The object of this study is the movement process of a vehicle convoy formed with the help of unmanned vehicles.

The research aims to solve the task related to improving the controllability, maneuverability, energy efficiency of vehicle convoys, as well as the throughput capacity of roads. One of the ways to address this issue is the use of unmanned vehicles.

The subject of this study is the assessment of the possibility to improve the indicators of maneuverability, controllability, energy efficiency of vehicle convoys, as well as the throughput capacity of roads, through the use of unmanned vehicles.

During the study, the concepts of controllability and maneuverability of unmanned vehicle convoys have been defined. The relationship between the use of unmanned vehicles and the improvement of maneuverability and controllability of convoys was established. The use of unmanned vehicles makes it possible to eliminate the need to consider braking distance when setting inter-vehicle distances and to reduce the safety gap from 5 meters to zero.

The paper shows that the use of unmanned vehicle convoys improves maneuverability and controllability compared to conventional convoys. For example, the time to pass a short road section for a convoy of 40 vehicles traveling at 90 km/h is reduced by 60 seconds, and the length of a convoy of 20 vehicles moving at the same speed is reduced by 800 meters.

An evaluation of the reduction in energy consumption for convoys with unmanned vehicles was carried out. A condition was derived, the fulfillment of which ensures a reduction in additional engine energy losses through the use of unmanned vehicles in a convoy.

Applying the results will make it possible to bring the efficiency of road transport to the level of railroad transport, which is achieved by assembling vehicle trains

Keywords: vehicle convoy, unmanned vehicle, convoy maneuverability, convoy controllability, convoy speed, road throughput capacity

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IMPROVING THE EFFICIENCY OF TRANSPORTATION CONVOYS USING UNMANNED VEHICLES

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1. Introduction

In the USA and European countries, considerable attention is paid to improving the controllability, maneuverability, and energy efficiency of transport convoys, in particular through the introduction of unmanned vehicles [1]. Thus, the first national bill on the operation of self-driving cars was adopted in the USA, which indicates a high level of state support for this area [2]. In the UK, the movement of self-driving vehicles on public roads is allowed [3], which laid the foundation for the further development of unmanned transport in Europe.

It is also significant that Turkey has already introduced its own model of an unmanned electric bus [4], and in Malaga (Spain) [5] and Vilnius [6], the operation of unmanned buses in an urban environment was allowed.

The use of unmanned convoys has a significant impact on increasing road throughput and reducing the load on the infrastructure. The efficiency of convoys increases with decreasing distance between vehicles, which has become possible due to the introduction of telemetric control systems [7], information and analytical monitoring of technical condition and traffic dynamics [8], as well as improvement of braking algorithms, in particular in case of ABS malfunction [9].

The functioning of such systems depends on the quality of the road surface [10] and the efficiency of dynamic characteristics control means [11]. One of the promising approaches is to organize braking from the tail of the convoy – that is, sequentially from the last vehicle to the lead, which makes it possible to minimize accident risks and determine the reserve distance behind only one vehicle. This requires the use of electronic control systems for mechanical transmissions [12] or the use of unmanned vehicles [13].

The results of available studies indicate the importance of precise positioning, trajectory planning software [14], and system design [15] that ensure the functional stability of the convoy in motion. By increasing the accuracy of controlling the position of vehicles in the convoy, the reserve distance can be reduced to almost zero, which is proven in study [16]. Paper [17] considers algorithms for multi-objective planning of vehicle movement among obstacles, and [18] – the possibilities of using intelligent mobile platform control systems. In the context of road safety, it is important to take into account weather and road conditions [19], in particular through the application of the concepts of "smart road" [20]. An analysis of available studies conducted earlier confirms the possibility of implementing the movement of automobile convoys with unmanned vehicles while precisely adjusting the distance between adjacent vehicles.

Reducing the distance between vehicles not only increases the capacity of roads but also improves the energy efficiency of convoys. In addition, this makes it possible to bring the efficiency of road transport to the level of railroad transport, which is ensured by assembling railroad-type road trains.

The relevance of further research on improving the efficiency of transport convoys with unmanned vehicles is predetermined by the complexity of the task:

– to design optimal control systems for a set of unmanned vehicles as a single object;

– to devise a rational law for controlling acceleration and braking of an individual vehicle within a convoy;

– to develop algorithms for maintaining high maneuverability at reduced distances.

This would make it possible to reduce the length of convoys, as well as fuel consumption, and increase the economic efficiency of their use.

Thus, the use of transport convoys with unmanned vehicles is becoming increasingly popular in various sectors of the economy, and the need for research aimed at improving the efficiency of their application is beyond doubt.

2. Literature review and problem statement

In study [21], the concept of maneuverability is formulated as a set of basic navigational qualities of a vessel (or aircraft) that provide a quick change in direction (trajectory) and speed of movement under the action of rudders and other controls. But these concepts are not defined for cars and automobile convoys. In addition, maneuvering is considered as a transitional process from one mode of movement to another. It is believed that a maneuver can be simple and complex. This work defines indicators and criteria for maneuverability of a single car. It follows that it is possible to conduct a quantitative assessment of the maneuverability of a single car as a complex operational property. The problems that arise when considering a complex maneuver are related to the fact that without decomposing a complex maneuver into simple ones, it is impossible to evaluate the process of maneuvering a car under difficult traffic conditions.

It is shown that terminology should also be distinguished. Maneuvering is a process, and a maneuver is a completed action. In [21], the following definition is given: "Maneuvering is a macro-transient process of wheeled vehicle movement, which is accompanied by a change in the velocity vector due to the execution of control actions by the driver or an automatic device." During a complex maneuver, a multiple sequential change in the velocity vector occurs. The definition of controllability is also given there: "The controllability of a wheeled vehicle (car) characterizes its ability to adequately respond to control actions." As maneuverability criteria, this work proposes the maneuver time t_{man} and the average (angular or linear) maneuver speed. The authors of the work consider these parameters to be quantitative characteristics of the level of maneuverability of a wheeled vehicle and specify the definition of the concept of maneuverability. "Maneuverability is a complex (complex) operational property that characterizes the ability of a wheeled vehicle to maneuver (maneuver) in a limited space with the necessary accuracy and speed" [21]. However, the maneuvering of a group (convoy) of vehicles by a common control signal, i.e., changes in the parameters of the movement of the main vehicle of the convoy, was not considered. In addition, indicators for assessing the maneuverability of a group of vehicles in a convoy remain undeveloped. The lack of a scientific and methodological apparatus does not make it possible to assess the maneuverability of vehicles as a complex operational property.

Recently, indicators and criteria for assessing the stability of a vehicle's movement during steady motion have appeared [22], which make it possible to increase the stability of vehicles against yaw. Mobile registration measuring systems based on three-axis accelerometers are becoming an effective means of controlling the parameters of vehicle movement [23]. However, these indicators and criteria for such component properties of maneuverability as controllability, stability of movement, maneuverability, and fit of vehicles and road trains have not been considered under other operating conditions.

The authors of work [24] consider the parameters of the time and path of maneuvering to be quantitative characteristics of the level of maneuverability of a wheeled vehicle and clarify the definition of the concept of maneuverability. In their opinion, "maneuverability is a complex (integrated) operational property that characterizes the ability of a wheeled vehicle to maneuver (make a maneuver) in a limited space with the necessary accuracy and speed". This made it possible to determine the rational speed of a motor vehicle convoy when overcoming a dangerous section of the road in the shortest time. However, the study only partially solves the problem of choosing a rational speed of the convoy under dynamic conditions because it does not take into account autonomy and unmannedness as a control factor.

The task to synchronize the movement of cars included in an organized automobile convoy is considered in [25]. In the study, a model of multicomponent complex movement is proposed. In this case, the portable movement corresponds to the average speed of the automobile convoy. For each car in the convoy, the relative speed of movement is determined by the difference between its own speed and the speed of the car moving in front. The number of cars in the convoy is equal to the number of relative movements of multicomponent complex movement. This makes it possible, for example, to solve the problem of safe movement of a military convoy under combat conditions, but the work does not consider convoys that include unmanned vehicles.

In [26], the authors defined a motor vehicle convoy but did not define the concepts of its maneuverability and controllability of vehicles. The problem is that without defining these concepts, it is not possible to increase the maneuverability of the convoy and its productivity. Under combat conditions, increasing maneuverability helps reduce losses of equipment and personnel.

In [27], it was proposed to assess the mobility of a motor vehicle convoy through the interaction of tires with the road surface but the presence of cars of different types and brands in the convoy complicates the assessment process. In addition, the work does not define the criteria for assessing the maneuverability and controllability of motor vehicles.

Research aimed at optimizing energy consumption by vehicles moving in a convoy by determining the optimal distance between them is reported in [28]. A new technology of an automated modular vehicle is proposed, which provides for the possibility of connecting several vehicles together (bumper to bumper) to reduce energy consumption and the length of the motor vehicle convoy. But the proposed technology significantly reduces the maneuverability of vehicles, and when one of the vehicles breaks down, the convoy is forced to stop.

To improve energy efficiency, work [29] proposed the use of the environmentally-friendly driving method by introducing an automatic speed control system. This system makes it possible to maintain the optimal speed and distance to other vehicles, reducing sudden accelerations and braking. However, the energy efficiency of using convoys with unmanned vehicles with a hybrid power plant is not considered.

In [30], a model of road throughput capacity and a condition for the stability of mixed traffic flow with a convoy of unmanned vehicles based on a probability distribution were proposed. In addition, some characteristics of the influence of the maximum size of the convoy on the capacity of roads were analyzed, but the influence of the distance between unmanned vehicles on the capacity of roads was not considered.

However, known studies did not consider the execution of a maneuver by a group (convoy) of cars according to a common control signal, i.e., changes in the movement parameters of the lead vehicle of the convoy. This is due to the fact that unmanned vehicles have developed in recent years, and therefore we have raised this issue for the first time.

3. The aim and objectives of the study

The purpose of our study is to devise an approach to increasing the productivity of the transport process by using convoys with unmanned vehicles by improving their operational properties. This makes it possible to bring the efficiency of road transport to the level of railroad transport, which is ensured by assembling railroad-like road trains.

To achieve the goal, it is necessary to solve the following tasks:

– to define the concept and criteria for assessing the maneuverability and controllability of road convoys;

– to determine the increase in maneuverability and controllability of transport convoys using unmanned vehicles;

– to conduct an assessment of the energy efficiency of using transport convoys with unmanned vehicles;

– to conduct an assessment of the increase in the throughput of roads when using convoys with unmanned vehicles.

4. The study materials and methods

The object of our study is the process of movement of a motor convoy, which consists of unmanned vehicles.

The subject of this study is the assessment of the possibility of improving the maneuverability, controllability, energy efficiency of motor convoys, as well as the road throughput capacity through the use of unmanned vehicles.

The main hypothesis of the study assumes that the use of unmanned vehicles as part of a motor convoy could make it possible to obtain an increase in the indicators of maneuverability, energy efficiency of transport convoys, as well as the road throughput capacity, provided that the quality of distance control between unmanned vehicles is high.

The assumptions adopted when considering the object of our study are that an ideal distance control system between adjacent unmanned vehicles and a similar type of rolling stock of a motor convoy are considered.

The methods used in this study are based on:

– the theory of operational properties of vehicles, which are used to determine the maneuverability, controllability of automobile convoys with unmanned vehicles, and to calculate the increase in the road throughput capacity in this case;

– the theory of mechanisms and machines in terms of considering an automobile convoy with unmanned vehicles as mechanisms, the links of which have kinematic pairs without a rigid connection between them;

– control theories, which are used when devising methods for controlling the distance between adjacent unmanned vehicles in convoys, building mathematical models, and developing algorithms for controlling unmanned convoys.

The study used methods of classical mechanics; automobile theory (theory of operational properties). We have proposed a new method of multi-component complex motion to analyze the movement of automobile convoys. Unmanned vehicles included in the convoy were considered from the perspective of the theory of mechanisms and machines as links of a kinematic chain that do not have rigid kinematic pairs.

In the technical literature on the theory of operational properties of cars, it is quite common to encounter the use of the same term by different authors, but used in slightly different, distinct meanings. Therefore, for an unambiguous understanding of the text of our study, we give selected definitions of some reference terms used in it.

The maneuverability of automobile convoys is understood as a set of maneuverability properties of cars entering the convoy, which provide a change in traffic parameters with the necessary accuracy and speed.

The controllability of a car convoy is determined by the ability of cars entering the convoy to adequately process a signal to change traffic parameters in the minimum time.

A change in the traffic parameters of cars entering the convoy can occur in the event of a change in the traffic resistance parameters. The ability of a car convoy to maintain unchanged traffic parameters during a sharp change in the traffic resistance of cars characterizes the stability of its movement.

A maneuver of a car convoy can be considered ideal, in which all cars synchronously begin and complete their maneuver.

The mobility of a motorcade is characterized by the average speed of its movement from the starting point of the route to the final one [31].

The maneuver time of a car convoy must be determined from the moment the control signal is received by the main car until the maneuver is completed by the car at the tail of the convoy. For further research, unmanned cars with a combined electromechanical drive of the drive wheels were adopted because they are promising and provide high quality control over the distance between two adjacent cars. The parameters of the movement of cars (speed) were accepted based on analysis of the dynamic properties of modern cars. The overall length of cars in the considered examples is within the overall dimensions of cars and trucks.

The theoretical research reported here is a scientific basis for further simulation modeling of the movement of car convoys with unmanned cars under various situational conditions. The study applied methods of classical mechanics, car theory (theory of operational properties). To analyze the movement of car convoys, the method of multicomponent complex motion has been proposed.

5. Results of investigating the maneuverability and controllability of automobile convoys

5. 1. Definition of the concept and criteria for assessing maneuverability and controllability of automobile convoys

An important indicator of the maneuverability of an automobile convoy is the maximum change in its length (Fig. 1) during movement.

The length of an automobile convoy can be defined as:

$$L_k = l_{r_1} + T_{v_2} + \ldots + T_{v_i} + \ldots + T_{v_{i-1}} = l_{r_1} + \sum_{i=1}^{n-1} T_{v_i}, \quad (1)$$

where T_{v_i} is the movement interval between the i-th and i–1 cars in the convoy.

The movement interval can be determined from the following formula [6]:

$$T_{v_i} = l_{r_i} + S_{T_i} + l_z, \quad (2)$$

where l_{r_i} – overall length of the i-th car; S_{T_i} – braking distance of the i-th car from the initial braking speed to a complete stop; l_z=5 m – reserve distance [24].

The braking distance of the car depends on the speed of its movement. Therefore, with a change in the speed of the car convoy, the movement interval T_{v_i} and the length of the convoy L_k increase.

Fluctuations in the length of the car convoy can be caused by both a change in the speed of movement and a change in the distance. The ratio of the maximum possible length of the car convoy $L_{k\,max}$ during movement to its minimum possible value $L_{k\,min}$ can be characterized by the coefficient of change in the length of the convoy:

$$K_d = \frac{L_{k\max}}{L_{k\min}}. \quad (3)$$

Our study assumed that a convoy of N vehicles performs an "acceleration" maneuver. In this case, the speed of the convoy should increase by the value ΔV. The acceleration time of the i-th vehicle will be equal to:

$$t_{p_i} = \frac{\Delta V}{a_i}, \quad (4)$$

where a_i is the average acceleration of the i-th car during acceleration.

Each subsequent car in the convoy begins acceleration after the speed of the previous car has increased by ΔV. Then the time for performing the "acceleration" maneuver by the car convoy will be equal to:

$$t^*_{man} = \sum_{i=1}^{n} t_{pi} = \Delta V \sum_{i=1}^{n} a_i^{-1}. \quad (5)$$

In the case of simultaneous acceleration by all cars in the convoy and the same acceleration of all cars, the maneuver time t_{mp} will be equal to the ideal value:

$$t_{mp} = \frac{\Delta V}{a}, \quad (6)$$

where a is the acceleration, the same for all cars in the convoy.

It is obvious that the real time of the maneuver of the automobile convoy will be within:

$$t_{mp} < t_{man} < t^*_{man}. \quad (7)$$

In order to reduce the maneuver time (increase the maneuverability of the automobile convoy), it is necessary to increase the acceleration of the cars in the convoy. In the ideal case, they should be the same and equal to the maximum possible value a_i=a_{max}; expression (5) will take the form:

$$t^{**}_{man} = \frac{\Delta V}{a_{max}}. \quad (8)$$

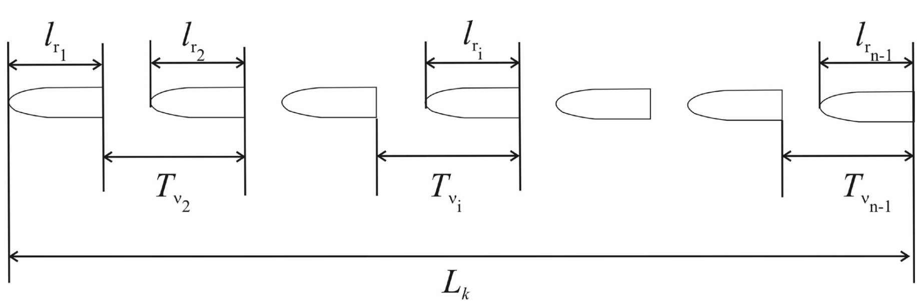

Fig. 1. Car convoy length

Thus, new indicators have been proposed: "maneuver time" and "coefficient of change in convoy length", which can be criteria for assessing the maneuverability and controllability of automobile convoys.

5. 2. Determining the increase in maneuverability and controllability of transport convoys when using unmanned vehicles

The dynamic increase (during the march) of the convoy length is determined by the accumulated sum of relative movements of the cars, which are caused by the relative speeds of the cars (relative to the leader car). Reducing the sum of relative movements of the cars in the convoy makes it possible to reduce its length and the time of the march.

The expression for the length of the automobile convoy can be represented as:

$$L_k = l_{r_1} + l_{r_2} + \ldots + l_{r_i} + S_{T_1} + S_{T_2} + \ldots + S_{T_i} + (n-1)l_z = = \sum_{i=1}^{n} l_{r_i} + \sum_{i=1}^{n} S_{T_i} + + (n-1)l_z. \quad (9)$$

Braking distance of the i-th car (the distance traveled by car during the braking period was not taken into account):

$$S_{T_V} = \frac{V^2}{2 j_{x\max i}}, \quad (10)$$

where $j_{x\max i}$ is the maximum possible deceleration of the vehicle during braking, with the technical condition of the brake system meeting the technical conditions:

$$j_{x\max i} = \varphi_{x\max} \cdot g, \quad (11)$$

$$S_{T_V} = S_T = \frac{V^2}{2g\varphi_{x\max}}, \quad (12)$$

where $\varphi_{x\max}$ is the maximum value of the longitudinal coefficient of adhesion of the wheels to the road; $\varphi_{x\max}=0.8$; g is the acceleration of gravity, $g=9.81$ m/s^2.

After substituting (12) into (9), we obtain:

$$L_k = \sum_{i=1}^{n} l_{r_i} + \frac{nV^2}{2g\varphi_{x\max}} + (n-1)l_z. \quad (13)$$

If, when a convoy moves, its speed can vary in the range $[V_{\min}, V_{\max}]$, then the length of the convoy will be within limits $[L_{k\min}, L_{k\max}]$:

$$\sum_{i=1}^{n} l_{r_i} + \frac{V_{\min}^2}{2g\varphi_{x\max}} + + (n-1)l_z \le L_k \le \sum_{i=1}^{n} l_{r_i} + \frac{nV_{\max}^2}{2g\varphi_{x\max}} + (n-1)l_z. \quad (14)$$

Convoy length change factor:

$$K_d = \frac{L_{k\max}}{L_{k\min}} = \frac{\sum_{i=1}^{n} l_{r_i} + \frac{nV_{\max}^2}{2g\varphi_{x\max}} + (n-1)l_z}{\sum_{i=1}^{n} l_{r_i} + \frac{nV_{\min}^2}{2g\varphi_{x\max}} + (n-1)l_z}. \quad (15)$$

The difference in the lengths of the car convoy at $V=V_{\max}$ and at $V=V_{\min}$:

$$\Delta L_k = L_{k\max} - L_{k\min} = \frac{\left(V_{\max}^2 - V_{\min}^2\right)n}{2g\varphi_{x\max}} = \frac{\bar{V} \cdot \Delta V \cdot n}{g \cdot \varphi_{x\max}}, \quad (16)$$

where ΔV is the difference in speeds $V_{\max}$–$V_{\min}$.

The sensitivity of the length of the convoy to changes in the speed of the lead vehicle was determined from expression (13):

$$\frac{dL_k}{dV} = \frac{nV}{g\varphi_{x\max}}. \quad (17)$$

From expression (17) it is seen that the sensitivity of the length of the convoy L_k to changes in the speed of movement is proportional to the product of the number of cars in the convoy and its speed of movement. When using unmanned vehicles, the interval between cars will be equal to:

$$T_{V_i} = l_{r_i} + l_z. \quad (18)$$

Expression (18) differs from expression (2) in the absence of the value of the braking distance S_{T_i}.This is due to the fact that the braking control of cars in the convoy is centralized from the lead car. In this case, the control signal for braking is transmitted sequentially from the closing car to the lead.

The length of the convoy of unmanned cars L_{kd} is determined by:

$$L_{kd} = \sum_{i=1}^{n} l_{r_i} + (n-1)l_z. \quad (19)$$

From expression (19) it is clear that in this case the length of the convoy L_{kd} does not depend on the speed of its movement, and the sensitivity of the convoy length dL_{kd}/dV to the change in speed is zero. The marching time when using unmanned vehicles t_{md} was found using expression (19) in the form:

$$t_{md} = \frac{S_m + \sum_{i=1}^{n} l_{r_i} + (n-1)l_z}{\bar{V}}, \quad (20)$$

where S_m is the length of the convoy march, km; $\bar{V}$ – average speed of the march.

In the absence of unmanned vehicles in the convoy:

$$t_m = \frac{S_m + \sum_{i=1}^{n} l_{r_i} + (n-1)l_z + \frac{n\bar{V}^2}{2g\varphi_{x\max}}}{\bar{V}}. \quad (21)$$

Comparing expressions (20) and (21), we can conclude that, all other things being equal:

$$t_{md} < t_m. \quad (22)$$

Cars with a combined power plant, in the case of automatic maintenance of the distance between cars $l_z=5$ m, allow movement at higher permissible speeds of the convoy. As can be seen from expression (20), increasing the average speed $\bar{V}$ makes it possible to reduce the march time t_{md}.

It should be noted that the brakes of each subsequent car in the convoy must operate either simultaneously with the brakes of the previous car, or ahead of the brakes of the latter by time $\Delta\bar{t}_{mid}$.

In this case, traffic safety will be ensured due to the reserve distance l_z if for some reason the brakes of the previous car operate before the brakes of the next. The permissible delay time $\Delta\bar{t}_{mid}$ of the brakes of the next car in relation to the brakes of the previous one can be determined from the following dependence:

$$\Delta\bar{t}_{mid}=\frac{l_z}{V}. \qquad (23)$$

Fig. 2 shows the dependence $\Delta\bar{t}_{mid}$ on the average convoy speed V at l_z=5 m. The plotted data were calculated using formula (23).

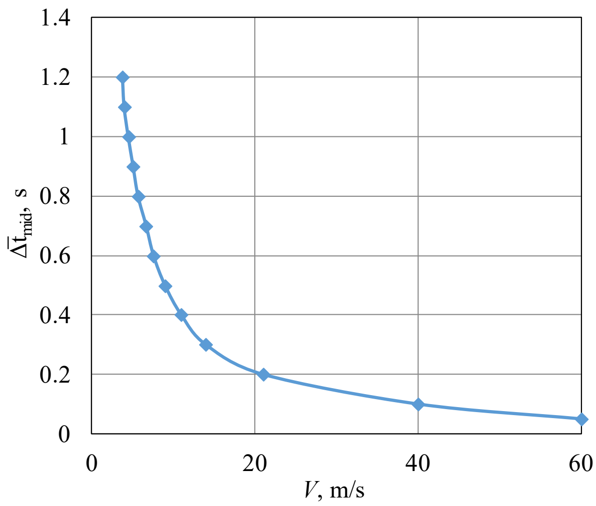

Fig. 2. Dependence of the permissible delay time $\Delta\bar{t}_{mid}$ of the next unmanned vehicle's brake application on the brake application time of the previous one

A comparison of the marching time of automobile convoys consisting of conventional and unmanned vehicles was carried out. To this end, we transform expressions (20) and (21) to the form:

$$t_{md}=\frac{S_m}{\bar{V}}+\frac{n\bar{l}_r+(n-1)l_z}{\bar{V}}, \qquad (24)$$

$$t_m=\frac{S_m}{\bar{V}}+\frac{n\left(\bar{l}_r+\frac{\bar{V}^2}{2g\varphi_{x\max}}\right)+(n-1)l_z}{\bar{V}}, \qquad (25)$$

where $\bar{l}_r$ is the average overall length of cars in the convoy:

$$l_r=\frac{1}{n}\sum_{i=1}^{n}l_{r_i}. \qquad (26)$$

Reducing the time of marching when using unmanned vehicles:

$$\Delta t_m=t_m-t_{md}=\frac{n\bar{V}}{2g\varphi_{x\max}}. \qquad (27)$$

Comparing expressions (17) and (27), we can conclude that:

$$\frac{dL_k}{dV}=2\Delta t_m. \qquad (28)$$

Fig. 3 shows a plot of the dependence of reduction in time Δt_m of the march when using unmanned vehicles on the average speed $\bar{V}$ at different numbers of cars in the convoy. The plot was built using dependence (27) at $\varphi_{x\max}$=0.8.

Fig. 3 demonstrates that even at a speed of V=25 m/s (90 km/h), the reduction in the time of the march is only (60 s) even when the number of cars in the convoy is 40 units. This reduction in time is relevant when moving over short distances, for example, when overcoming a dangerous section of the road. However, the use of unmanned vehicles makes it possible to reduce the length of the convoy (improve its compactness), or at the same length, increase the number n of cars in the convoy.

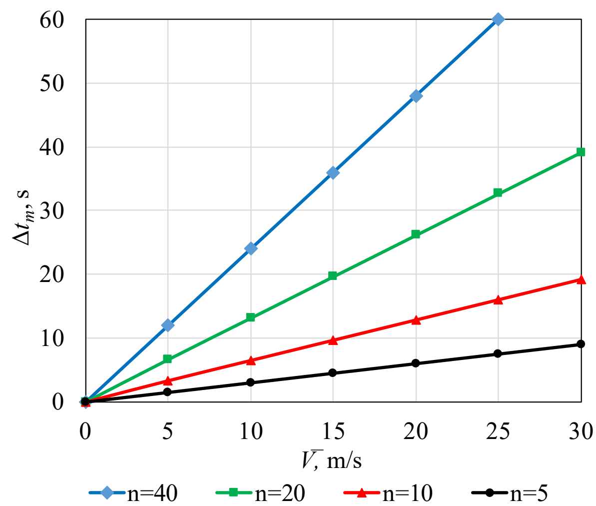

Fig. 3. Dependence $\Delta t_m(\bar{V})$ for different number of cars n in the convoy: — n=40 cars in the convoy; — n=20 cars in the convoy; — n=10 cars in the convoy; — n=5 cars in the convoy

The reduction in convoy length was found using expressions (13) and (19) at $V=\bar{V}$:

$$\Delta L=L_k-L_{kd}=\frac{n\bar{V}^2}{2g\varphi_{x\max}}. \qquad (29)$$

Fig. 4 shows a plot of the dependence of reduction in the length ΔL of a convoy of 20 cars on average speed $\bar{V}$ in the case of using unmanned vehicles, which was constructed according to dependence (29) at $\varphi_{x\max}$=0.8.

Fig. 4 demonstrates that the use of unmanned vehicles in a convoy at n=20 makes it possible to reduce the length of the latter by 800 m at a speed of L_k=L_{kd}=25 m/s (90 km/h).

The use of unmanned vehicles makes it possible to increase the number of cars in it with an equal length of the convoy. Let n_d be the number of cars in a convoy with unmanned vehicles. Then, from the condition of equality L_k=L_{kd}, equating the right-hand sides of expressions (13) and (19) at $V=\bar{V}$, taking into account expression (26), we obtain:

$$n_d\cdot\bar{l}_r+(n_d-1)l_z=n\bar{l}_r+(n_d-1)l_z+\frac{n\bar{V}^2}{2g\varphi_{x\max}}. \qquad (30)$$

From expression (30), we found:

$$\frac{n_d}{n}=1+\frac{n\bar{V}^2}{2g\varphi_{x\max}(\bar{l}_r-l_z)}. \qquad (31)$$

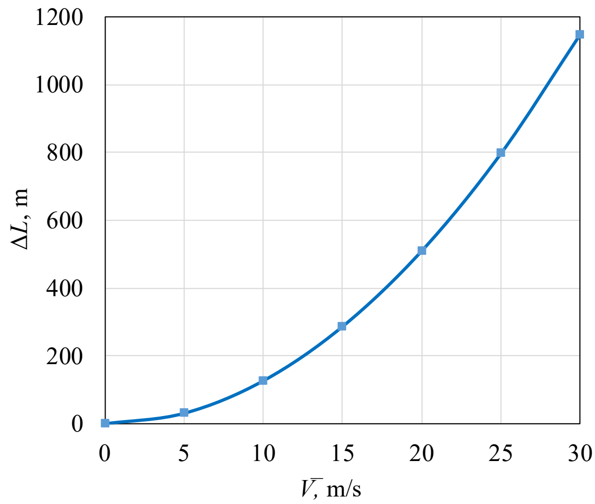

Fig. 4. Dependence $\Delta L(\bar{V})$ for a motorcade at $n=20$

For a convoy with unmanned vehicles at l_r=7 m, Fig. 5 shows a plot of dependence $n_d/n=F(\bar{V})$ in accordance with dependence (31) at $\varphi_{x\max}$=0.8.

Fig. 5 shows that a convoy with unmanned vehicles with the same length as a conventional convoy (with piloted vehicles) at l_r=7 m and V=25 m/s (90 km/h) can include four times more vehicles in its composition.

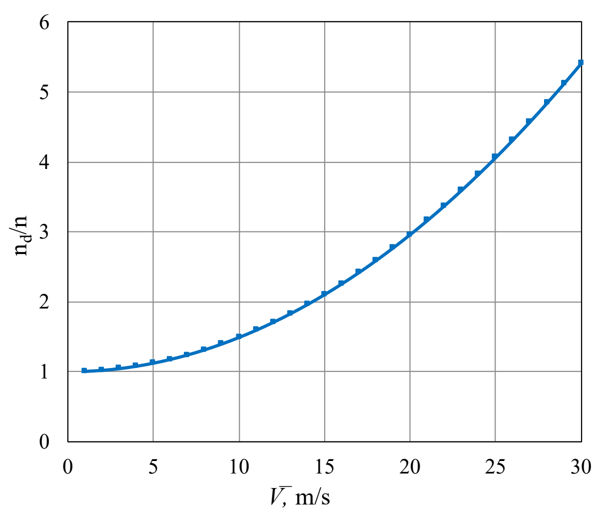

Fig. 5. Dependence $n_d/n=F(\bar{V})$ at $\bar{l}_r=7$ m

Thus, the implementation of traffic control over a convoy of unmanned vehicles equipped with a combined power plant, unlike a convoy of vehicles controlled by drivers, will make it possible:

– to reduce the time for passing sections of the road of short length (for example, for a convoy of 40 vehicles at a speed of 25 m/s (90 km/h), the reduction of the time will be 60 s);

– to reduce the length of a convoy of 20 unmanned vehicles moving at a speed of 25 m/s (90 km/h) by 800 m.

– to increase the number of vehicles in the convoy four times while keeping its length and speed unchanged;

– to reduce sensitivity of the length of a convoy of unmanned vehicles to changes in speed since the distance between vehicles is not determined by the braking distance and speed but is equal only to the reserve distance l_r=5 m.

5. 3. Energy efficiency assessment of the use of transport convoys with unmanned vehicles

Unmanned vehicles are links of a mechanical (kinematic) chain – a convoy. The difference of such a kinematic chain from the classical one, which is considered in the theory of mechanisms and machines, is the absence of mechanical kinematic pairs. The interaction between the links is carried out due to information (telemetric) communication. Therefore, the connection between the links is flexible (not rigid).

The use of a system for automatic control of the distance between vehicles reduces the amplitude of linear velocity fluctuations and the range of kinetic energy fluctuations, which affects fuel consumption by vehicles, i.e., the energy efficiency of the use of automobile convoys [26].

In the case of automatic control over the distance between vehicles, the relative speeds [32] tend to zero. In the ideal case of control, they are equal to zero and the system (automobile convoy) can be considered rigid.

Additional energy losses in the movement of the car due to unevenness (fluctuations) of the traction force [32]:

$$\Delta W=\frac{A_p}{\pi}S, \tag{32}$$

where A_p is the amplitude of the oscillations of the traction force; π is the Pythagorean number, π=3.1416; S is the distance traveled by car.

Let the speed of the automobile convoy obey the harmonic law:

$$V=\bar{V}+A_v\sin(\Omega t), \tag{33}$$

where $\bar{V}$ – average (portable) speed of the automobile convoy; A_v – amplitude of fluctuations of relative speed V_r:

$$V_r=A_v\sin(\Omega t), \tag{34}$$

Ω – circular frequency of oscillations of the relative speed of the car; t – time.

In the case of driving cars by drivers, the amplitude of oscillations of relative speeds A_v is greater than the amplitude of oscillations A_v' in unmanned cars.

The energy losses caused by oscillations of the car speed are determined by its amplitude [32] per cycle:

$$\Delta W_s=\frac{M\left(V_{\max}^2-V_{\min}^2\right)}{2\eta_{tr}}-\frac{M}{\eta_{tr}}\bar{V}\Delta V_{\max}, \tag{35}$$

where M is the mass of the vehicle; $V_{\max}$, $V_{\min}$ are the maximum and minimum vehicle speeds; $\Delta V_{\max}$ is the maximum change in vehicle speed; η_{tr} is the efficiency of vehicle transmission (the same for all vehicles).

In the case under consideration, the average (transmitted) vehicle speed is defined as:

$$\bar{V}=\frac{V_{\max}-V_{\min}}{2}. \tag{36}$$

The plots of speed versus time for driver-controlled and driverless cars are shown in Fig. 6 when the speed of the cars changes according to the harmonic law (33).

Obviously:

$$\Delta V_{\max}=2A_v. \tag{37}$$

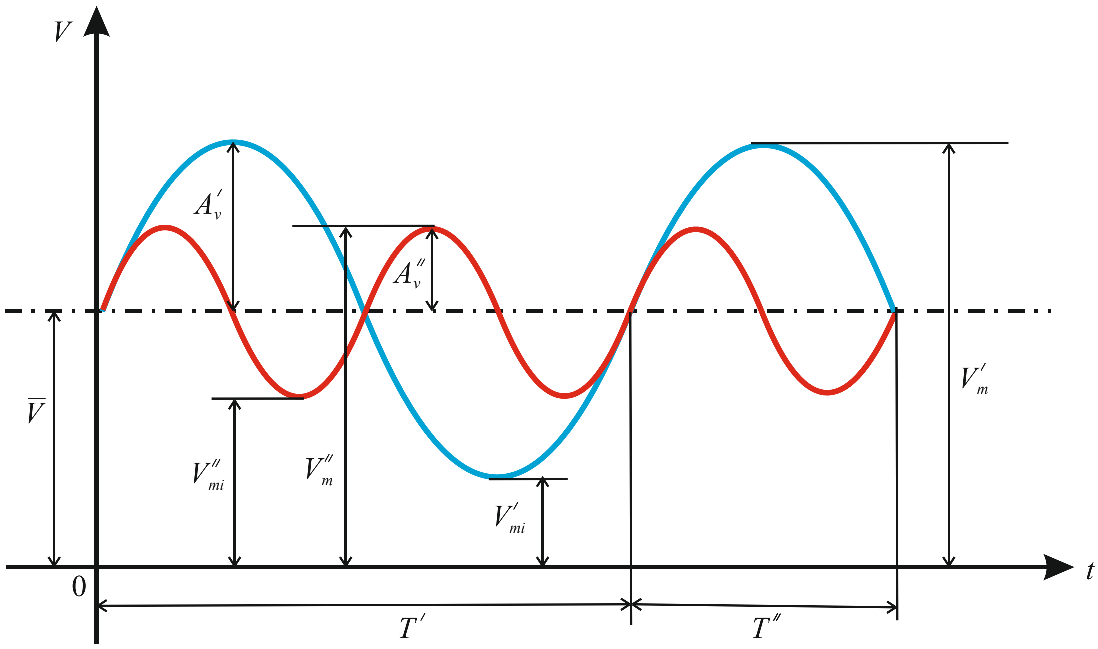

Fig. 6. Plots of the speed of a car in a convoy versus time: — cars with drivers; — driverless cars

Expression (35), taking into account (37), will take the form:

$$\Delta W_s = \frac{2A_v M\bar{V}}{\eta_{tr}}. \quad (38)$$

Cycle time of vehicle speed oscillations (oscillation period):

$$T_k = \frac{2\pi}{\Omega}. \quad (39)$$

Additional motor energy losses during time t:

$$\Delta W_t = \Delta W_s \frac{t}{T} = M\bar{V}\frac{A_v}{\pi\eta_{tr}} t\Omega. \quad (40)$$

Considering that:

$$S = \bar{V}t. \quad (41)$$

The formula (40) is as follows:

$$\Delta W_{dS} = M\frac{A_v}{\pi\eta_{tr}} S\Omega. \quad (42)$$

In the case of movement in a convoy, the total additional energy losses of the engine will be equal to:

$$\Delta W_\Sigma = \sum_{i=1}^{n} \Delta W_{dSi} = \frac{S}{\pi\eta_{tr}} \sum_{i=1}^{n} M_i A_{vi}\Omega_i, \quad (43)$$

where ΔW_{dSi}, M_i, A_{vi}, Ω_i are the parameters of the i-th car in the convoy; n is the number of cars in the convoy.

For driver-controlled cars:

$$\Delta W'_\Sigma = \frac{S}{\pi\eta_{tr}} \sum_{i=1}^{n} M_i A'_{vi}\Omega'_i. \quad (44)$$

For a convoy with unmanned vehicles:

$$\Delta W''_\Sigma = \frac{S}{\pi\eta_{tr}} \sum_{i=1}^{n} M_i A''_{vi}\Omega''_i. \quad (45)$$

For all cars in the convoy, parameters $A'_v = A'_{vi} = \text{const}$, $A''_v = A''_{vi} = \text{const}, \Omega' = \Omega'_i = \text{const}, \Omega'' = \Omega''_i = \text{const}$. Then (44) and (45) are written in the form:

$$\Delta W'_\Sigma = \frac{SA'_v\Omega'}{\pi\eta_{tr}} \sum_{i=1}^{n} M_i, \quad (46)$$

$$\Delta W''_\Sigma = \frac{SA''_v\Omega''}{\pi\eta_{tr}} \sum_{i=1}^{n} M_i. \quad (47)$$

Comparing expressions (46) and (47), it was determined:

$$\frac{\Delta W'_\Sigma}{\Delta W''_\Sigma} = \frac{A'_v}{A''_v}\frac{\Omega'}{\Omega''} = \frac{A'_v}{A''_v}\frac{V'}{V''}, \quad (48)$$

where V', V'' are the frequencies of speed fluctuations of cars with drivers and unmanned cars, respectively.

From equation (48) it is clear that to reduce additional engine energy losses in the case of a convoy of unmanned cars, it is necessary to meet the condition:

$$A''_v V'' < A'_v V', \quad (49)$$

or

$$\frac{A''_v}{A'_v} < \frac{V'}{V''}. \quad (50)$$

The condition for increasing the energy efficiency of using convoys with unmanned vehicles corresponds to inequality (50).

Thus, a physical and mathematical model of the occurrence of additional engine energy losses caused by fluctuations in the relative speeds of vehicles in the convoy has been proposed. Condition (50) is derived, the fulfillment of which ensures a reduction in additional engine energy losses in the case of using unmanned vehicles in the convoy.

5. 4. Increasing the road throughput capacity when using convoys with unmanned vehicles

The throughput capacity of a highway [24] is determined by the following relationship:

$$N = 1{,}000\frac{V}{T_v}. \quad (51)$$

When using the SI system of units, velocity is measured in m/s. In this case, equation (51) will take the form:

$$N = 3{,}600\frac{V}{T_v}. \quad (52)$$

The interval between two cars in a convoy is calculated according to expressions (2), (12). After substituting these expressions into equation (52), we obtained:

$$N' = 3{,}600\frac{V}{l_r + l_z + \dfrac{V^2}{2g\varphi_{x\max}}}. \quad (53)$$

When using unmanned convoys [24], the braking distance S_T is not taken into account when determining the interval T_v and dependence (2) will take the form:

$$T_v = l_{r_i} + l_z. \quad (54)$$

Dependence (52) given (54) for a convoy with self-driving cars is as follows:

$$N'' = 3{,}600\frac{V}{l_r + l_z}. \quad (55)$$

Throughput growth factor when using unmanned vehicles in a convoy:

$$K_N = \frac{N''}{N'} = \frac{l_r + l_z + \dfrac{V^2}{2g\varphi_{x\max}}}{l_r + l_z} =$$

$$= 1 + \frac{V^2}{2g\varphi_{x\max}\left(l_r + l_z\right)} = 1 + AV^2, \quad (56)$$

where A – proportionality factor:

$$A = \frac{1}{2g\varphi_{x\max}\left(l_r + l_z\right)}. \quad (57)$$

Analysis of dependence (53) reveals that N' at the beginning of the increase in velocity V also increases, then reaches a maximum value, and then decreases [30].

The velocity at which N' reaches a maximum can be determined from the dependence:

$$V^* = \sqrt{2g\phi_{x\max}\left(l_r + l_z\right)}. \quad (58)$$

When $V>V^*$ with increasing V, the capacity of the road N' for automobile convoys without unmanned vehicles will decrease. Fig. 7 shows the plots of dependence of $K_N(V)$ for possible values of coefficient A (expression (56)). Analysis of the plots shown in Fig. 7 reveals that the use of unmanned vehicles makes it possible to increase the capacity of the road ($K_N \geq 1$) in the entire range of increasing the speed of the convoys.

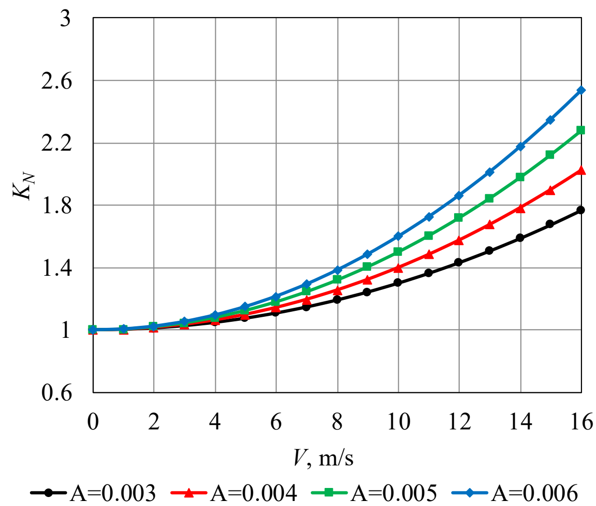

Fig. 7. Dependence plots of $K_N \geq 1$ on different values of coefficient A: —●— proportionality coefficient A=0.003; —▲— proportionality coefficient A=0.003; —■— proportionality coefficient A=0.005; —◆— proportionality coefficient A=0.006

The use of unmanned vehicles makes it possible to reduce the reserve distance l_z almost to zero $\left(l_z \cong 0\right)$. Expression (7) in this case will take the form:

$$N'' = 3{,}600\frac{V}{l_r}, \quad (59)$$

and coefficient A in dependence (56):

$$A = \frac{1}{2g\varphi_{x\max}l_r}. \quad (60)$$

Fig. 8 shows the plots of dependence of the road throughput capacity N'' on the convoy length l_r at different values of the convoy speed, which consists of unmanned vehicles (expression (59)).

Analysis of the plots shown in Fig. 8 reveals that with increasing the length of the unmanned convoy, the road throughput capacity decreases in the entire range of convoy speed. Thus, for any speed, with an increase in the convoy length by 5 times, the capacity also decreases by 5 times.

Dependence (56) at l_z=0 will take the form:

$$K_N = 1 + \frac{V^2}{2g\varphi_{x\max}l_r}. \quad (61)$$

Fig. 9 shows a plot of the dependence of $K_N(V)$ at the speed of movement of a convoy of cars with unmanned vehicles V=16.7 m/s (60 km/h) and $\varphi_{x\max}$=0.8, which was constructed in accordance with dependence (61).

Analysis of the plots shown in Fig. 9 reveals that with the overall length of the car l_r=6 m coefficient K_N of the increase in road throughput capacity is 4, and at l_r=2 m it is 10. Therefore, the use of automobile convoys with unmanned vehicles makes it possible to increase the road throughput capacity several times.

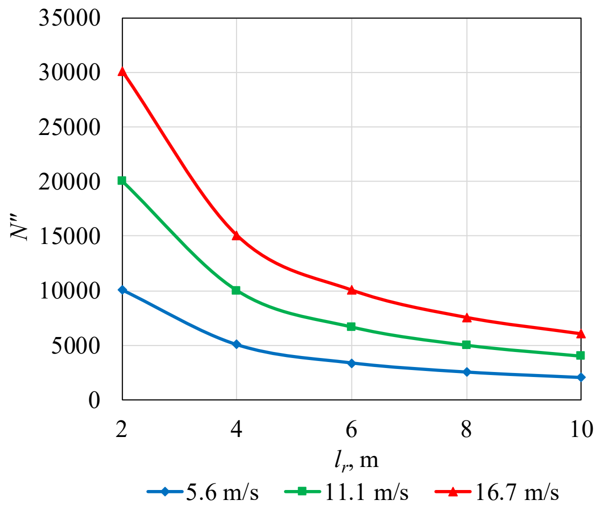

Fig. 8. Dependence plots of $N''(l_r)$ on different values of convoy speed V: — convoy speed V=16.7 m/s (60 km/h); — convoy speed V=11.1 m/s (40 km/h); — convoy speed V=5.6 m/s (20 km/h)

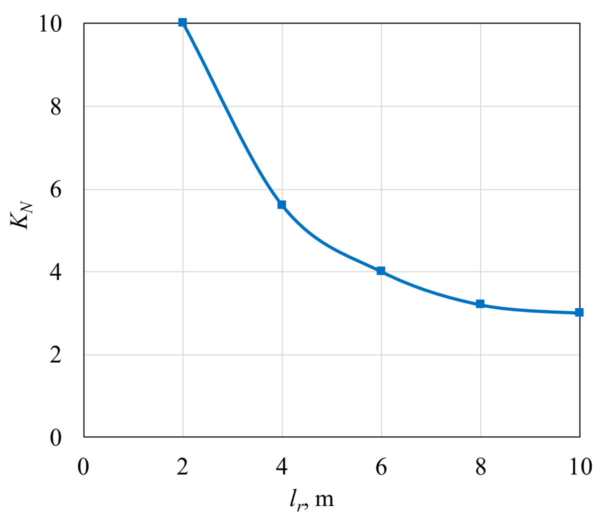

Fig. 9. $K_N(l_r)$ dependence plot at $\varphi_{x\max}$=0.8; V=16.7 m/s (60 km/h)

Thus, when using convoys with unmanned vehicles, it is possible to reduce the distance between adjacent cars to the value of the reserve path l_z=5 m. In this case, at the maximum speed of movement V=20 m/s (72 km/h), the value of the coefficient of the increase in road throughput capacity reaches value K_N=3. Also, the use of unmanned vehicles makes it possible to reduce the reserve path to l_z=0. In this case, coefficient K_N of the increase in capacity at a speed of movement of 16.7 m/s (60 km/h) depending on the overall length l_r reaches the value of 2–10.

6. Discussion of results based on investigating the maneuverability and controllability of unmanned automobile convoys

Previously, in studies [7, 8, 26, 27], the concepts of maneuverability and controllability of automobile convoys were not defined, which complicated analysis of the effectiveness of their use. In contrast to [7, 8], it is proposed to evaluate the quality of control over an automobile convoy using the coefficient of change of its lengths (3), which makes it possible to compare the effectiveness of different techniques for controlling the convoy. It is obvious that the use of unmanned vehicles will bring this coefficient much closer to unity.

The definition of the concept of "maneuverability and controllability of an automobile convoy" made it possible to introduce new indicators and criteria:

– time of maneuvering (4) to (8);

– coefficient of change of the length of the convoy (3).

Sensitivity of the length of a convoy to changes in the speed of the lead vehicle (13) has also been determined. When using unmanned vehicles in a convoy, the length of the convoy does not depend on its speed (19), and sensitivity of the length of the convoy dL_{kd}/dV with unmanned vehicles to changes in speed is zero. We also see that the march time (20), (21) when using unmanned vehicles is less than for cars driven by drivers.

A comparative assessment of the energy efficiency of convoys with unmanned vehicles and cars driven by drivers showed that in the first case, the additional energy consumption of engines (43) is less than in the second case (44). With high quality control over the distance between two adjacent cars in the convoy, this is explained by smaller fluctuations in the kinetic energy of the cars, part of which is lost and then compensated, as a result of which the energy consumption of the engines is reduced.

Reducing the distance between adjacent unmanned vehicles makes it possible to increase the road throughput capacity. With ideal control over this distance, with the help of automatic control systems, it is possible to assemble road trains similar to railroad trains, which provides higher efficiency of transport by increasing productivity.

An alternative technical solution proposed in [16, 17] is the use of multi-axle and multi-chain vehicles. However, this solution is associated with lower maneuverability and controllability of these vehicles, which worsens road safety. Car convoys with unmanned vehicles and conventional road trains can be considered as multi-link mechanisms, but only the former lack a rigid connection between the links. From the standpoint of classical mechanics and the theory of mechanisms and machines, multi-link unmanned car convoys can be considered as mechanisms in which kinematic pairs do not have a rigid connection.

The application scope of our study is the commercial and military use of unmanned vehicle convoys in solving logistical tasks. In the commercial and military domains, the results of our study are limited by the possibility of using unmanned convoys only on paved roads.

Unlike previously applied approaches, this makes it possible to improve the performance of automobile convoys with unmanned vehicles compared to convoys formed from piloted vehicles.

The disadvantage of this approach is the increased requirements for the control systems of the movement of an unmanned automobile convoy, the sensitivity of control errors to the functional stability of the system elements. It also requires a higher qualification of the driver of the lead vehicle (leader vehicle).

A further area of research is the development of algorithms and control systems for the movement of unmanned automobile convoys and simulation modeling under various situational conditions.

7. Conclusions

1. The concepts of "maneuverability" and "controllability" of a motor vehicle convoy have been defined. The maneuverability of motor vehicle convoys is understood as a set of maneuverability properties of the vehicles in the convoy, which ensure the change of the traffic parameters with the required accuracy and speed. The controllability of a motor vehicle convoy is determined by the ability of the vehicles in the convoy to adequately process the signal for changing the traffic parameters in the minimum time. New indicators have been proposed: "maneuver time" and "coefficient of change in the length of the convoy", which can be criteria for assessing the maneuverability and controllability of motor vehicle convoys. In order to reduce the maneuver time, it is necessary to increase the acceleration of the vehicles in the convoy. Ideally, they should be the same and equal to the maximum possible value. The ratio of the maximum possible length of the motor vehicle convoy during movement to its minimum possible value can be characterized by the coefficient of change in the length of the convoy.

2. Implementing traffic control over a convoy of unmanned vehicles equipped with a combined power plant, unlike a convoy of vehicles controlled by drivers, will make it possible:

– to reduce the time for passing sections of a short distance (for example, for a convoy of 40 vehicles at a speed of 25 m/s (90 km/h)) by 60 s;

– to reduce the length of a convoy of 20 unmanned vehicles moving at a speed of 25 m/s (90 km/h) by 800 m;

– to increase the number of vehicles in the convoy four times while keeping its length and speed unchanged;

– to reduce sensitivity of the length of a convoy of unmanned vehicles to changes in speed since the distance between vehicles is not determined by the braking distance and speed but is equal only to the reserve distance = 5 m.

3. As a result of our study, physical and mathematical models of the occurrence of additional engine energy losses caused by fluctuations in the relative speeds of cars in a convoy have been proposed. A criterion for increasing the energy efficiency of the use of convoys was obtained, the implementation of which ensures a reduction in additional engine energy losses when using unmanned vehicles in a convoy. This criterion involves ensuring a condition when the ratio of the amplitudes of relative speed fluctuations is less than the ratio of the frequency of speed fluctuations of cars with drivers and unmanned vehicles, respectively.

4. When using convoys with unmanned vehicles, it is possible to reduce the distance between adjacent cars to the amount of the reserve path $l_z = 5$ m. At the same time, at a maximum speed of movement $V = 20$ m/s (72 km/h), the value of coefficient of the increase in the capacity of the highway K_N reaches 3. The use of unmanned vehicles makes it possible to reduce the reserve path l_z almost to zero ($l_z = 0$). In this case, the coefficient of the increase in the road throughput capacity K_N increases (depending on the overall length l_r) at a speed of 16.7 m/s (60 km/h) by 2–10 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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