INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 17, ISSUE 1, 7749 – 7757
DOI: https://doi.org/10.15282/ijame.17.1.2020.21.0576

ORIGINAL ARTICLE

Research of a Truck Train Movement when Driving Semi-Trailer by Slow Downing Wheels of One Axis Pin on the Model

V. P. Sakhno[1], D. M. Yashchenko[1], R. M. Marchuk[2], N. M. Marchuk[2] and O. L. Lyashuk[3]

[1]Automobile Department, National Transport University, Suvorova Str., 1, Kiev, 01010 Ukraine.
[2]Automobile Department, National University of Water and Environmental Engineering, Soborna Str., 11, Rivne, 33002 Ukraine.
[3]Department of Automobile Transport, Ternopil Ivan Pul'uj National Technical University, 56 Rus'ka Str., Ternopil, 46001 Ukraine.

ABSTRACT – A free-running model of a truck train, which simulates a truck train consisting of a tow truck MAN TGS 19.360 and a biaxial semitrailer Utility VS2DC with a steerable front axis, has been developed. A semitrailer model is active with the wheel drive enables to control its movement by slow downing one of the wheels. The model was equipped with all necessary control equipment. It proved that driving a semitrailer by slow downing one of its wheels is identical to driving a semitrailer front axis with direct drive and a driver transmission ratio of 0.5. Differences in all cases have not exceeded 12% that is slowingdown one of the wheels of a semitrailer is reasonable for driving a truck train with a long base semitrailer.

ARTICLE HISTORY
Revised: 10th June 2019
Accepted: 12th Dec 2019

KEYWORDS
Truck train, Model, Semitrailer, Semi-trailer base, Braking moment, Locus, Speed, Shift.

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 organisations. The containers freight transportation is widely used around the world due to the high level of safety and the simplicity of customs registration. The modern motor-service for transporting containers has available a wide range of cars, trailers and semi-trailers the volumes of such transportations grow from year to year [1].

To transport 45-foot containers by carryall container trucks, it is necessary to elongate the long haul trucks. Such elongation decreases the vehicles' cornering performance. 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 [2].

Manoeuvrability indicators of a long-haul truck consisting of a carryall semi-trailer - container with an adjustable axle are defined in this work [3]. In particular, the long-haul truck with an adjustable axle proved to meet the requirements of Council Directive 96/53/EC and Directive 2002/7/EC for manoeuvrability. In previous work, [4] to ensure safe traffic conditions, which are regulated by international and national rules and standards, the dynamic parameters, in particular, stability and handling of the vehicles were studied. Rather sophisticated models for numerical simulation of vehicle dynamics on an uneven road are known [5-9].

In previous work [10], it was proved that a considerable performance improvement of a truck train agile handling with a long base semi-trailer can be reached when slow downing one of the wheels of rear-axis. In such way, with braking moment value in between 2 kNm on one of the rear axis wheels the locus curve of a semi-trailer increases by 33% and correspondingly the semi-trailer turning radius becomes less by the same value and its locus approaches the tow truck locus, which is identical to turning of the truck train with driven semi-trailer axis (wheels). However, the dependences require experimental check. Such checking was done on the scaled truck train model [11]. 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.

MATERIAL AND METHOD

A physical model is a reduced research object copy having the same physical properties as the original does, that is why it is the model under experiment. A mathematic model is not necessary for the physical model, so the calculations are simplified and data can be received directly from the research object using gauges, recording elements, and movement can be done with actuating mechanisms [12].

A model of a truck train consists of a tow truck model and a semi-trailer is shown in Figure 1. The base for the tow truck model was chosen as a long-haul truck MAN TGS 19.360. This is the vehicle with wheel arrangement of 4×2. Its unladen weight is 6790 kg, load capacity for long-haul coupling mechanism is 12210 kg. Its length makes up 5872 mm, its track width is 2240 mm, and seat height is 1185 mm. The base for calculation of a semi-trailer model is a biaxial semi-trailer Utility VS2DC with steerable rear axes. The length of its body is 16154 mm, its wheel base is 8075 mm, its total width is 2600 mm, its coupling height is 1190 mm. Full truck train weight is 22 tons.

*CORRESPONDING AUTHOR | R. M. Marchuk | ✉ r.m.marchuk@nuwm.edu.ua

First of all, in order to develop the model it is needed to define element dimensions (dimensional or non-dimensional number) and derivative (which numbers will be taken as basic ones and which can be defined from others). To study mechanical features it is enough to enter three basic measurements: for length, weight or power, and time. Dependence of derivative number measurement from basic numbers' measurements can be shown as a dimensional formula. The most spread dimensional system for now is CGS which is used to determine physical similarity. In this dimension system all measurements look like exponential monomial:

$$L^l M^m T^t \tag{1}$$

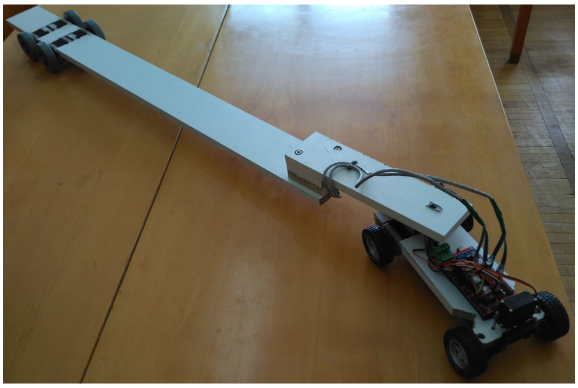

Figure 1. A truck train model with a steerable coupling link.

When calculating similarity it is common to use π-theorem according to which model construction requires and has enough $p=n-k$ of non-dimensional numbers, where n is a quantity of physical variables which are described with the help of k of fundamental measurements. It comes out from π-theorem that if two dynamic systems are described with the same differential equations, the solution of differential equations will be scale unchangeable for the same π groups. So that the model was dynamically similar to original, numbers of these π groups should be equal for both systems. On the basis of this idea it is possible to pick out model sizes which correspond to real ones [13-15].

Selected scale is 1:20. Chassis length of the real and the reduced vehicle is fixed. The length of the tow truck model is 280 mm, its wheel base is 210 mm, its track is 145mm, its seat height is 60 mm. The length of the semi-trailer is 1170 mm, distance from the coupling point with the tow truck to the first axes can be changed within 370-570 mm, its wheel base is 100 mm, its track is 140 mm. A model tire size is counted by equating of π group that corresponds to the tire size of the reduced copy to π group of the real vehicle that is:

$$(R/l)_{original}=(R/l)_{model} \tag{2}$$

The tow truck tire size is 315/80 R22.5; the semi-trailer has tires 385/65 R22.5. By inserting the original measurements we get R_{model}=62 mm. Tire width of the tow truck model is 25 mm, of the semi-trailer is 20 mm. To count the model weight we suppose that the model's and original's densities are the same:

$$(\rho l^3/m)_{model}=(\rho l^3/m)_{original} \tag{3}$$

Then from the similarity we receive unladen weight of the tow truck model of 2.1 kg, weight of the semi-trailer model with maximal load of 4.5 kg. The tow truck base is made of 2 mm chipboard. This material is easily processed, enables to change elements fast and easy and adjust fixing for reading devices. The most appropriate from existing wheels as to sizes were chosen for driving axes, their width makes up d=25 mm, their radius is R=62 mm. The turn is driven by a servo controlled drive MG995 in Figure 2(a), which makes steering arm strut moving, which in its turn turns wheel pins. The model is driven by two stepped motors 17HS8401 in Figure 2(b), from which the torque is passed to driven wheels of the tow truck. Stepped motor 17HS8401 is a commutatorless 2 – phase motor with maximal torque of 0,52 N·m, motor weight is 0,37 kg. Engines work from power of 12-24 V.

Tires of driving wheels have diameter of 62 mm and width of 25 mm, as it is the nearest similarity to the necessary sizes among existing wheels. With materials chosen for truck train elements production the tow truck weight makes up 0.7 kg, that is why additional load of 0.8 kg on the front part of model is used during the ride.

The semi-trailer model is made of chipboard. Front overhang is shortened because of steering rod installation which is situated on the tow truck. Gauge of turning angle, which is used to measure bending angle between the tow truck and the semi-trailer, works as coupling pivot axel. In this system we use the analog rotation gauge shown in Figure 2(c), Arduino which is a compliant rotation gauge, its maximal turn angle is 270°, its measuring accuracy is 0,2°. The gauge is connected in three contacts: to power of 5V, to earth and to analog inlet of a microcontroller. In the truck train model rotation gauge is firmly fixed on the semi-trailer, and its torque works as a pivot axel which is put in the semi-trailer coupling device and is fixed in it. Gauge handle location corresponds the direction of the tow truck during movement, and card location corresponds to the direction of the semi-trailer. In such a way, gauge readings are equal to the angle of the truck train bending.

Wheels with tires width of d = 20 mm and radius R = 75 mm are used on the semi-trailer. Stepped motors 17HS8401 are installed on the wheels of the first and the second axis. Weight of the semi-trailer makes up 1.2 kg, and weight on the semi-trailer axes makes up 0.8 kg. Truck train speed and turn during kinematic way of driving (by turning of the semi-trailer front axes) is given by operator with the help of a control board. Signals from the remote control are transmitted to the card microcontroller Atmel 2560 for programming of Arduino Mega 2560 shown in Figure 2(d). In its turn, after processing of these signals and performing of given algorithms of the movement, it transmits the signal to the engines drive A4988 in Figure 2(e). For the installation of drivers we use coordinating card Ramps 1.4 in Figure 2(f). Peculiarities of A4988 are the adjustable current, high-voltage and overheat protection. This driver also has five variants of microstep (up to 1/16 of a step), it works from the voltage of 8-35 V, and it can provide current up to 1A.

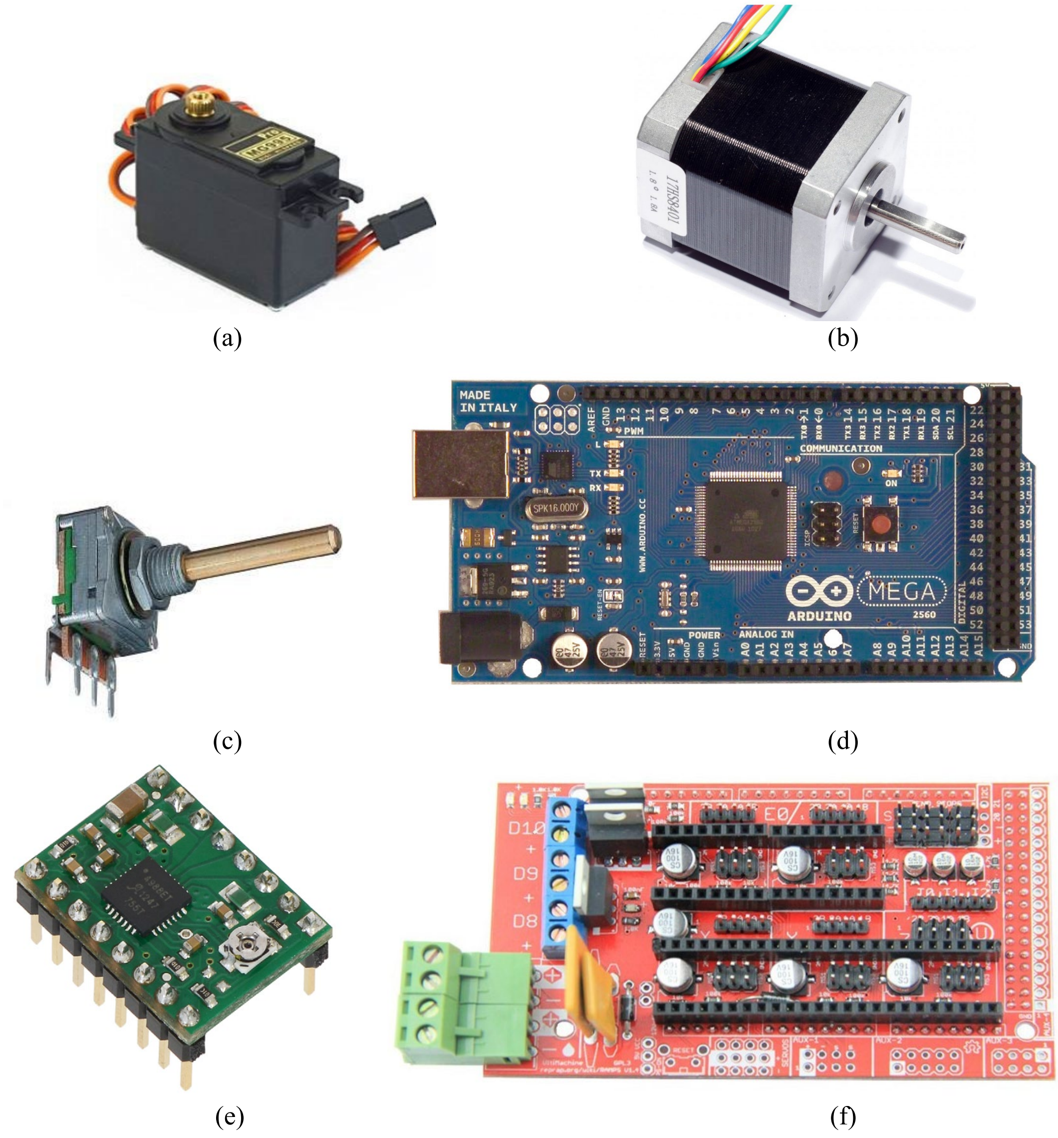

Figure 2. (a) Servo controlled drive MG995, (b) stepped motor 17HS8401, (c) rotation gauge, (d) microprocessor card, (e) engines drive A4988 and (f) ramps card 1.4.

After signal amplification the steering wheel and the semi-trailer front axes driving takes place during kinematic way of turning and also by wheels' drivers of the semi-trailer axes during dynamic way of turn. Microcontroller allows programing necessary actions of the engine work on programming language C++ Program is designed in such a way. First, the speed parameter is checked; second, the wheel turn parameter is checked if the truck train moves forward then only engines of the semi-trailer drive wheels work. If the wheels turn parameter is changed and the truck train should turn, then a turning signal is given to the semi-trailer front axis servo controlled drive (MG995). Output spindle of servo controlled drive revolves for about 120 degrees and has maximal torque of 0,85 N×m. To drive MG995 any controllers with power of 5 V can be used.

In a dynamic way of turn and depending on the truck train speed the frequency of wheels rotation of one of the semi-trailer's sides increases, herewith, the opposite side begins to lowering the frequency of wheels rotation, in such a way semi-trailer precision steering takes place depending on the angle of the turn and the truck train speed.

Paying attention to the fact that the model was developed to estimate the truck train maneuver effectiveness taking into account the developed driving law for the semi-trailer rear axis moving with small speed, elements of arbor support were not designed. Software of the designed truck train consists of a program recorded straightforward into the microcontroller Arduino and after successful compilation the program of the model driving is transmitted into the processor by the means of a virtual COM port. It allows the dialogue with the user entering commands from the keyboard to make a movement, wheel turn or definite maneuvers. Data about turning angles of driving wheels, bending angle, direction and side of movement are shown each 2 seconds.

Two external libraries are used in the driving program. AccelStepper.h and Servo.h which are used for the motor card work with direct current engines and servo controlled drivers correspondingly. A monitor installed into development area allows realizing backlink with the card in the process of program fulfillment. Transmission of commands to processor and also reading and displaying of data is possible. Experiment program included determining of the semi-trailer locus deviations as to the tow truck locus when the truck train moves in a circle locus, when doing maneuvers such as "turn" and "elk test" when the semi-trailer base and braking moment on one of the wheels are changed.

RESULTS

To trace locus of characteristic points' movement, red diodes for the tow truck axes and green one for semi-trailer axes are installed on them. There is a camera SJCAM SJ5000 above testing stand which makes pictures in the given time periods. Received pictures are processed by the program, all except markers is dropped out from the picture. Then received points are grouped with rides and by connecting them it is possible to receive the locus of movement of characteristic model points for each test ride.

More than 10 pictures were done for each ride. Results of 4 test rides for the truck train with the semi-trailer base of 370 mm in case of absence of braking moments on one of the semi-trailer wheels is shown on Figure 3. Points on this scheme correspond to the location of characteristic points at the moment of taking pictures. Approximate locus of movement of driving axes middle was defined as a middle between the points which are the nearest and the furthest from the center of the made circle. Averaged movement locuses of both markers have slight deviations, that is, that the model behavior can be taken as adequate for circle maneuver. Deviations between calculated and experimental numbers of the semi-trailer shifting according to the tow truck locus do not exceed 5.2%.

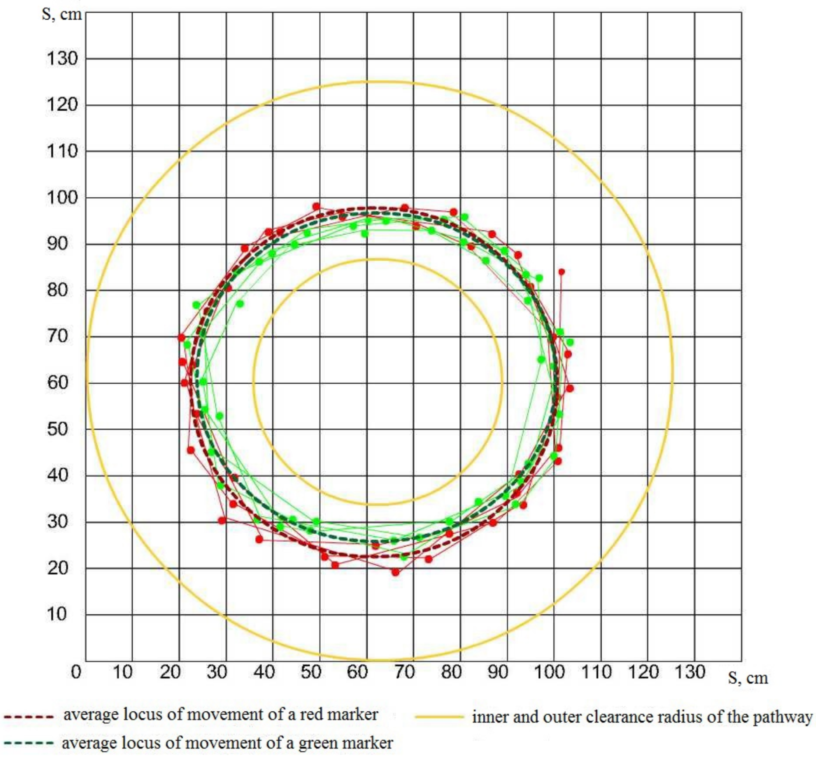

Figure 3. Results of round rides.

Methods of experiment planning were applied on one of the semi-trailer wheels to analyze the influence of a semi-trailer base and braking moment. During experiment planning the following factors were checked: semi-trailer base, braking moment on one of the semi-trailer wheels, truck train speed. Since all mentioned factors correspond to the demands as to factors that are used during planning of experiment [16] (driver, simple, directly effect the object, defined operationally, non-correlational, possibility of different combination installation) they can be used as factors in the experiment.

Maximal and minimal numbers, that is, changing intervals, are set for each factor. For the semi-trailer base L_n minimal value corresponds to typical base size of modern semi-trailers, maximal one comes out of the condition of maximal truck train length according to Traffic Regulations of Ukraine (22 m). For breaking movement M_r maximal value is chosen between 0.5 N·m (maximal moment on wheel in reverse mode), minimal one is 0 (without any breaking moment on the wheel). For truck train speed V_{an} maximal value realized in the model makes up 1.5 m/s (for real truck train it is 30 m/s), minimal one corresponds to minimal stable truck train speed of 0.1 m/s. Corresponding values of factors are given in Table 1.

Table 1. Factor change intervals.

Factors	Minimum (X_{imin})	Maximum (X_{imax})	Naught level
Semitrailer base (mm)	370	570	470
Breaking moment (N.m)	0	0.50	0.25
Truck train speed (m/s)	0.10	1.50	0.80

For considerable simplification of further calculation we will come from natural factors to coded ones. Receiving [16-17]:

$$X_{0i} = 0,5(X_{i\max} + X_{i\min}) \tag{4}$$

$$\chi = \frac{1}{\Delta X_i} \tag{5}$$

$$\Delta X_i = 0,5(X_{i\max} - X_{i\min}) \tag{6}$$

where X_{0i} - factor's zero points; ΔX_i - half range of factor's change. Change from coded variables to natural ones and vice versus is done according to the next dependence:

$$x_i = \frac{X_i - X_{i0}}{\Delta X_i}, \tag{7}$$

$$X_i = x_i \Delta X_i + X_{i0}, \tag{8}$$

where X_i, x_i – natural and coded factor number correspondingly. Experiment task is to receive regression equation which looks like the following using of three factors [18]:

$$\begin{aligned} Y = {} & b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + {}, \\ & + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \end{aligned} \tag{9}$$

where b_{ij} – regression coefficient and x_1, x_2, x_3 – factors. To make the coding, the value X_{imax} corresponds to coded value "+1", and "-1" corresponds to the value X_{imin}. In Table 2 (coded factor values, natural factor values) a matrix of orthogonal plan of the second degree of a complete factor experiment is given, in which three factors are changed on two levels (FFE^3 – full factorial experiment) [18]. The values of the semi-trailer locus shifting as to the tow truck locus on the truck train circle movement during three repetitions are given in Table 3.

Experiment results were processed according to Table 3. Regression coefficients were calculated according to dependences [17-18]:

$$b_0 = \frac{1}{N}\sum_{u=1}^{N} y_u, \qquad b_i = \frac{\sum_{u=1}^{N} x_{iu} y_u}{\sum_{u=1}^{N} x_{iu}^2}$$
$$b_{ij} = \frac{\sum_{u=1}^{N} x_{iu} x_{ju} y_u}{\sum_{u=1}^{N} \left(x_{iu} x_{ju}\right)^2} \qquad b_{ii} = \frac{\sum_{u=1}^{N} x'_{iu} y_u}{\sum_{u=1}^{N} \left(x'_i\right)^2} \tag{10}$$

where y_u – state change, that is a value of the semitrailer locus shifting as to the tow truck locus, x_{iu}, x_{ju} – coded factor numbers of corresponding research, x'_i – fixed numbers (given in Table 4) and N =15 – total quantity of experiments. As a result of calculations such coefficient data were received: b_0=-7.0191; b_1=-4.7551; b_2=-3.0918; b_3=15.1602; b_{11}=1.2551; b_{22}=0.1511; b_{33}=0.0651; b_{12}=-1.2511; b_{13}=-2.1751; b_{23}=0.4201; b_{123}=0.4995.

Table 2. FFE matrix organisation.

№	Coded factor values				Natural factor values		
	X_0	X_1	X_2	X_3	L_s, mm	M_t, N×m	V_{tt}, m/s
1	+1	+1	+1	+1	570	0.5	1.5
2	+1	-1	+1	+1	370	0.5	1.5
3	+1	+1	-1	+1	570	0.5	1.5
4	+1	-1	-1	+1	370	0.5	1.5
5	+1	+1	+1	-1	570	0.5	0.1
6	+1	-1	+1	-1	370	0.5	0.1
7	+1	+1	-1	-1	570	0	0.1
8	+1	-1	-1	-1	370	0	0.1
9	+1	+1.215	0	0	692.55	0.25	0.80
10	+1	-1.215	0	0	449.55	0.25	0.80
11	+1	0	+1.215	0	470	0.6075	0.80
12	+1	0	-1.215	0	470	0	0.80
13	+1	0	0	+1.215	470	0.25	1.8225
14	+1	0	0	-1.215	470	0.25	0.1215
15	+1	0	0	0	470	0.25	0.8

Table 3. Values of the semi-trailer locus shifting as to the tow truck locus.

№	Semi-trailer base, $L_п$ (mm)		Torque moment (N.m)		Truck train movement speed (m/s)		Shifting during repetitions (mm)			
							first	second	third	average
	x_1	X_1	x_2	X_2	x_3	X_3	Δ_1	Δ_2	Δ_3	Δav
1	1	5.7	1	0.5	1	1.5	73	69	71	71
2	-1	3.7	1	0.5	1	1.5	52	50	54	52
3	1	5.7	-1	0	1	1.5	79	77	81	79
4	-1	3.7	-1	0	1	1.5	58	60	62	60
5	1	5.7	1	0.5	-1	0.1	66	70	68	68
6	-1	3.7	1	0.5	-1	0.1	48	50	52	50
7	1	5.7	-1	0	-1	0.1	76	78	74	76
8	-1	3.7	-1	0	-1	0.1	55	57	53	55
9	1.215	6.9	0	0.25	0	0.80	79	81	83	81
10	-1.215	4.5	0	0.25	0	0.80	67	69	65	67
11	0	4.7	1.215	0.6075	0	0.80	65	63	61	63
12	0	4.7	-1.215	0	0	0.80	69	73	68	70
13	0	4.7	0	0.25	1.215	1.8225	68	66	67	67
14	0	4.7	0	0.25	-1.215	0.1215	62	63	61	62
15	0	4.7	0	0.25	0	0.8	65	65	62	64

Table 4. Fixed parameter numbers

№	x'_1	x'_2	x'_3	№	x'_1	x'_2	x'_3
1	0.27	0.27	0.27	9	0.746	-0.73	-0.73
2	0.27	0.27	0.27	10	0.746	-0.73	-0.73
3	0.27	0.27	0.27	11	-0.73	0.746	-0.73
4	0.27	0.27	0.27	12	-0.73	0.746	-0.73
5	0.27	0.27	0.27	13	-0.73	-0.73	0.746
6	0.27	0.27	0.27	14	-0.73	-0.73	0.746
7	0.27	0.27	0.27	15	-0.73	-0.73	-0.73
8	0.27	0.27	0.27	-	-	-	-

Check of dispersion equal accuracy is done according to Cochran's test:

$$G_p < G_T(q, f_1, f_2), \tag{11}$$

where $G_p = \frac{s^2_{u\max}}{\sum_{u=1}^{N} s^2_u}$ – estimated value of Cochran's test, G_T – theoretical value of Cochran's test (chosen according to tables depending on numbers q, f_1, f_2), q=0.05 – significance level, $f_1 = m - 1 = 3 - 1 = 2$, $f_2 = N = 15$ – number of degrees of freedom, m = 3 – quantity of parallel researches, $s^2_u = \frac{1}{m-1}\sum_{k=1}^{m}(y_{uk} - \overline{y}_u)^2$ - line-by-line dispersion, and $\overline{y}_u = \frac{1}{m}\sum_{k=1}^{m} y_{uk}$ - average value of state variable. By making all necessary calculations and by comparing theoretical and calculated value of Cochran's test (Table 5) we make a conclusion about dispersion equal accuracy. Regression coefficients for significance was checked according to student's coefficient.

$$t_{ip}, t_{ijp}, t_{iip} > t_{Ò}(q, f), \tag{12}$$

where $t_{ip} = \frac{|b_i|}{s_{b_i}}, t_{ijp} = \frac{|b_{ij}|}{s_{b_{ij}}}, t_{iip} = \frac{|b_{ii}|}{s_{b_{ii}}}$ - estimated value Student's coefficient, t_T =2.04 – theoretical value of Student's coefficient (chosen according to tables depending on numbers q, f), $f = N(m-1) = 30$ – number of degrees of freedom; $s^2_{b_0} = \frac{s^2_0}{N}, s^2_{bi} = \frac{s^2_0}{\sum x^2_{iu}}, s^2_{bij} = \frac{s^2_0}{\sum (x_{iu}x_{ju})^2}, s^2_{bii} = \frac{s^2_0}{\sum (x'_{iu})^2}$ – dispersions of regression coefficient, and $s^2_0 = \frac{1}{N}\sum_{u=1}^{N} s^2_u$ – experimental error.

By making calculations of corresponding values of Student's coefficient (Table 5) and by comparing them with table values, we receive the following significant regression coefficients: b_0=-7.0191; b_1=-4.7551; b_2=-3.0918; b_3=15.1602; b_{11}=1.2551; b_{12}=-1.2511; b_{13}=-2.1751; b_{23}=0.4201; b_{123}=0.4995. Let's check regression equation for correspondence with the help of Fisher's ratio test:

$$F_p < F_T(q, f_{ad}, f_0), \tag{13}$$

where FT – table value of Fisher's ratio test (chosen according to tables [18] depending on numbers q, fad, f0), $F_p = \frac{s^2_{ad}}{s^2_o}$ – estimated value of Fisher's ratio test, $s^2_{ad} = \frac{1}{N-1}\sum_{u=1}^{N}\left(\overline{y_u} - \tilde{y}_u\right)^2$ – dispersion of adequacy, $\tilde{y}$ – change of state, which is received from regression equation, $f_{ad} = N - l$=15 – 9 = 6, $f_0 = m - 1 = 3 - 1 = 2$ - number of degrees of freedom and l = 9 is quantity of regression members which are left.

Having the calculated corresponding values (table 5) and compared calculated and table value of Fisher's ratio test we can make a conclusion about correspondence of regression equation.

Table 5. Calculated values when processing experiment results

Calculated value of Cochran's test, G_p		0.3119
Table value of Cochran's test, G_T		0.3346
Calculated value of Student's test	t_{0p}	364.32
	t_{1p}	43.49
	t_{2p}	26.73
	t_{3p}	136.10
	t_{11p}	7.27
	t_{22p}	0.87
	t_{33p}	0.37
	t_{12p}	9.78
	t_{13p}	16.88
	t_{23p}	3.22
	t_{123p}	3.68
Table value of Student's test, t_T		2.04
Calculated value of Fisher's test, F_p		2.31
Table value of Fisher's test, F_T		2.42

In such a way regression equation for the semitrailer locus shifting as to the tow truck locus has the following appearance:

$$\Delta=7.091+4.7551x_1+3.0918x_2-15.1602x_3-1.2551(x_1)^2+1.2511x_1x_2+2.1751x_1x_3-0.4201x_2x_3-0.4995x_1x_2x_3. \tag{14}$$

Let's move from an equation in coded values to an equation in natural values. We receive:

$$\Delta=56.102-27.075L_s+3.0918M_t-15.1602\,V_{tt}-1.2551(L_s)^2+1.2511\,L_s\,M_t+ \\ +2.1751\,L_s\,V_{tt}-0.4201\,M_t\,V_{tt}-0.4995\,L_s\,M_t\,V_{tt} \quad (15)$$

To define an experiment error for the value, which is calculated according to the measured values the following dependence is used [17-18]:

$$p_{\tilde{A}}^2=\left(\frac{\partial^2\Delta}{\partial x}\right)^2\cdot p_x^2+\left(\frac{\partial^2\Delta}{\partial y}\right)^2\cdot p_y^2, \quad (16)$$

where p_{Γ}^2 – value definition error Δ, p_x – relative error of X value defining, p_x – relative error of Y value defining and $\left(\frac{\partial^2\Delta}{\partial x}\right)$, $\left(\frac{\partial^2\Delta}{\partial y}\right)$ – partial derivatives. In our case Δ value is the semi-trailer locus shifting as to the tow truck locus. Then outcoming equation to find an error is:

$$p_{\Delta}^2=\left(\frac{\partial^2\Delta}{\partial L}\right)p_L^2+\left(\frac{\partial^2\Delta}{\partial M}\right)p^2 \quad (17)$$

Let's find components of the equation: $\left(\frac{\partial^2\Delta}{\partial L}\right)=-\frac{M}{L^2+M^2}$ and $\left(\frac{\partial^2\Delta}{\partial M}\right)=\frac{L}{L^2+M^2}$. Relative error is calculated according to the next dependence: $p_L=\frac{\Psi_L}{X}$ and $p_M=\frac{\Psi_M}{Y}$, where Ψ_L, Ψ_M – are absolute errors of measuring of correspondingly L and M. Absolute errors are instrument precision or half of the lowest graduation on the instrument scale. Measurement L was done with a tape measure with a half of the lowest graduation; $\Psi_L=\frac{1}{2}=0.5$ mm. Measurement M was defined from drive 17HS8401 characteristic and made up; $\Psi_M=0{,}05\ N\cdot m$.

Then, $p_{\Delta}=\left(-\frac{Y}{X^2+Y^2}\right)^2\times\left(\frac{0.5}{X}\right)^2+\left(-\frac{X}{X^2+Y^2}\right)^2\times\left(\frac{0.05}{Y}\right)^2$. The biggest error value of p_{Δ}, which was received according to the data from Table 3 makes up 0.67%. Values of the semi-trailer locus shifting as to the tow truck locus defined according to the Equation. (15) were compared with the same shifting received by driving the semi-trailer front axis with the help of direct drive and gear ratio of the drive 0.5. Differences in all cases did not exceed 12% that is slowing down of one of the semi-trailer wheels is identical to driving the semi-trailer front axis.

CONCLUSION

A free running model of the truck train, which simulates a truck train consisting of a tow truck MAN TGS 19.360 and a biaxial semi-trailer Utility VS2DC with steerable front axis, has been developed. The model is equipped with all necessary control equipment. Model software enables to realize an algorithm of semi-trailer rear axis driving, into the based on coincidence of locuses of characteristic points of the tow truck and the semi-trailer. Installed that driving of a semi-trailer by slowdowning of one of its wheels is identical to driving of the front semi-trailer axis with a direct drive and a driver transmission ratio of 0.5. Data about turning angles of driving wheels, bending angle, direction and side of movement are shown each 2 seconds. For truck train speed V_{an} maximal value realized in the model makes up 1,5 m/s (for real truck train it is 30 m/s), minimal one corresponds to minimal stable truck train speed of 0.1 m/s. On the basis of experimental studies, there were derived complex regression relationships to determine the semi-trailer locus shifting as to the tow truck locus. The biggest error value of p_{Δ}, makes up 0.67%. Differences in all cases did not exceed 12% that is slowingdown of one of the wheels of semi-trailer is potential for driving of the truck trains with long base semi-trailers.

REFERENCES

[1] Onishchuk VP. Marchuk RM, Pridyuk VM. To the analysis of lorry convoy design for ontainer transportation, Collection of reports 13 International scientific and practical conferences: Market of services of complex transport systems and applied problems of logistics. Kiev: 2011;180-182.

[2] Kuts NG, Sakhno VP, Timkov OM. Drives control of modern lorry convoys, Avtoshliakhovyk Ukrainy, Separate release, Bulletin of the TAU. 2003;5:78-79.

[3] Bodnaruk VB, Sakhno VP, Krestyanpol EA. On definition of manoeuvrability indicators of long haul truck with the adjustable axle of semi-trailer. System methods of management, technology and the organization of production, repair and operation of cars, Collection of scientific works. UTU, TAU. Kiev :1998;45-50.

[4] 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.

[5] Taghavifar H, Mardani A. Off-road vehicle dynamics: analysis, modelling and optimization. Switzerland: Springer International Publishing; 2017.

[6] Gillespie TD. Fundamentals of vehicle dynamics. Society of Automotive Engineers: Warrendale PA. 1992.

[7] Rill G. Road Vehicle dynamics: fundamentals and modeling. CRC Press, Boca Raton FL; 2012.

[8] Pečeliūnas R, Lukoševičienė O, Prentkovskis O. A mathematical model of the vibrating system equivalent to the vehicle in the mode of emergency braking. Transport. 2003;18:136-142.

[9] Sokil B, Lyashuk O, Sokil M, Popovich P, Vovk Y, Perenchuk O. Dynamic effect of cushion part of wheeled vehicles on their steerability International Journal of Automotive and Mechanical Engineering. 2018;15(1): 4880-4892.

[10] Sakhno VP, Marchuk MM, Marchuk RM. Study of long haul truck movement along the curviliniar trajectory while steering a carryall semi-trailer – container by braking the wheels of one axle. INMATEN – Agricultural Engineering, 2017;52:107-113.

[11] Sakhno V, Yashchenko D, Timkov O, Korpach O, Bosenko V, Lysenko O. Hybrid truck train movement maneuverability research for a combined method of managing a semi-trailer on a model. Systemy i Srodki Transportu Samochodowego. Badania, Konstrukcja i Technologia. Wybrane zagadnienia. 2017;8:107-116.

[12] Engelezi OA. Truck train kinematics rotation investigation on a physical model. Project Management, System Analysis and Logistics. 2008; 5: 105-110

[13] Prydiuk VM. Experimental installation of a container trailer to explore its maneuverability. Scientific notes, 2010; 28: 466-472.

[14] Onyshchuk VP. Automated complex for the studying of the experimental truck train for container transportation movement parameters. LNTU: Scientific notes, Lutsk, 2011.

[15] Humeniuk PO. Experimental truck train for container transportation. Transport problems. 2012;9:181-186.

[16] Wu C, Hamada M. Experiments: Planning, analysis, and parameter design optimization. New York: Wiley: 2000.

[17] Adler UP, Markova EV, Hranovsky UV. Design of experiments in the search for optimal solutions. Moscow : Science: 2002.

[18] Dushinsky VV. Basics of the scientific research. Kyiv: High school; 2002.