
- an expanded information system informs passengers of the route.

The convenience, safety and organization of the road, which is inevitably improving, is far from being able to give passengers a high-speed bus system. In this system, passenger express buses move along specially designated lanes. They are separated from

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the carriageway and equipped with closed passenger stations with level platforms and subways.

The rolling stock used in the BRT system is of two types: the first is a classic, two-deck metrobus with an engine running on both diesel and gas fuel; the second option is a new generation metrobus with a hybrid electric-gas engine. These two variants are inherent in articulated buses, 18 and 24 meters long [21].

2. Materials and methods

Studies conducted by domestic and foreign scientists found that the creation of a modern automobile vehicle (AV) with improved energy efficiency may be based on a hybrid power plant, but the unresolved issue of rational distribution of power between the internal combustion engine and electric motors implementation [5, 7, 9].

In fact, a metrobus combines the benefits of a subway in a modern city with the relatively low cost of building such lines. Moreover, with the help of traffic intensity it is possible to adjust the passenger flow. In general, metrobus lines are suitable for areas that require transportation of (15000-18000) passengers per hour. However, there are many examples where they have generally replaced the metrobus in large metropolitan areas. For example, in Istanbul or Chinese Shanghai.

Another advantage of BRT systems is the speed of construction of such lines that can be used by existing highways in cities. Typically, such a line is built in (1-2) years, while the construction of the subway, tram lines can take (3-10) years.

The special development of the buses was with the advent of three-seater buses, Figure 1, which can carry up to 300 passengers against 180 passengers, in two-seater buses. Thus, having 3-lane buses that move at short intervals (up to 1 minute) the metrobus line can solve the transport problems of many Ukrainian cities, and in particular, completely eliminate the issue of transport connections of remote arrays, especially in Kyiv [1, 8, 14].

New developments in the field of creation of multi-link AVs and methods of optimization of their designs are focused on minimizing fuel, energy consumption, improving mobility and controlling. Many theoretical data on the optimization of complex mechanical systems and multi-objective optimization methods are given in [3, 6, 13]. In [4] the circuit solutions and features of construction of vehicles with a hybrid power plant, electrical systems and complexes of a hybrid car are considered. The analysis of structures and classification of multi-axle vehicles of traditional construction, the general regularities of their movement are considered in [17, 18, 20].

Fig. 1. The modern Volvo chassis metrobus

The reliability of theoretical recommendations for improving the construction of metrobuses is determined by the most adequate tracking of the main relationships between its elements, the physical consistency of the initial assumptions in the formulation of the problem and the correctness of the mathematical model adopted to determine energy performance and especially maneuverability. For this reason, the **purpose of the work** is to improve the maneuverability of the three-lane subway by choosing a rational layout scheme and design parameters of its hitch links.

3. Results

The purpose of monitoring the rights of people with disabilities for accessibility to transport services is the creation of a basis for systematic analysis and synthesis of processes that develop in the system "transport - person" with emphasis on identifying the basic principles of its functioning, the nature of contradictions and the causes that lead to the problem in the logistics system transportation of people with disabilities. The results of the monitoring are the basis for establishing a list of measures to improve transport services.

Mobility of AV is estimated by nine indicators, six of which are kinematic and three dynamic. However, for a three-lane metrobus, two kinematic unit mobility values should be considered as the main ones [10, 11], namely:

- the overall traffic lane (OTL) equal to the difference of the radii of rotation of the points of the train, the farthest and closest to the center, that is, the difference of the overall radii of rotation - the outer (R_z = 12.5 m) and internal (R_v = 5.3 m);
- the ability to move backwards.

Given that the movement of the metrobus is carried out on dedicated lanes, the ability to move in reverse is not critical for him, that is, the maneuverability of the metrobus is advisable to determine by the OTL size.

When determining the maneuverability of the wheels of vehicles are taken as rigid in the lateral direction and elastic [19, 22]. The methodology for calculating OTL is based on determining the angles of assembly of the road train links and the offset of the driven links trajectories relative to the trajectory of the master. The discrepancy in the calculation of maneuverability when using rigid or elastic lateral wheels for two-lane highways can reach (13-15)%, and for three-lane highway trains it can be even greater. Therefore, determining the mobility of a three-row metrobus will be carried out on models with elastic laterally wheels.

In [15, 16], a system of equations is described describing the plane-parallel motion of a three-lane trailer trainset, which can be applied to a metrobus as well 1, in the form:

$$\left.\begin{aligned}
&m(\dot{u}+v\omega)=Y_1\cos\theta_1+Y_2+YA-YB\cos\gamma_1+XB\sin\gamma_1\\
&I\dot{\omega}=aYA-b(Y_2\cos\theta_1+X_2\sin\theta_1)+c(YB\cos\gamma_1)+M_1+M_2\\
&I_1\dot{\omega}_1=-YA\lambda\cos\theta+XA\lambda\sin\theta-M_1=0\\
&I_2\dot{\omega}_2=d_1YB-b_1Y_3+c_1YC-M_3\\
&I_3\dot{\omega}_3=d_2YC-b_{22}(Y_4\cos\theta_3+X_4\sin\theta_3)+M_2-M_3
\end{aligned}\right\} \quad (1)$$

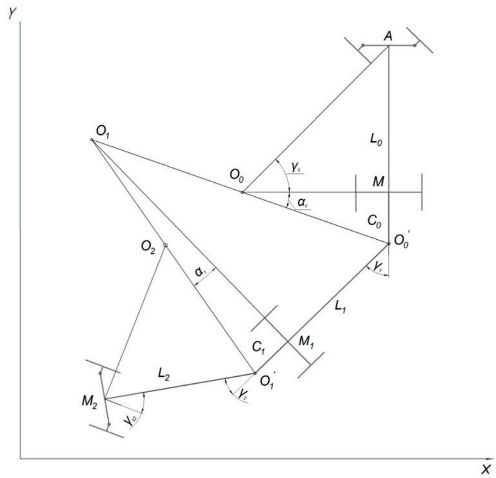


Fig. 2. The scheme of rotation of a three-lane metrobus with a controlled second trailer

The reactions at the points of connection of the metrobus are recorded in the form [15]:

$$\left.\begin{aligned}
&XC = m_3\dot{v}_3 - m_3\omega_3 u_3 + X_4\cos\theta_3 - Y_4\sin\theta_3\\
&YC = m_3\dot{u}_3 + m_3\omega_3 v_3 - Y_4\cos\theta_3 - X_4\sin\theta_3\\
&XB = m_2\dot{v}_2 - m_2\omega_2 u_2 + m_3\dot{v}_3\cos\varphi_2 - m_3\omega_3 u_3 + \cos\varphi_2 X_4\cos\theta_3 - \cos\varphi Y_4\sin\theta_3 -\\
&-\sin\varphi_2 m_3\dot{u}_3 - \sin\varphi_2 m_3\omega_3 v_3 + \sin\varphi_2 Y_4\cos\theta_3 + \sin\varphi_2 X_4\sin\theta_3\\
&YB = m_2\dot{u}_2 + m_2\omega_2 v_2 + \sin\varphi_2 m_3\dot{v}_3 - \sin\varphi_2 m_3\omega_3 u_3 + \sin\varphi_2 X_4\cos\theta_3 -\\
&-\sin\varphi_2 Y_4\sin\theta_3 + \cos\varphi_2 m_3\dot{u}_3 + \cos\varphi_2 m_3\omega_3 v_3 - \cos\varphi_2 Y_4\sin\theta_{32}\\
&XA = -\cos\theta m_1\dot{v}_1 + \cos\theta m_1\omega_1 u_1 - \cos\theta X_1 + m_1\dot{u}_1\sin\theta + m_1\omega_1 u_1\sin\theta_1 - Y_1\sin\theta\\
&YA = -\sin\theta m_1\dot{v}_1 + \sin\theta m_1\omega_1 u_1 - \sin\theta X_1 - m_1\dot{u}_1\cos\theta - m_1\omega_1 v_1\cos\theta + Y_1\cos\theta
\end{aligned}\right\} \quad (2)$$

The longitudinal forces on the wheels of the axles of the road train are defined as [15]:

$$X_i = Z_i \times k_f, \quad (3)$$

The transverse forces on the wheels of the axles of the road train are defined as:

$$Y_i = \frac{k_i\delta_i}{\sqrt{1 + \dfrac{k_i^2\delta_i^2}{(\varphi_i Z_i)^2}}} \quad (4)$$

In these equations the following notation is accepted:

v – the longitudinal component of the speed of the center of mass of the bus; λ (lambda) – take-off of the steering wheel of the bus; $a; b$ – the distance from the center of mass of the bus to the attachment points of the front (steered) axis and its rear axle; c – the distance from the center of mass of the bus to the front axle of the first trailer; c_2 – distance from the center of mass of the bus to the point of contact with the first trailer; d_1 – the distance from the center of mass of the first trailer (second link) to the point of contact with the bus; d_2 – the distance from the center of mass of the second trailer (third link) to the point of engagement with the first trailer; m, J – mass and central moment of inertia of the bus;

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

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

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

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

ω_1 – the angular speed of the bus control wheel module;

m_2, J_2 – mass and central moment of inertia of the first trailer;

v_2, u_2 – longitudinal and transverse projections of the velocity vector of the center of mass of the first trailer;

ω_2 – angular speed of the first trailer;

m_3, J_3 – the mass and central moment of inertia of the control wheel module of the second trailer;

v_3, u_3 – longitudinal and transverse projections of the velocity vector of the center of mass of the control wheel module of the second trailer;

ω_3 – angular speed of the control wheel module of the second trailer;

m_4, J_4 – mass and central moment of inertia of the second trailer;

v_4, u_4 – longitudinal and transverse projections of the velocity vector of the center of mass of the second trailer;

V – acceleration in the longitudinal direction;

X_1, X_2, X_3, X_4 – longitudinal forces on wheels of axles of a road train.

$M_{1,3}$ – the stabilizing moments of the tires of the steering wheel module of the bus and the second trailer, described as nonlinear dependence on the angle of withdrawal,

$$M_{1,3} = \sigma_1 \times \delta_{1,3}^1 + \sigma_2 \times \delta_{1,3}^2 - \sigma_1 \times \delta_{1,3}^3 \tag{5}$$

where:

$\delta_{1,3}$, $\sigma_1, \sigma_2, \sigma_3$ – the characteristics of the axis of the steering wheel module of the bus and the second trailer;

$M_{2,3}$ – moments of viscous friction in the steering of the bus and the second trailer, which are proportional to the angles of rotation of the driven wheels [15]:

$$M_{2,3} = h_{1,3} \times \dot{\theta}_{1,3} \tag{6}$$

where:

h_1 i h_3 – the coefficients of viscous friction in the steering details of the bus and trailer;

$M_{3,3}$ – the moments of elasticity in the steering of the front and rear axles are proportional to the angles of rotation of the driven wheels:

$$M_{3,3} = \chi_{1,3} \times \dot{\theta}_{1,3} \tag{7}$$

where $\chi_{1,3}$ – the coefficients of rigidity of the steering wheel of the bus and trailer.

The integration of the original equation system was accomplished using Maple software. In this case, each mode was modeled by one or another law of rotation of the steering wheel of the tractor. For computer simulation of the most typical 90o metrobus, which moved in a straight line before, the law of control of a bus driven wheels is given in the form [15]:

$$\theta = \begin{cases} 0 & \text{for } 0 \le t \le t_0 \\ \beta t & \text{for } t_0 < t \le t_1 \\ \beta t & \text{for } t_1 \le t \le t_2 \\ -\beta t & \text{for } t_2 < t \le t_3 \\ 0 & \text{for } t > t_2 \end{cases} \tag{8}$$

where:

$[0;\ t_0]$ i $[t_3;\ t_k]$ – the time of movement of the road train on a straight line according to the entrance to the turn and after leaving the turn;

$[t_0;\ t_1]$ – turn-in time interval, tractor-driven steering wheels rotate evenly at speed β = 0.05 s^{-1};

$[t_1;\ t_2]$ – the interval of the time of the movement of the road train in a circle (may be absent);

$[t_2;\ t_3]$ – Interval of exit time of the road train from a turn (the driven wheels of the tractor-car evenly return to a neutral position).

To study the behavior of the road train in such a turn were taken speeds of 5 m/s at the angle of rotation of the driven wheels of the tractor from θ = (3.0-35) grade.

Scheme of the metrobus components is shown in Figure 3.

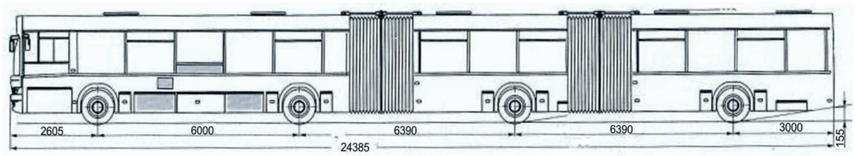


Fig. 3. Scheme of the metrobus components

The following initial data were accepted for the calculation:

v = 5; λ (lambda) = –0.023, a = 3.68; b = 2.32; c = 8.71; d_1 = 4.17; d_2 = 4.17; c_2 = (2-4); m = 18000; J = 38500; m_1 = 400, J_1 = 18.5; m_2 = 9500; J_2 = 31200; m_3 = 400; J_3 = 11.2; m_4 = 9500; J_4 = 31200; k_f = 0; $k1$ = 160000; k_2 = 320000; k_3 = 180000; k_4 = 180000; χ_1 = 2600, χ_3 = 2200; h_1 = 30; h_3 = 30; φ_{11} = 0.8; φ_{22} = 0.8; φ_{33} = 0.8; φ_{44} = 0.8; θ_0 = 0; $\theta = \theta_0 + k_{\theta \times n}$; k_θ = 0.05; n = (1.2-10); $\theta_3 = 0.2 \times \theta$; V = 0.

Figure 4 shows the trajectories of motion of characteristic points of the links of the metrobus (midpoints of the axes B_i) when turning the metrobus on 90°: B_1 – the trajectory of the specific point of the bus, B_2 – the trajectory of the specific point of the first trailer, B_3 – the trajectory of the characteristic second driven trailer, B_4 – the trajectory of the characteristic point of the second unruled trailer.

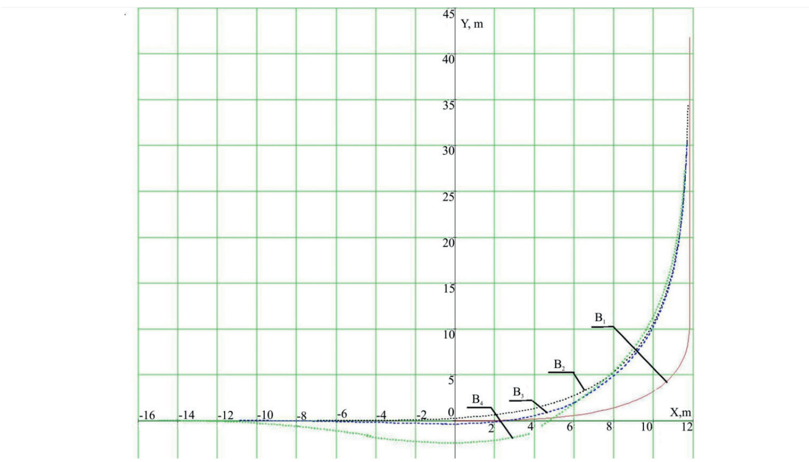


Fig. 4. Trajectories of the links points of the road train

The calculations found that the parameter was changed c_2 – distance from the rear axle of the bus to the point of contact with the first trailer from 1000 mm to 0 leads to a decrease in the radii of rotation on the circular trajectory of the last link, Figure 5. It also reduces the distance between the trajectories of the tractor and the links that follow it.

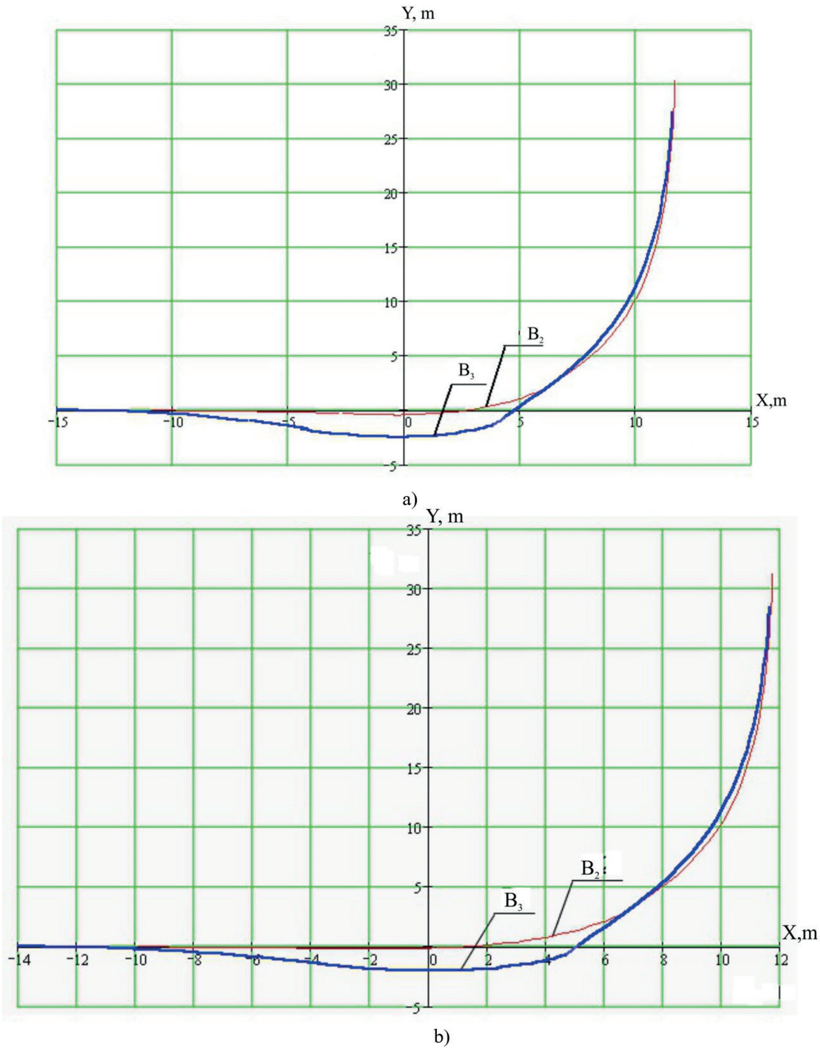


Fig. 5. Trajectories of the characteristic points of the first B_2 trailer and the second managed trailer B_3: a) where c_2 = 4 m; b) where c_2 = 2 m

The influence of the location of the coupling point of the first trailer with the second is similar to the effect of the parameter c_2 (Figure 6).

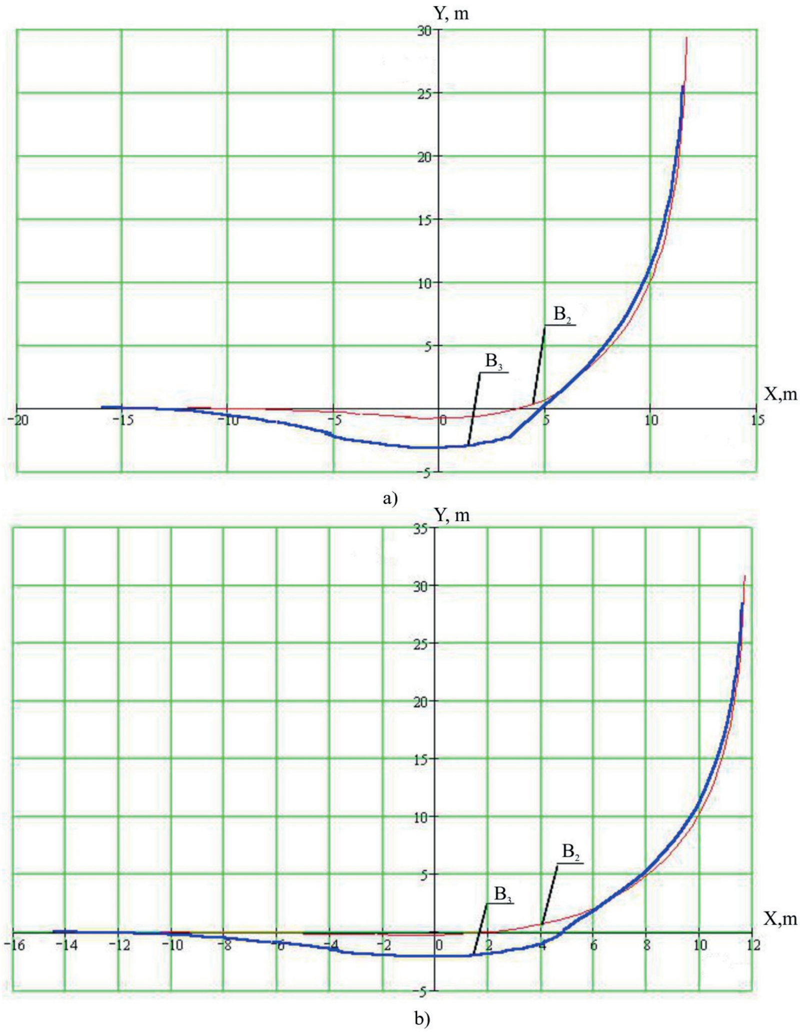
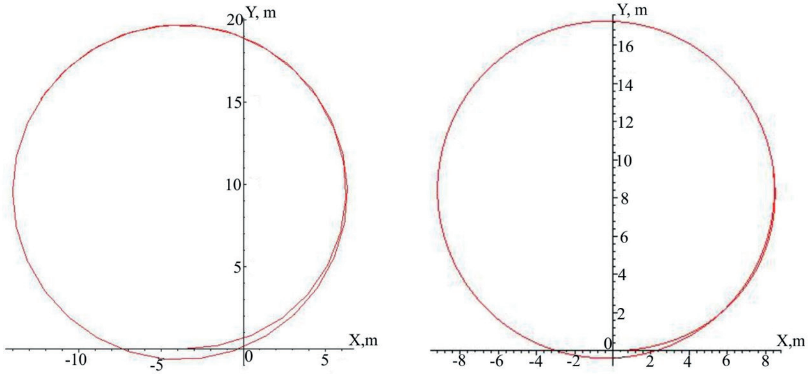


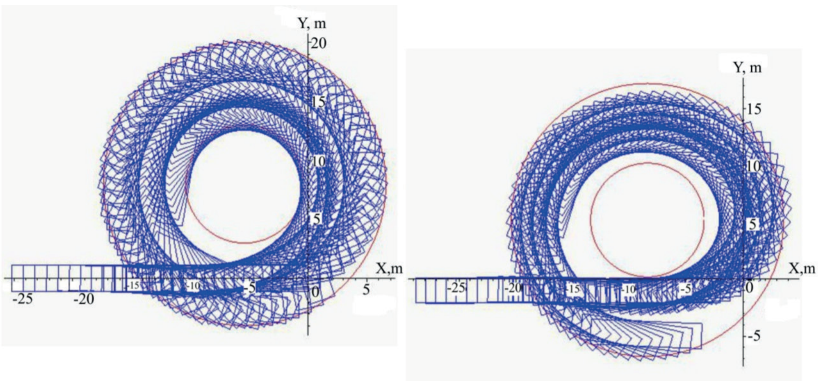
Fig. 6. Trajectories of the characteristic points of the first trailer B_2 and a second trailer B_3:
a) at d_2 = 4 m; b) at d_2 = 2.5 m

In the circular motion of the metrobus, the angles of rotation of the driven wheels of the bus and the second trailer were set, as well as the speed of the road train and the trajectories of the center of mass of the bus were located [21], Figure 7 after which the overall traffic lane of the metrobus was constructed, Figure 8.



a) b)

Fig. 7. The trajectories of the center of mass of the metrobus with a speed 5 m/s:
a) second unruled trailer; b) second ruled trailer



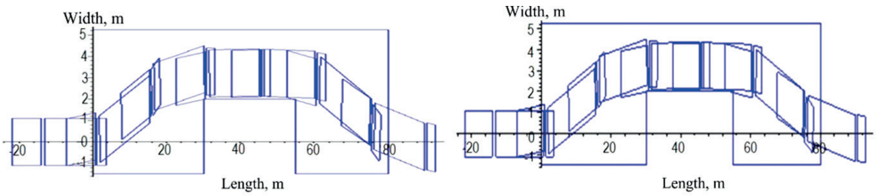
a) b)

Fig. 8. Overall traffic lane of the metrobus with a speed 5 m/s:
a) second unruled trailer; b) second ruled trailer

When performing such tactics as 'rearrangement', ISO the steering angle of the steered wheels of the bus was set in the form [15]:

$$\theta 0 = \begin{cases} \dfrac{\pi \cdot t}{10} & -t < 0 \;\; and \;\; t < \dfrac{10}{3} \\ \dfrac{\pi}{3} & -t < \dfrac{10}{3} \;\; and \;\; t < 7 \\ \dfrac{\pi}{3} - \dfrac{\pi \cdot (t-7)}{10} & -t < -7 \;\; and \;\; t < \dfrac{41}{3} \\ -\dfrac{\pi}{3} & -t < -\dfrac{41}{3} \;\; and \;\; t < \dfrac{52}{3} \\ -\dfrac{\pi}{3} + \dfrac{\pi \cdot (t - \frac{52}{3})}{10} & -t < -\dfrac{52}{3} \;\; and \;\; t < \dfrac{62}{3} \\ 0 & otherwise \end{cases} \tag{9}$$

The trajectories of the movement of the metrobus links when performing the ISO maneuver at speeds of 5 m/s and 10 m/s are shown in Figures 9 and 10.



a) b)

Fig. 9. Trajectories of the movement of the metrobus links with unruled second trailer a) and a driven second trailer b) when performing an ISO maneuver and speed 5 m/s

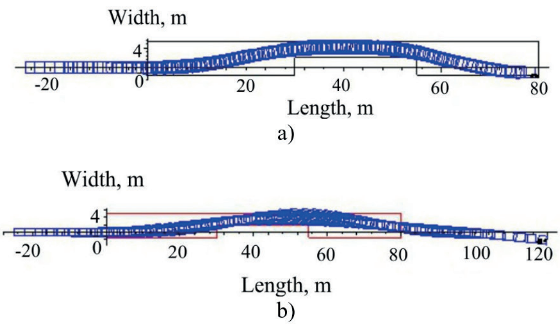


Fig. 10. Trajectories of the movement of the metrobus links with unruled second trailer a) and a driven second trailer b) when performing an ISO maneuver and speed 10 m/s

4. Conclusions

The results of these studies proved that:

- promising for big cities, in particular, for the city of Kyiv is the use of three-lane buses capable of carrying up to 300 passengers instead of 180 in two-lane buses. With such a capacity of three-lane buses operating at short intervals (up to one minute); the BRT system can be competitive with the metro line;
- in the one-way rotation of the trajectories of the trailer links are shifted with respect to the trajectory of the bus to the center of rotation, thus increasing the overall traffic lane , and the offset of the trajectories and the overall traffic lane increased with the increasing of the base of trailers;
- the standardized value of the overall traffic lane for the real design parameters of the three-lane metrobus, taking into account all its possible limitations (bus base, location of coupling points, trailer base, etc.) can provide a three-lane metrobus, both with unruled and driven second trailer.
- at the same time, for controlled second trailer OTL is mixed by (12-15)% and it depends on the location of the coupling points of the trailers with the bus and with each other.
- when performing an ISO maneuver at a 5 m/s highway speed, both the unruled and guided second trailer will fit into the normalized traffic corridor. However, a speed of 10 m/s, oscillations of the second guided trailer are already observed, and exceed the permissible ones, it can lead to loss movement stability of the metrobus.

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