STUDY OF LONG HAUL TRUCK MOVEMENT ALONG THE CURVILINEAR TRAJECTORY WHILE STEERING A CARRYALL SEMI-TRAILER - CONTAINER BY BRAKING THE WHEELS OF ONE AXLE
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ДОСЛІДЖЕННЯ РУХУ АВТОПОЇЗДА ПО КРИВОЛІНІЙНІЙ ТРАЄКТОРІЇ ПРИ УПРАВЛІННІ УНІВЕРСАЛЬНИМ НАПІВПРИЧІПОМ-КОНТЕЙНЕРОВОЗОМ ШЛЯХОМ ГАЛЬМУВАННЯ КОЛІС ОДНІЄЇ ОСІ

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Keywords: *long haul truck, semi-trailer, container, axle, bogie, trajectory, braking*

ABSTRACT
The long-haul truck movement along the curvilinear (in plan) trajectory is studied in this article. Braking the wheels of the bogie's one side is proved to lead to the fact that the absolute instantaneous centre of the bogie turn, when coming into a corner and coming out of a corner, will be on different sides of the semi-trailer bogie axles. The side force of the bogie is directed towards the transfer centre of semi-trailer angular velocity when coming into a corner and, in the opposite direction, when coming out of a corner. Therefore, braking the wheels of one side frame of a bogie rear axle is considered more efficient.

РЕЗЮМЕ
У статті розглядається рух автопоїзда по криволінійної (в плані) траєкторії. Встановлено, що гальмування коліс одного борту возика призводить до того, що абсолютний миттєвий центр обертання возика на вході в поворот і виході з повороту буде лежати по різні боки від осі возика. Показано, що на вході в поворот бічна сила на возику спрямована в бік центру переносної кутової швидкості напівпричепа, а на виході з повороту - в протилежну сторону. Тому доцільним є гальмування коліс одного борту задньої осі возика напівпричепа.

INTRODUCTION
The container transportation is known to be one of the most convenient and economic cargo delivery types, which is carried out by the local and international transportation organizations. The containers freight transportation is widely used around the world due to the high level of safety and the simplicity of customs registration. The volumes of such transportations grow from year to year (*Onishchuk V.P., and others 2011*).

The modern motor-service for transporting containers has available a wide range of cars, trailers and semi-trailers. However, transportation of containers by carryall semi-trailers is more rational. For example, "Fliegl" Company produces a wide scale of container trucks, in particular, carryall ones for transporting all types of containers, including tank containers (from 20 to 45 foot) and HQ containers.

To transport the 45-foot containers by carryall container trucks, it is necessary to elongate the long haul trucks. Such elongation decreases the vehicles' cornering performance. The enlargement of the overall traffic lane (OTL) creates a danger to the oncoming transport, complicates the movement in the city conditions and reduces the average movement speed of the entire transport stream. It is possible to improve the long haul truck's cornering performance by means of steered (adjustable) axels (wheels) of the semi-trailer or by braking the wheels of the semi-trailer's one side (*Kuts N.G., and others 2003*).

Manoeuvrability indicators of a long-haul truck consisting of a carryall semi-trailer - container with an adjustable axle are defined in this work (*Bodnaruk V.B., and others 1998*). In particular, the long-haul truck with an adjustable axle is proved to meet the requirements of Council Directive 96/53/EC and Directive 2002/7/EC for manoeuvrability. However, its stability is insufficient. The objective of this work is to define the peculiarities of long haul truck pivoting movement when the carryall semi-trailer - container is steered by braking the wheels of one axle.

MATERIALS AND METHODS

To determine the semi-trailer turning radius when steering by braking the wheels of the bogie's one side, it is necessary to determine the normal reactions of the bearing surface to the wheels of the bogie's one side and the steering resistance coefficients inside and outside wheels. The wheels are functions of both normal load and braking torque acting on the bogie's wheel or side.

To determine the redistribution of vertical loads on the wheels of a semi-trailer bogie, the pivoting movement of a long-haul truck should be considered (*Pridyuk V.M., and others 2011*).

The centrifugal force acting on the semi-trailer bogie can be deduced by the formula:

$$P_{jn} = m_n \frac{v^2}{R} \quad [\text{N}] \tag{1}$$

where m_n – weight acting on the semi-trailer bogie, kg;

v – long haul truck speed, m/s;

R – turning radius of the semi-trailer bogie, m.

Then, the centrifugal force acting on certain axles of the bogie is determined as:

$$P_{jni} = \frac{m_{ni} v^2}{R} \quad [\text{N}] \tag{2}$$

where m_{ni} – weight acting on a certain axle of the bogie, kg.

Normal reactions of the bearing surface acting on the inside and outside wheels of the semi-trailer bogie are defined as:

$$Z_{\text{int}} = \frac{a_n}{2L_{nn}} G_1 - \frac{h_{g1}}{2L_{nn}} P_{jxi} - \frac{h_{g1}}{2B} P_{jn} \quad [\text{N}] \tag{3}$$

$$Z_{ext} = \frac{a_n}{4L_{nn}} G_1 - \frac{h_{g1}}{2L_{nn}} P_{jxi} + \frac{h_{g1}}{2B} P_{jn} \quad [\text{N}] \tag{4}$$

where a_n – distance from the point of coupling the semi-trailer with the truck to the semi-trailer mass centre, mm;

h_{g1} – height of semi-trailer mass centre, mm;

G_1 – gravity of semi-trailer gross weight, H;

P_{jxi} – semi-trailer inertia force, H;

L_{nn} – semi-trailer wheelbase, mm;

B – bogie wheel tread, mm.

Therefore, as the force reactions along the semi-trailer bogie sides are changed, the resistance coefficient of steering the wheels of its axles from the normal load on the wheel is changed as well. In this case, D.A. Antonov dependence for determining the cornering force of the wheels of the semi-trailer bogie axles should be applied (*Antonov D.A., 1978*).

The braking torque, which occurs when braking the wheels of the semi-trailer bogie, is deduced by the formula:

$$M_{brk} = Z_{ext} \times \frac{B}{2} \times \varphi \quad [\text{N·m}] \tag{5}$$

where φ - adhesion coefficient of the semi-trailer bogie wheels, *φ = 0.6*;

B – semi-trailer bogie wheel-tread, mm.

In case of braking the one-axle wheels, the position of the axle is determined during the unstable pivoting movement of a long-haul truck. The change in the curvature sign is known to cause the change in the direction of normal acceleration, and hence, the side force (*Onishchuk V.P. and others, 2009*). The direction of normal acceleration is determined by the position of the absolute instantaneous turn centre, which (for the tri-axle semi-trailers under study) depends on the angles ratio of steering the bogie axle's wheels and its base. Braking the wheels of the bogie's one side can lead to the fact that the absolute instantaneous centre of a bogie turn, when coming into a corner and coming out of a corner, will be on different sides of the bogie axles. Changing the position of the absolute centre of a bogie turn relative to the semi-trailer movement trajectory indicates a change in the side force direction of the bogie mass centre, which coincides with the centre of the bogie relative angular velocity ω_T. Besides, when coming into a corner, the bogie side force is directed towards the centre of the bogie transfer angular velocity and when coming out of a corner - in the opposite direction.

The movement of the long-haul truck under study along the curvilinear (in plan) trajectory is the plane-parallel one. Therefore, the theorem on adding the rotations around parallel axles can be applied in studying the unsteady turn of the given long-haul truck (*Yablonsky A.A., 1971*). During the long-haul truck motion along the input transitional trajectory, Fig. 1 (a), the direction of relative angular velocity of the front steered axle coincides with the bogie transfer velocity direction. In this case, the magnitude of the axle absolute angular velocity is equal to the sum of the angular-rate components, that is:

$$\omega_1' = \omega_T' + \dot{\delta}_1' \tag{6}$$

where ω_T - relative angular velocity of the semi-trailer bogie;

$\dot{\delta}_1'$ – relative angular velocity of the bogie's front steered axle.

In this case, the absolute instantaneous turning centre is in the point O_{11}'.

Normal acceleration of the front axle can be determined as:

$$a_1' = V_1'\omega'_1 = V_1'\left(\dot{\delta}_1' + \omega_T'\right) \tag{7}$$

where V_1' - vector magnitude of the front axle velocity.

Additional side force $P_{\omega 1}'$ on the front axle acts from the rotation transfer centre O_2' and coincides in terms of direction with the force $P_{\omega c}'$.

Rear axle relative velocity $\dot{\delta}_3'$ does not coincide with the direction of the bogie's transfer velocity ω_T'. Therefore, at the beginning of a turn, the following ratio is deduced $\dot{\delta}_3' > \omega_T'$. Then, according to the theorem on adding the rotations around parallel axles, the absolute instantaneous turn centre in this section of the curvilinear motion will be at the point O_{31}', that is, further along the bogie longitudinal axle relative to its turn centre, at the point O_2'.

In this case, the magnitude of the rear axle absolute angular velocity is equal to the difference in the angular-rate components:

$$\omega_3' = \dot{\delta}_3' - \omega_T' \tag{8}$$

where $\dot{\delta}_3'$ – relative angular velocity of the given steered rear axle of the semi-trailer bogie.

Normal acceleration is deduced by the formula

$$a_3' = V_3'\omega_3' = V_3'\left(\dot{\theta}_3' - \omega_T'\right) \tag{9}$$

where V_3' - vector magnitude of the rear steered axle velocity;

$\dot{\theta}_3'$ - relative steering angle of the bogie rear steered axle.

The additional side force $P_{\omega 3}'$ on the rear steered axle will be directed from the absolute instantaneous centre of rotation O_{31}' to the centre O_2'. In this case, its direction is opposite to the direction of the side force on the semi-trailer bogie $P_{\omega c}'$.

The direction of relative velocity $\dot{\delta}_2'$ of a middle-steered axle depends on the angles ratio of steering the front and rear axles' wheels.

Whereas $\delta_1 > \delta_3$, the direction of the relative angular velocity $\dot{\delta}_2'$ coincides with the direction of the bogie's transfer velocity.

Then

$$\omega_2' = \omega_T' + \dot{\delta}_2' \tag{10}$$

$$a_2' = V_2'\omega_2' = V_2'\left(\omega_T' + \dot{\delta}_2'\right) \tag{11}$$

where V_2' - vector magnitude of the middle axle velocity.

$\dot{\delta}_2'$ – relative angular velocity of the bogie's middle steered axle.

The direction of additional side force on the middle axle $P_{\omega 2}'$ coincides with force $P_{\omega c}'$ direction.

When $\delta_1 < \delta_3$, the direction of the middle axle $\dot{\delta}_2'$ relative angular velocity does not coincide with the bogie transfer velocity direction. For this case, the following formulae are deduced:

$$\omega_2' = \dot{\delta}_2' - \omega_T' \tag{12}$$

$$a_2' = V_2'\omega_2' = V_2'\left(\dot{\delta}_2' - \omega_T\right) \tag{13}$$

Moreover, the additional side force will act in the opposite direction of the side force on the semi-trailer bogie.

When coming out of a corner in the given section of bogie trajectory, Fig. 1 (b), the direction of relative angular velocity $\dot{\delta}_1''$ of the front axle does not coincide with the direction of the bogie transfer velocity ω_T''.

Thus, the ratio $\omega_T'' > \dot{\delta}_1''$ is quite obvious, therefore, the absolute instantaneous turn centre is at the point O''_{11}, that is, apart the point O''_2. The absolute angular velocity of the front axle in this section of the path can be determined as:

$$\omega_1'' = \omega_T'' - \dot{\delta}_1'' \tag{14}$$

where ω_T'' - semi-trailer bogie transfer velocity;

$\dot{\delta}_1''$ – relative angular velocity of the front steered axle when coming out of a corner.

The normal acceleration is deduced by the formula:

$$a_1'' = V_1'\omega_1'' = V_1'\left(\omega_T'' - \dot{\delta}_1''\right) \tag{15}$$

The additional side force $P_{\omega 1}''$ when completing a turn in the curve section will act in the same direction as in the previous case, namely, it will act from the centre of the rotation transfer O_2''. Its direction also coincides with the direction of the bogie side force $P_{\omega c}''$.

The truck-tractor Scania P230 CB6 × 4ENZ equipped with the front steered axle and two rear-driving axles, and the carryall semi-trailer - container produced by Fliegl Company in structure of a long-haul truck are studied in this work (Onishchuk V.P. and others (2010)). Equations for determining the parameters of the curvilinear motion of the given long-haul truck under study are developed.

Based on the conducted calculations, the following conclusions have been drawn. First, the long-haul truck can move along the circular trajectories if the curve radius is bigger than the semi-trailer base. Second, a long-haul truck with an uncontrolled bogie ensures the OTL permissible value, which equals 7.3 m, only if the length of the long haul truck does not exceed 16.8 m (the maximum base of the semi-trailer does not exceed 7.0 m). Third, providing that the semi-trailer base exceeds the specified value, the bogie should be controlled both by the adjustable axle and by braking the wheels of one side.

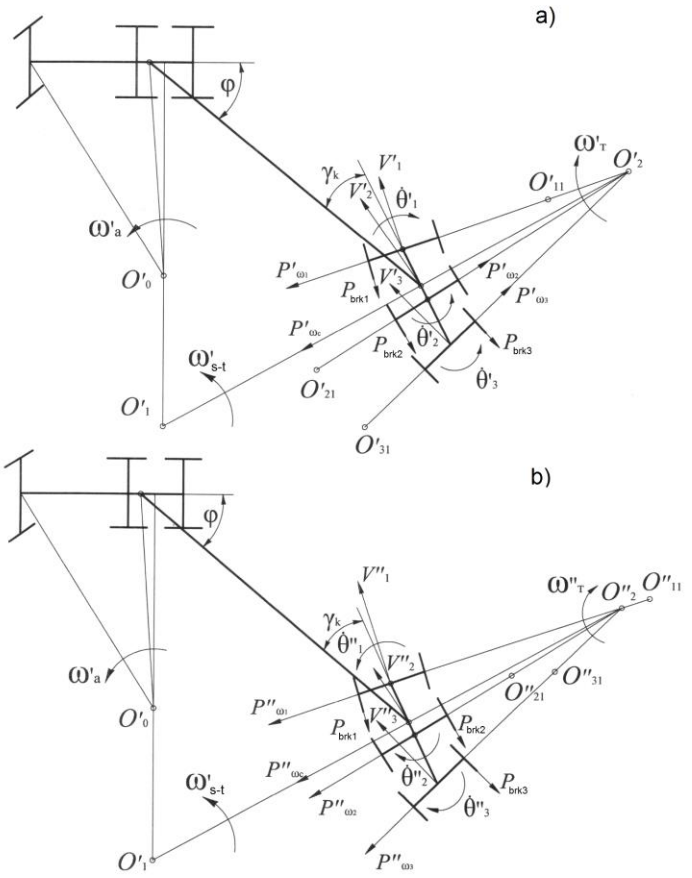

Fig. 1 - Scheme of turning a long haul truck with a dual control system of a semi-trailer bogie axle by braking the wheels of one side

RESULTS

The same change in the bogie trajectory curvature, Fig. 2, is achieved at various values of the braking forces applied to the wheels of its axles. At the same time, the weakest braking force should be applied to the rear axle wheels, somewhat stronger – to the front axle wheels, and much stronger – to the middle axle wheels.

The greatest rate of changing the trajectory curvature occurs during the first three seconds, and then its value stabilizes. It means the cessation of the transition process, meaning that the long haul truck goes to circular mode, Fig. 3.

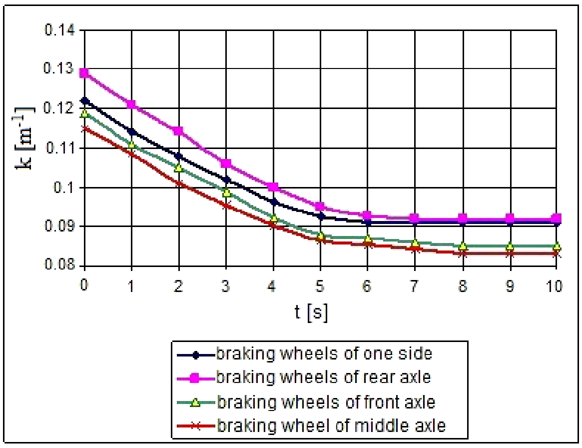

Fig. 2 - Dependence of semi-trailer trajectory curvature on the breaking torque of the bogie axles' wheels:

k – semi-trailer trajectory curvature, m^{-1}; t – time, s; braking torque, M_{brk} = 2,0 kH·m

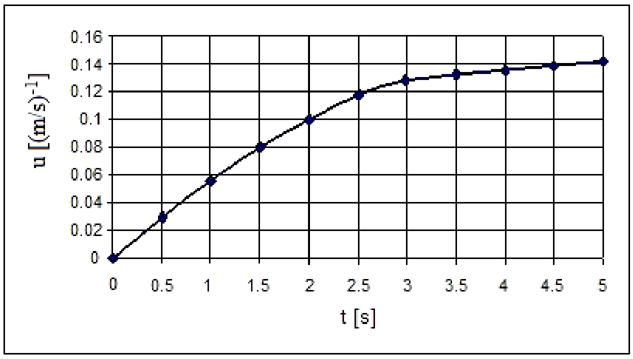

Fig. 3 - Rate of changing the trajectory curvature of a semi-trailer bogie in a time function of transition process:

u – rate of changing the semi-trailer trajectory, $(m/s)^{-1}$; t – time, s

The change in the semi-trailer bogie trajectory curvature due to braking the wheels of one side is advisable to use at the minimum turning radius of the tractor (from 15 to 20 m).

The turning radius increases, the efficiency of correcting the bogie trajectory by braking the wheels of one side decreases; after reaching 50 m, the difference in the turning radii of controlled and uncontrolled long-haul trucks does not exceed 10%.

CONCLUSIONS

The movement trajectory of the semi-trailer steered by braking the wheels of one side in an unsteady turn always consists of two sections, which differ in terms of curvature. Therefore, to correct the bogie trajectory, it is necessary to change the axle wheels that must be braked. Braking the wheels of the front axle changes the bogie movement trajectory the least. Therefore, braking the wheels of one side of the bogie rear axle is considered rational.

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