

# Increasing the stability of the articulated lorry at braking by locking the fifth wheel coupling

G I Skotnikov, M M Jilevkin and A I Komissarov

Department of Wheeled Vehicles, Bauman Moscow State Technical University,  
Moscow, 105005 Russian Federation

E-mail: skotnikovg@bmstu.ru

**Abstract.** The jackknifing of the articulated lorry is determined by the loss of stability with respect to the vertical axis of the fifth wheel coupling, which can be caused by the failure of the brake system, the displacement of the center of mass of the semitrailer or tractor from the longitudinal axis of the vehicle, the road parameters (longitudinal and transverse slopes), the difference in the friction coefficients under the sides of the articulated lorry. In this regard, the issue of creating devices that prevent the jackknifing, and their control systems is important. A method is proposed for maintaining the stability of the movement of articulated lorry when braking both on a straight line and in a turn by blocking the relative rotation of the tractor and the trailer. Blocking occurs due to the creation of a stabilizing moment in the direction opposite to the angular rate of folding. To test the developed algorithm for locking the fifth wheel coupling, a mathematical model of the spatial motion of the articulated lorry was developed, including the models of interaction of an elastic tire with a rigid terrain, suspension systems, transmission, steering, fifth-wheel coupling. The efficiency and effectiveness of the coupling locking control system is proved by comparing the results of the simulation of a straight-line braking and braking in turn. It is shown that the application of the control system significantly increases the stability of the road train.

## 1. Introduction

At emergency braking of articulated lorry even on a road with a high coefficient of friction, stability loss in the form of jackknifing is possible. Jackknifing is the loss of the stability of the towing vehicle and (or) the semi-trailer when braking, when the angle between the longitudinal axes of the tractor and the trailer (the folding angle) exceeds the value necessary for driving along the trajectory specified by the driver. Jackknifing can be caused by the failure of the brake system, the displacement of the center of mass of the trailer or the tractor from the longitudinal axis of the vehicle, road parameters (longitudinal and transverse slopes), difference in the friction coefficients under the sides of the articulated lorry. This type of loss of stability may lead to the lane departure, which can in turn lead to collision with the other vehicles, including those moving in the opposite direction. Modern active safety systems, such as the anti-lock braking system "ABS", the electronic stabilization system "ESP" and others significantly improve the stability of the articulated lorry, but do not exclude the danger of jackknifing, in this connection, the issue of developing systems and devices which would eliminate this effect [1] is of great importance.



As the analysis of patents has shown, there are several ways of fixing the relative rotation of the tractor and the semi-trailer around the pin axis: by equipping the fifth wheel coupling with elements the position of which significantly limits the folding angle; by equipping the fifth wheel coupling with friction mechanisms that limit the folding speed to a full stop in a wide range of folding angles. The drawbacks of the first embodiment are the impacts caused by the selection of the gaps between the fixing elements, as well as the impossibility of locking the coupling device during cornering with a predetermined folding angle, so the second method is more preferable.

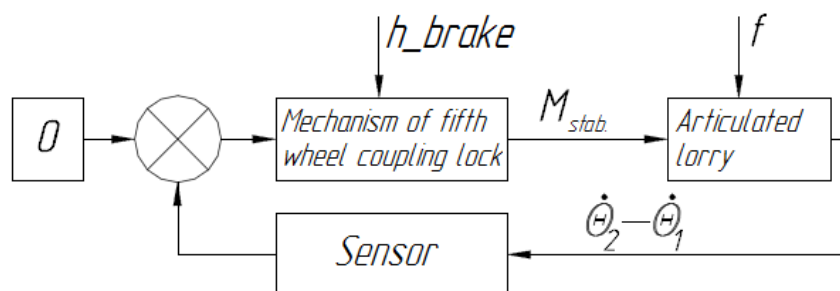
The aim of the work is the development of a system that increases the stability of the movement of an articulated lorry when it brakes both on a straight line and in a turn by locking the fifth wheel coupling.

## 2. Description of the developed algorithm

The control system of the locking mechanism of the fifth wheel coupling is a closed loop system. External disturbance  $f$  (figure 1) causes the jackknifing, while the folding speed increases. The angular speed  $\dot{\theta}_2 - \dot{\theta}_1$  of rotation of the semitrailer relative to the tractor around the axis of the kingpin is measured by the sensor and compared with zero.

Based on the received signal  $h\_brake$  from the comparison unit and the signal of the driver pressing the brake pedal, the proportional regulator generates a control action, which by the locking mechanism is converted into a stabilizing moment  $M_{stab}$ , which prevents the jackknifing of the articulated lorry. The magnitude of the moment is proportional to the angular velocity of the folding. One of the possible ways to meet the requirements set by the developed control system is to install a mechanism similar to the wheel brake on the fifth wheel coupling of the tractor. In this case, the direction of the stabilizing moment will be provided by the direction of the frictional forces, and the magnitude - by the degree of pressing of the brake pads.

The folding rate control as contrasted to the angle control used by many researchers makes it possible to stabilize the movement of the articulated lorry not only when braking on a straight line, but also when braking on a curved trajectory, when the probability of loss of stability is much higher.



**Figure 1.** Block diagram of the control system of the locking mechanism of the fifth wheel coupling.

The law of operation of the control system is determined by the following equation:

$$\begin{cases} h\_brake = 0 & M_{stab} = 0; \\ h\_brake = 1 & M_{stab} = P(\dot{\theta}_2 - \dot{\theta}_1); \end{cases} \quad (1)$$

0 value of  $h\_brake$  means that the brake pedal is not pressed, 1 – that it is pressed;  $P$  – coefficient of proportional regulator.

Verification of the efficiency and efficiency of the algorithm was carried out by simulation, for this, a mathematical model of the spatial motion of the road train was used.

### 3. Description of the mathematical model.

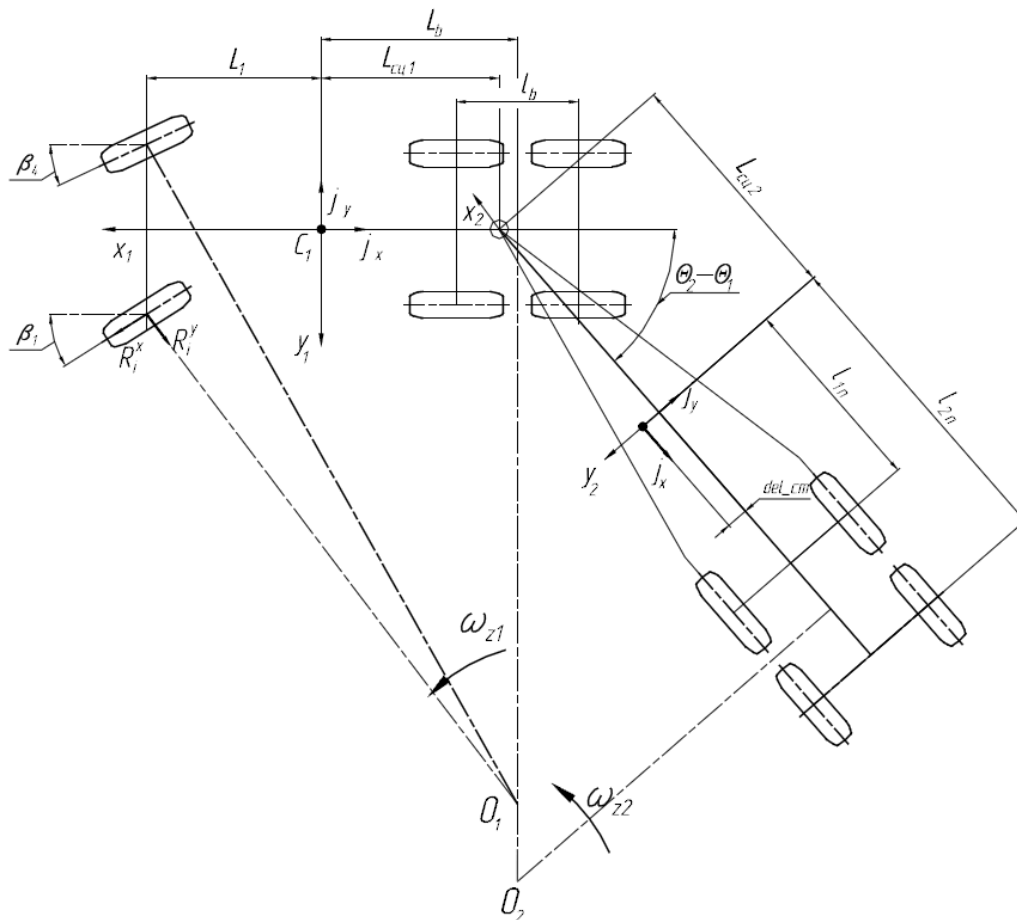
The spatial motion of an articulated lorry, consisting of a three-axle vehicle – a tractor, and a two-axle semi-trailer (figure 2), is regarded as the motion of two bodies connected by a hinge. The simulation model includes the model of interaction of an elastic tire with a rigid terrain, models of dependent and balanced tractor and semitrailer suspensions, model of the tractor transmission, steering, braking system and fifth wheel coupling.

In accordance with paragraphs 5.2.1.22 and 5.2.2.13 of GOST R 41.13-99 (UNECE Regulation No. 13), motor vehicles of categories M<sub>2</sub>, M<sub>3</sub>, N<sub>2</sub> and N<sub>3</sub> with not more than four axles, trailers of categories O<sub>3</sub> and O<sub>4</sub> should be equipped with anti-lock systems, so the simulation of braking a road train without an anti-lock system (ABS) does not make sense [2]. In the brake system model, the ideal ABS algorithm is realized, according to which the braking torque  $T_i$  on the  $i$ -th wheel, taking into account the work of the ABS, will be calculated in accordance with the following equation [3]:

$$\begin{cases} T_i = \frac{\omega_{wi} J_i}{V_x} M_{\pi}, & V_x \neq 0; \\ T_i = 0, & V_x = 0; \end{cases} \quad (2)$$

The kinematic parameters and external disturbances are coupled by a set of differential equations.

Using the theorems of variation of translational and angular momentum of a rigid body in the projections on the movable coordinate system axis, we obtain the equations of motion for the tractor and semi-trailer [4,5]:



**Figure 2.** Kinematic diagram of the articulated lorry.

$$\begin{cases}
(m_t + 2N_t m_{kt}) \dot{V}_{cxt} + (m_t + 2N_t m_{kt}) (\omega_{yt} V_{czt} - \omega_{xt} V_{czt}) = G_{xt} + F_{xt} + \sum_{i=1}^{2N_t} R_{it}^x + R_{tZ_2 fwc} \\
(m_t + 2N_t m_{kt}) \dot{V}_{czt} + (m_t + 2N_t m_{kt}) (\omega_{xt} V_{cxt} - \omega_{xt} V_{czt}) = G_{yt} + F_{yt} + \sum_{i=1}^{2N_t} R_{it}^y + R_{tY_2 fwc} \\
m_t \dot{V}_{czt} + m_t (\omega_{xkt} V_{czt} - \omega_{yt} V_{cxt}) = G_{zt} + F_{zt} + \sum_{i=1}^{2N_t} P_{it}^z + R_{tZ_2 fwc} \\
I_{xt} \dot{\omega}_{xt} + \omega_{yt} \omega_{xt} (I_{xt} - I_{yt}) = M_{xt}(F) + \sum_{i=1}^{2N_t} M_{xt} [P_{it}] + R_{tY_2 fwc} (h_{ct} - h_{fwc}) \\
I_{yt} \dot{\omega}_{yt} + \omega_{xt} \omega_{yt} (I_{yt} - I_{xt}) = M_{yt}(F) + \sum_{i=1}^{2N_t} M_{yt} [P_{it}] + R_{tZ_2 fwc} L_{cfwc} + R_{tX_2 fwc} (h_{ct} - h_{fwc}) \\
I_{zt} \dot{\omega}_{zt} + \omega_{xt} \omega_{yt} (I_{zt} - I_{xt}) = M_{zt}(F) + \sum_{i=1}^{2N_t} M_{zt} [R_{it}] + \sum_{i=1}^{2N_t} M_{nkit} + R_{tY_2 fwc} L_{cfwc} - M_{zt}
\end{cases} \quad (3)$$

$$\begin{cases}
(m_{zt} + 2N_{zt} m_{kzt}) \dot{V}_{czt} + (m_{zt} + 2N_{zt} m_{kzt}) (\omega_{yzt} V_{czt} - \omega_{xzt} V_{czt}) = G_{zst} + F_{zst} + \sum_{i=1}^{2N_{zt}} R_{ist}^x + R_{ztX_2 fwc} \\
(m_{zt} + 2N_{zt} m_{kzt}) \dot{V}_{czt} + (m_{zt} + 2N_{zt} m_{kzt}) (\omega_{xzt} V_{czt} - \omega_{xzt} V_{czt}) = G_{yzt} + F_{yzt} + \sum_{i=1}^{2N_{zt}} R_{ist}^y + R_{ztY_2 fwc} \\
m_{zt} \dot{V}_{czt} + m_{zt} (\omega_{xkt} V_{czt} - \omega_{yzt} V_{czt}) = G_{zst} + F_{zst} + \sum_{i=1}^{2N_{zt}} P_{ist}^z + R_{ztZ_2 fwc} \\
I_{zst} \dot{\omega}_{zst} + \omega_{yzt} \omega_{zst} (I_{zst} - I_{yzt}) = M_{zst}(F) + \sum_{i=1}^{2N_{zt}} M_{zst} [P_{ist}] + R_{ztY_2 fwc} (h_{ct} - h_{fwc}) + R_{ztZ_2 fwc} del_{czt} \\
I_{yzt} \dot{\omega}_{yzt} + \omega_{xzt} \omega_{yzt} (I_{yzt} - I_{xzt}) = M_{yzt}(F) + \sum_{i=1}^{2N_{zt}} M_{yzt} [P_{ist}] + R_{ztZ_2 fwc} l_{1c} + R_{ztX_2 fwc} (h_{czt} - h_{fwc}) \\
I_{xzt} \dot{\omega}_{xzt} + \omega_{xzt} \omega_{yzt} (I_{xzt} - I_{zst}) = M_{xzt}(F) + \sum_{i=1}^{2N_{zt}} M_{xzt} [R_{ist}] + \sum_{i=1}^{2N_{zt}} M_{nkit} + R_{ztY_2 fwc} l_{1c} + R_{ztX_2 fwc} del_{czt} + M_{xt}
\end{cases} \quad (4)$$

- $\omega_x, \omega_y, \omega_z$  - projections of the angular velocity vector on the axes of coordinate system  $OXYZ$ ;  
 $\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$  - projections of the angular acceleration vector on the axes of coordinate system  $OXYZ$ ;  
 $V_{cx}, V_{cy}, V_{cz}$  - projections of the velocity of center of mass vector on the axes of coordinate system  $OXYZ$ ;  
 $\dot{V}_{cx}, \dot{V}_{cy}, \dot{V}_{cz}$  - projections of the acceleration of center of mass vector on the axes of coordinate system  $OXYZ$ ;  
 $G_x, G_y, G_z$  - projections of the gravity vector on the axes of coordinate system  $OXYZ$ ;  
 $F_x, F_y, F_z$  - projections of the external force vector on the axes of coordinate system  $OXYZ$ ;  
 $R_i^x, R_i^y, R_i^z$  - projections of the interaction force between the ground and the wheel on the axes of coordinate system  $OXYZ$ ;  
 $R_{X_2 fwc}, R_{Y_2 fwc}, R_{Z_2 fwc}$  - projections of the reaction vector in the fifth wheel coupling;  
 $P_i$  - forces of the suspensions of the wheels;  
 $M_x(F), M_y(F), M_z(F)$  - projections of the moment on the force of external influence on the axes of coordinate system  $OXYZ$ ;

$M_x(R_i), M_y(R_i), M_z(R_i)$	- projections of the moment of the interaction force between the ground and the wheel on the axes of coordinate system $OXYZ$ ;
$M_{st}$	- the stabilizing moment created by the locking mechanism of the fifth wheel coupling;
$I_x, I_y, I_z$	- moments of inertia relative to the axes the axes of coordinate system $OXYZ$ ;
$M$	- mass of sprung parts;
$m_k$	- mass of unsprung parts;
$h_c$	- the height of the center of mass of the sprung parts in the fixed coordinate system;
$h_{fvc}$	- the height of the center of the fifth wheel coupling in the fixed coordinate system;
$L_{cfvc}$	- longitudinal coordinate of the fifth wheel coupling in the fixed coordinate system;
$l_{lc}$	- longitudinal coordinate of the fifth wheel coupling in the semi-trailer coordinate system;
$del_{cst}$	- lateral displacement of the center of mass of the semi-trailer relative to the longitudinal axis;
$N$	- number of axles of the semi-trailer or truck.

\* index  $t$  refers to the tractor, index  $st$  refers to the semi-trailer.

#### 4. Verification of the efficiency and effectiveness of the developed algorithm

To check the efficiency of the control system of the locking mechanism of the fifth wheel coupling, the following computational experiments were carried out: "Emergency braking on a straight line", "Emergency braking in a turn" for the articulated lorry equipped with a locking mechanism and for the same lorry without the locking mechanism. All experiments were carried out with the characteristics of the road, corresponding to the asphalt-concrete coating, namely: the maximum longitudinal and transverse friction coefficients  $\mu_{x\max} = 0.7$ ;  $\mu_{y\max} = 0.7$ , the coefficients of  $\mu(S)$  equation  $S_1 = 0.1$ ,  $S_0 = 0.05$ , the coefficient of rolling resistance  $f = 0.01$  [6].

The jackknifing of the articulated lorry occurred in the case of the lateral displacement of the center of mass of the semi-trailer from the longitudinal axis by 30 mm.

The parameters of the tractor and the trailer are shown in Tables 1 and 2.

**Table 1.** Characteristics and parameters of the tractor.

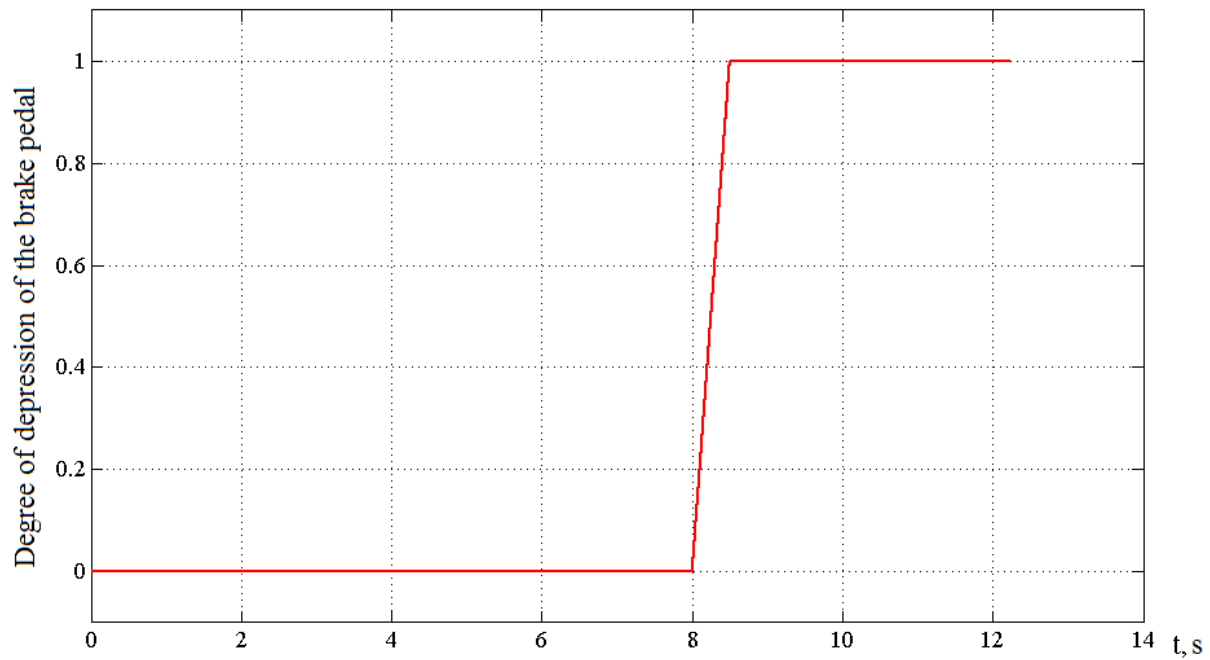
Sprung mass	7850 kg
Axle mass	500 kg
Wheel mass	120 kg
Moment of inertia relative to the transverse axis	56892 kg·m <sup>2</sup>
Moment of inertia relative to the longitudinal axis	19238 kg·m <sup>2</sup>
Moment of inertia relative to the vertical axis	40000 kg·m <sup>2</sup>
Moment of inertia of the axle	190 kg·m <sup>2</sup>
Moment of inertia of the wheel	16.5 kg·m <sup>2</sup>
Wheelbase	4450 mm

Distance from the center of mass to the 1 <sup>st</sup> axle	1905 mm
Distance from the center of mass to the equalizer axle	1803 mm
Distance between the 2 <sup>nd</sup> axle and the 3 <sup>rd</sup> axle	1430 mm
Distance from the center of mass to the fifth wheel coupling	1830 mm
Wheel track	2020 mm
Distance between the suspension springs	1616 mm
Center of mass height	1430 mm
Loaded tire radius	530 mm

**Table 2.** Characteristics and parameters of the semi-trailer.

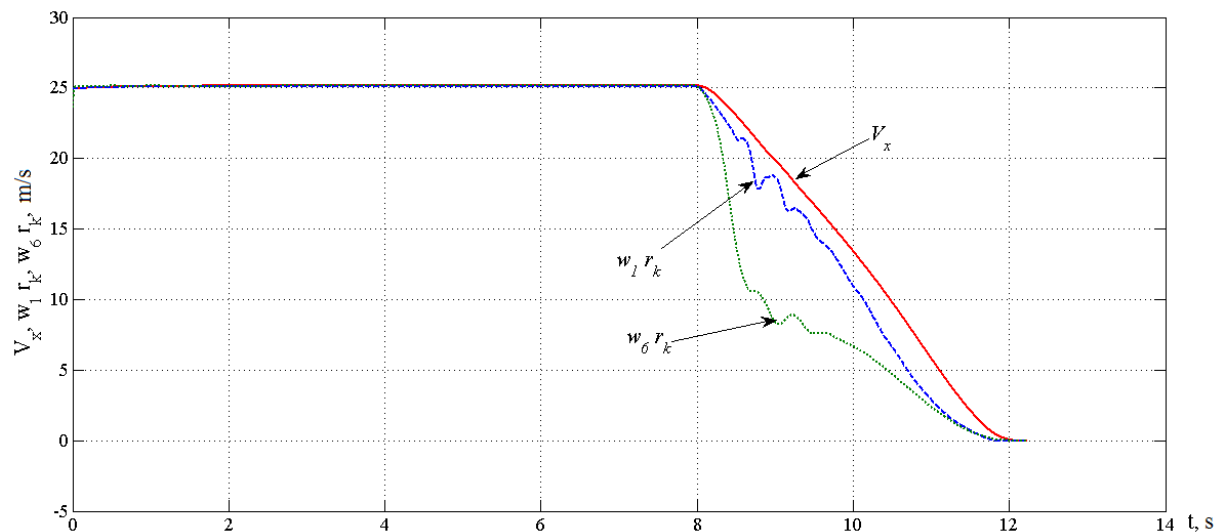
Sprung mass	29400 kg
Axle mass	300 kg
Wheel mass	120 kg
Moment of inertia relative to the transverse axis	75000 kg·m <sup>2</sup>
Moment of inertia relative to the longitudinal axis	30000 kg·m <sup>2</sup>
Moment of inertia relative to the vertical axis	10000 kg·m <sup>2</sup>
Moment of inertia of the axel	210 kg·m <sup>2</sup>
Moment of inertia of the wheel	16.5 kg·m <sup>2</sup>
Wheelbase	8900 mm
Distance from the center of mass to the 1 <sup>st</sup> axle	3500 mm
Distance from the center of mass to the equalizer axle	4900 mm
Distance from the center of mass to the fifth wheel coupling	4000 mm
Wheel track	2100 mm
Distance between the suspension springs	1680 mm
Center of mass height	2300 mm
Loaded tire radius	530 mm

The simulation of emergency braking was carried out at the initial speed of 90 km/h. The diagram of pressing the brake pedal is shown in figure 3.

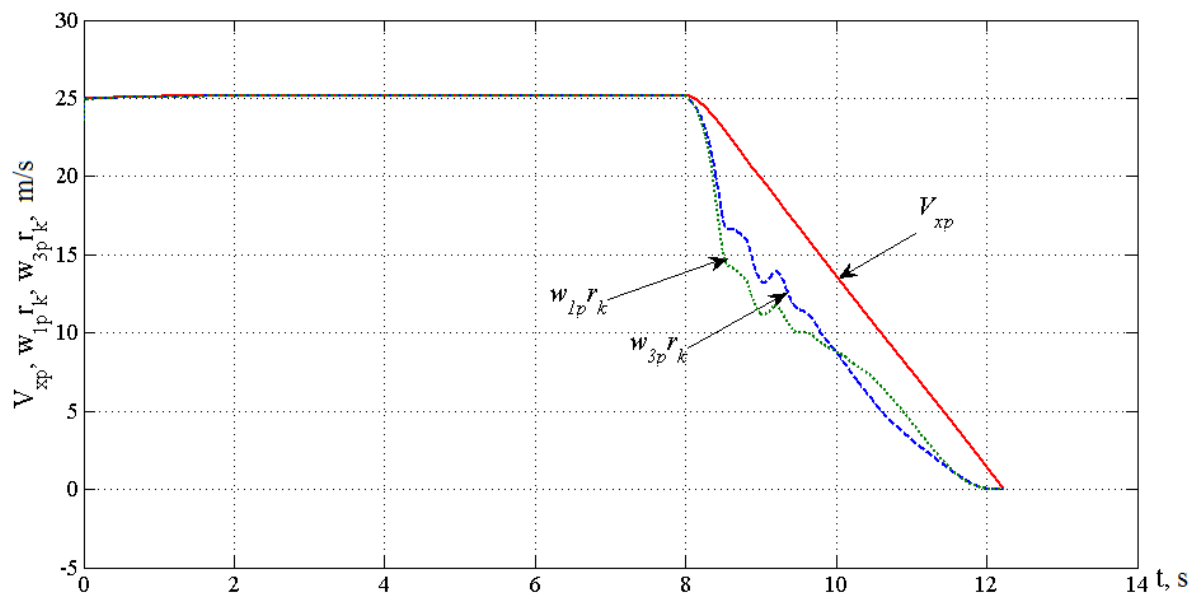


**Figure 3.** Brake pedal actuation.

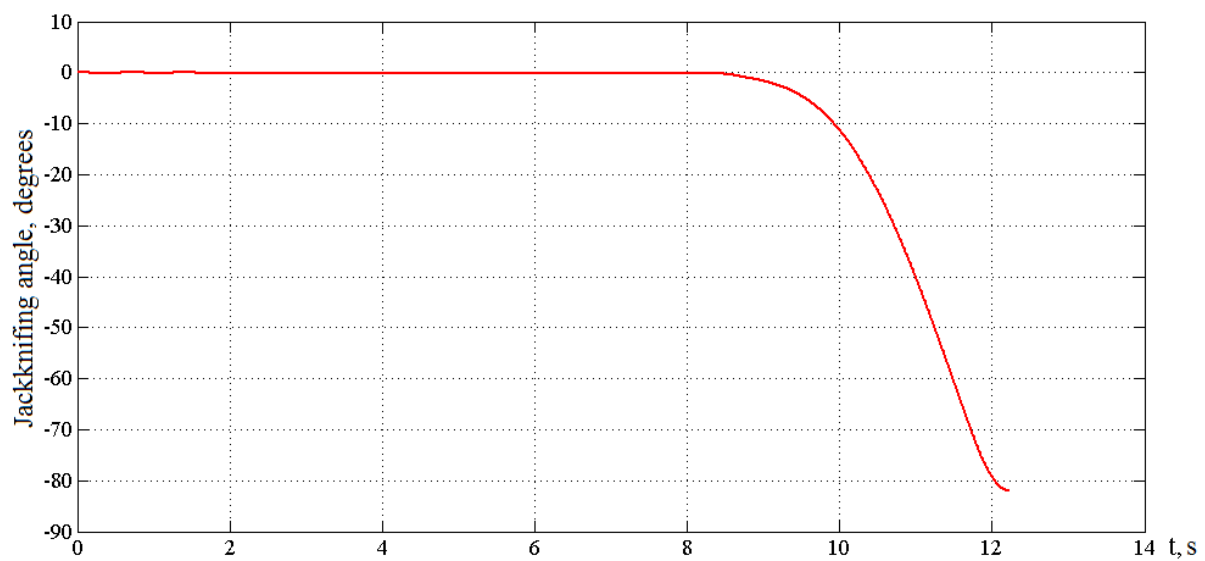
Figure 4 shows the time histories of the tractor speed and the speed of the centers of mass of the 1<sup>st</sup> and 6<sup>th</sup> wheels when rolling without sliding. Figure 5 presents similar graphs for the center of mass of the trailer and the centers of mass of the 1<sup>st</sup> and 3<sup>rd</sup> wheels. Figures 6 and 7 show the time histories of the jackknifing angle and the jackknifing rate. Figure 8 shows the position of the articulated lorry after a complete stop (black solid lines depict the dimensions of the lane in accordance with GOST R 52399-2005, red line is the trajectory of the centers of the tractor and the semi-trailer).



**Figure 4.** Longitudinal velocity of the tractor center of gravity and the speeds of the centers of mass of the wheels without sliding.

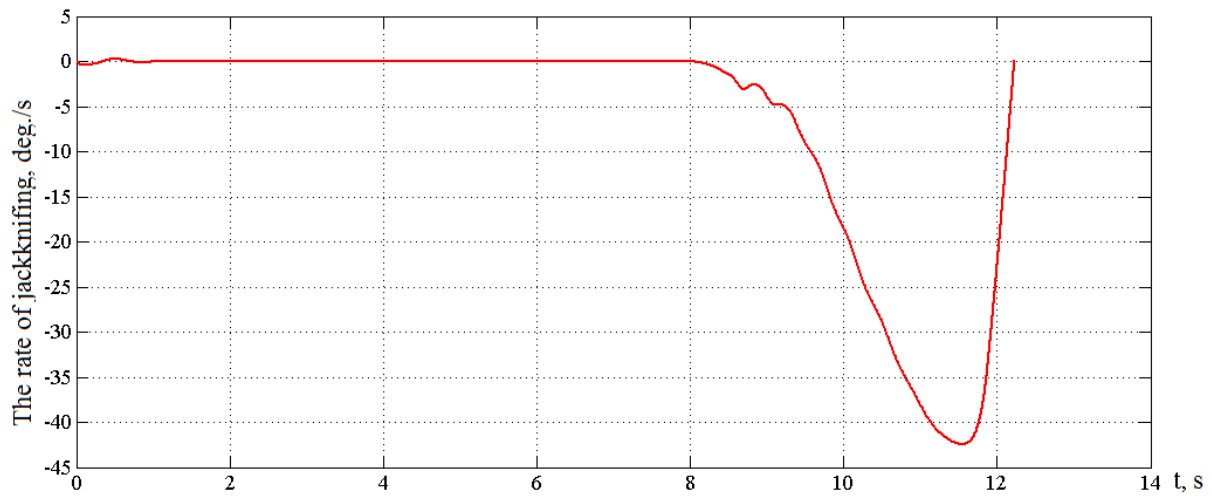


**Figure 5.** Longitudinal velocity of the semi-trailer center of gravity and the speeds of the centers of mass of the wheels without sliding.

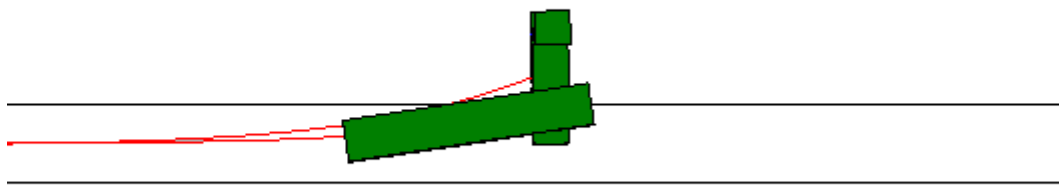


**Figure 6.** Jackknifing angle.





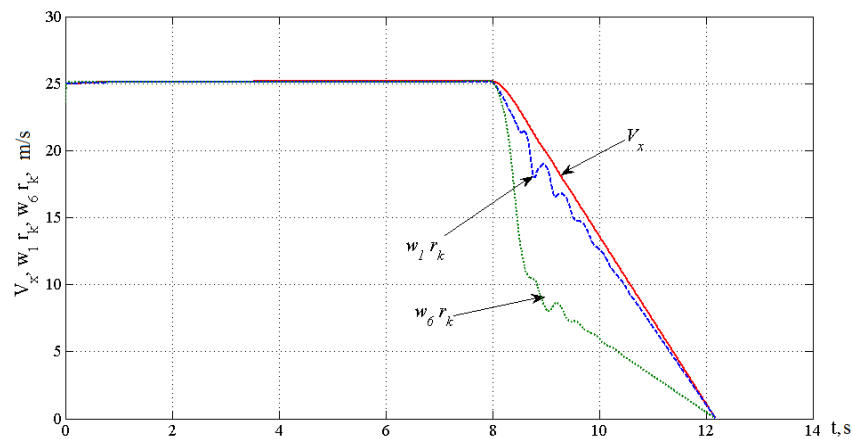
**Figure 7.** Jackknifing rate.



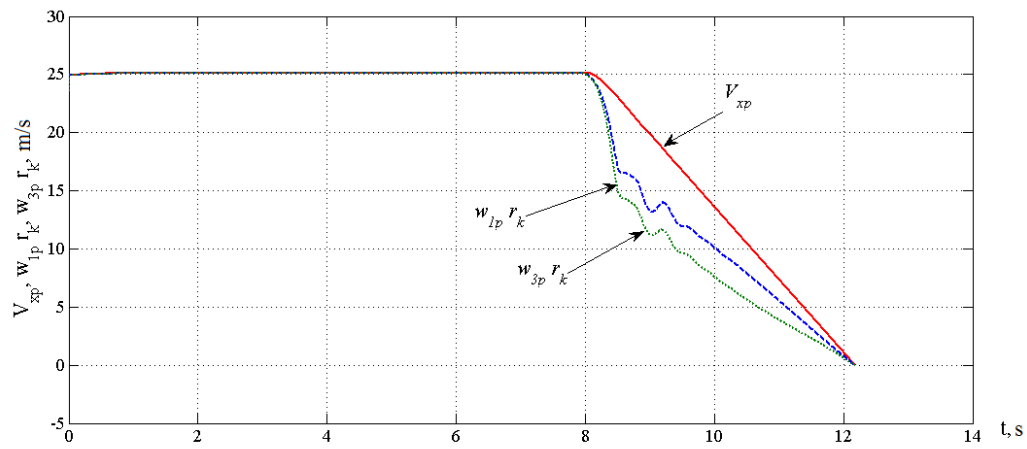
**Figure 8.** Position of the articulated lorry after a complete stop.

The simulation of the braking of the articulated lorry with the coupling locking device was carried out under identical conditions.

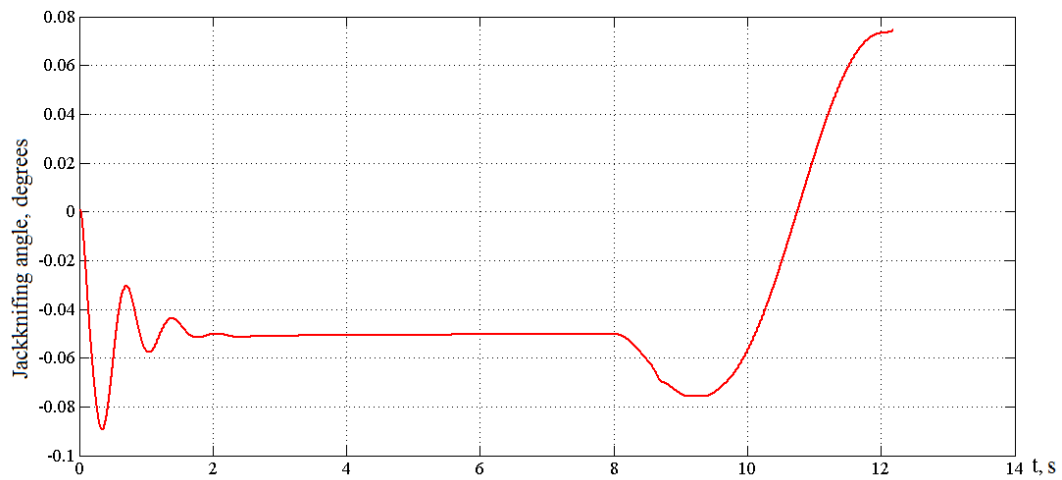
Figures 9 and 10 are similar to figures 4, 5. Figures 11 and 12 show time histories of the jackknifing angle and the jackknifing rate. Figure 13 shows the position of the articulated lorry after a complete stop (the elements of the figure are similar to ones of figure 8).



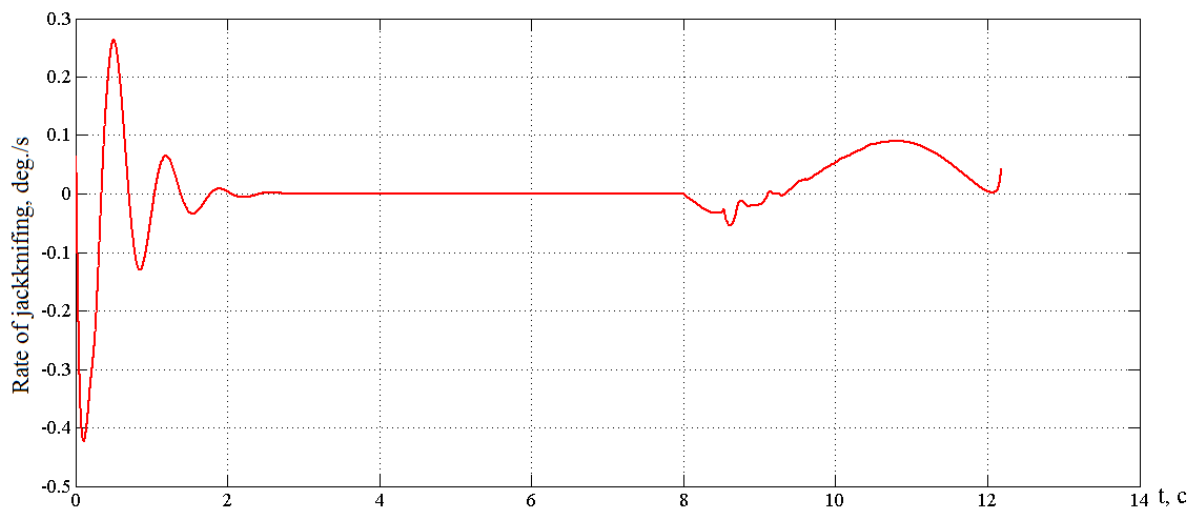
**Figure 9.** Longitudinal velocity of the tractor center of gravity and the speeds of the centers of mass of the wheels without sliding.



**Figure 10.** Longitudinal velocity of the semi-trailer center of gravity and the speeds of the centers of mass of the wheels without sliding.



**Figure 11.** Jackknifing angle.



**Figure 12.** Jackknifing rate.

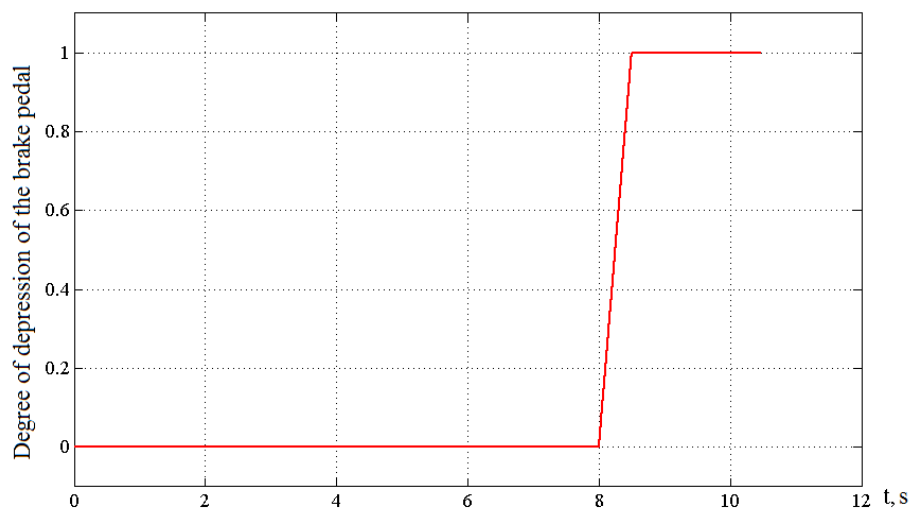


**Figure 13.** Position of the articulated lorry after a complete stop.

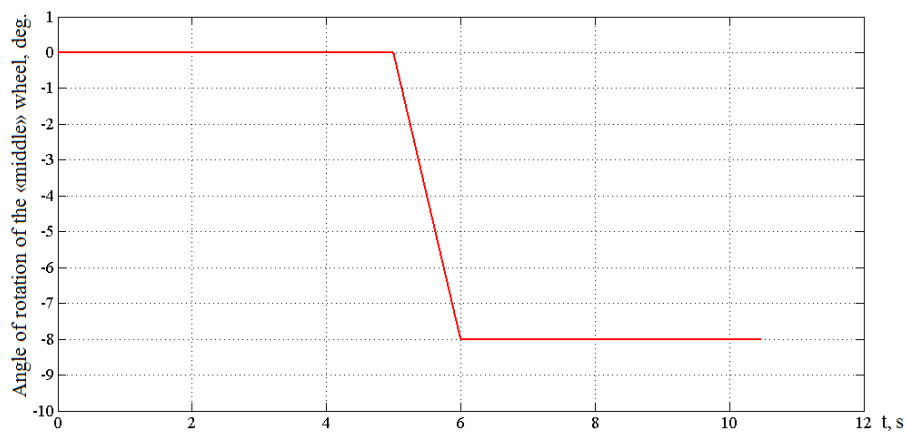
From the presented results, it can be concluded that in case of emergency straight-line braking of an articulated lorry without a locking device, there is a risk of jackknifing. Usually, the heavier semitrailer "pushes" the tractor to the adjacent lane (with the jackknifing angle reaching  $80^\circ$ ) despite the ABS system installed on the vehicles of this type. These results are confirmed by the situations occurring in real-life operation, which once again proves the adequacy of the developed mathematical model.

The use of this locking system allows keeping the articulated lorry within the lane without the need of the driver control inputs. The jackknifing angle decreases by 3 orders of magnitude to  $0.08^\circ$ .

Simulation of emergency braking of the articulated lorry in a turn was carried out with the following initial conditions: initial speed 50 km/h, maximum average angle of the steered wheels  $8^\circ$ , turn radius 50 m. Time histories of the brake pedal actuation and the average angle of the steered wheels are shown in figure 14, 15.

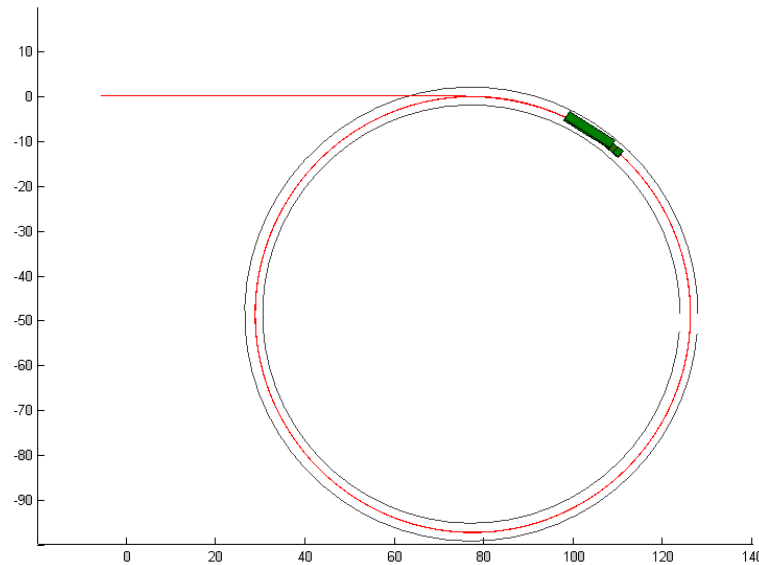


**Figure 14.** Brake pedal actuation.



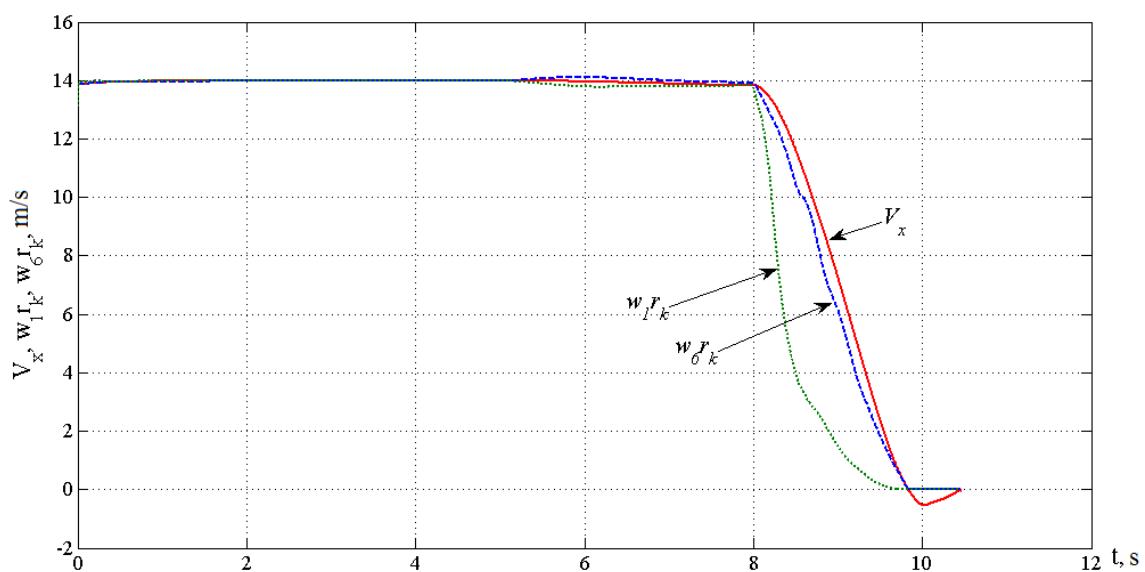
**Figure 15.** Average angle of the steered wheels.

In order to make sure that the articulated lorry steadily moves along the trajectory with the given initial conditions, the motion was simulated without braking. Figure 16 shows the trajectory and the marking of the corridor of motion.

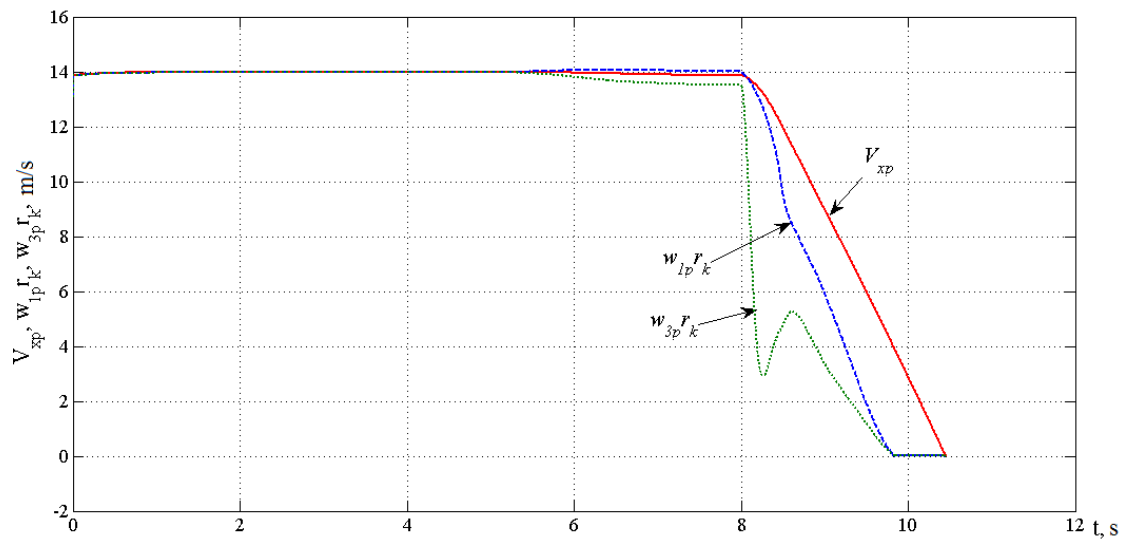


**Figure 16.** Trajectory of the articulated lorry in a turn.

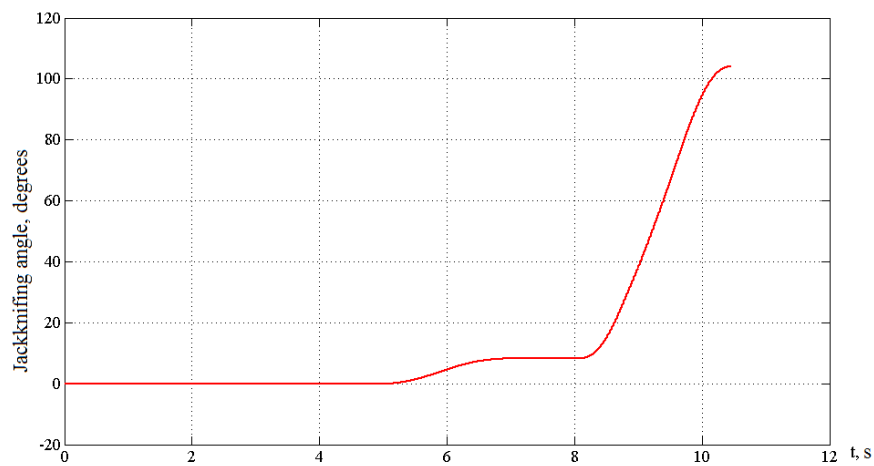
Figures 17 and 18 show the time histories of the rate of the tractor and semi-trailer centers of mass and the speed of rolling without sliding the centers of mass of the wheels during emergency braking of the articulated lorry in a turn without activating the locking of the fifth wheel coupling. In figures 19 and 20 show the time histories of the jackknifing angle and the rate. Figure 21 shows the position of the articulated lorry after a complete stop. Figures 22 and 23 show graphs similar to those shown at figure 17, 19, but with the operating device locking the fifth wheel coupling. Figures 24 and 25 show the angle of jackknifing and the rate of jackknifing. Figure 26 shows the position of the articulated lorry after a complete stop.



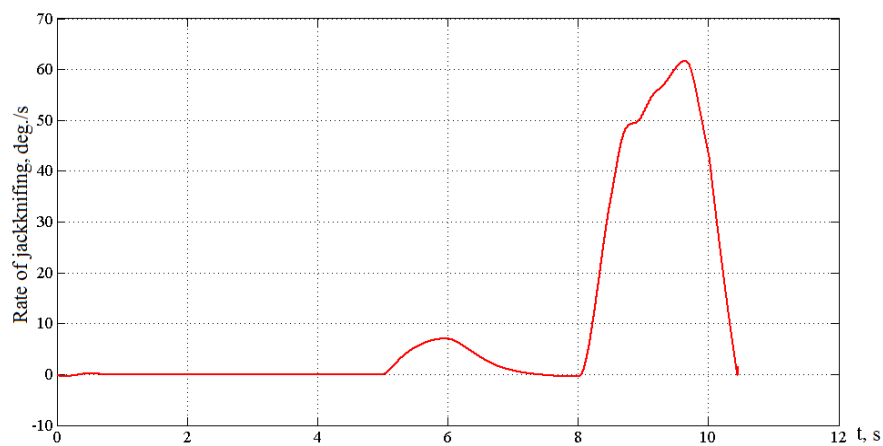
**Figure 17.** Longitudinal velocity of the tractor center of gravity and the speeds of the centers of mass of the wheels without sliding.



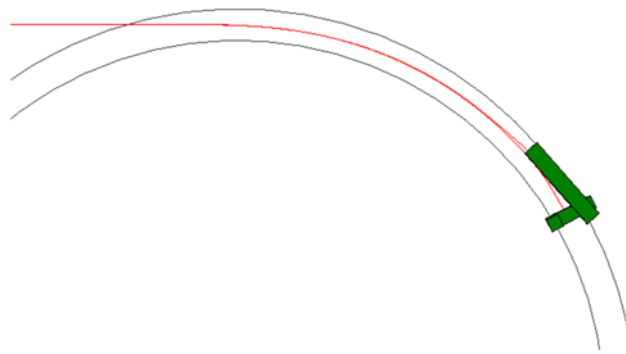
**Figure 18.** Longitudinal velocity of the semi-trailer center of gravity and the speeds of the centers of mass of the wheels without sliding.



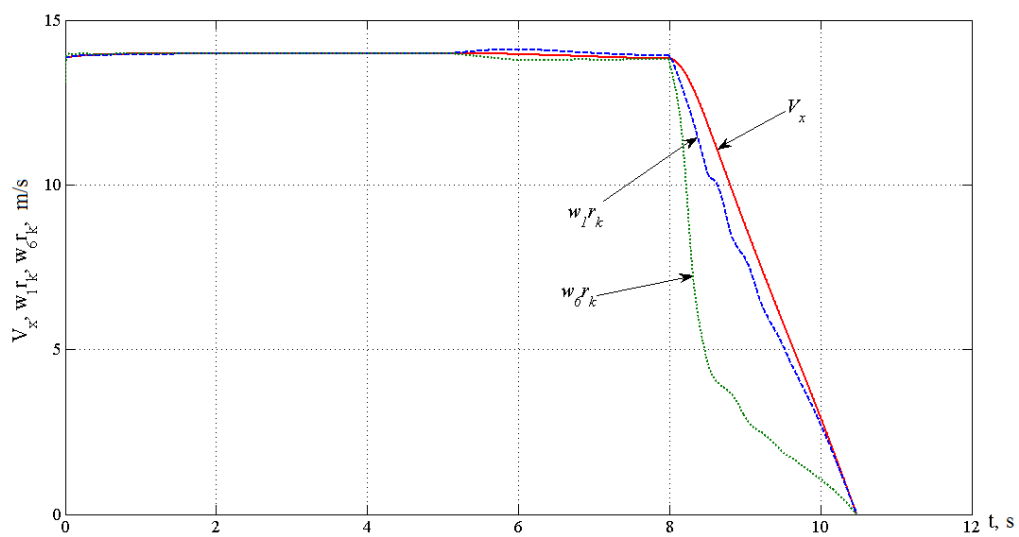
**Figure 19.** Jackknifing angle.



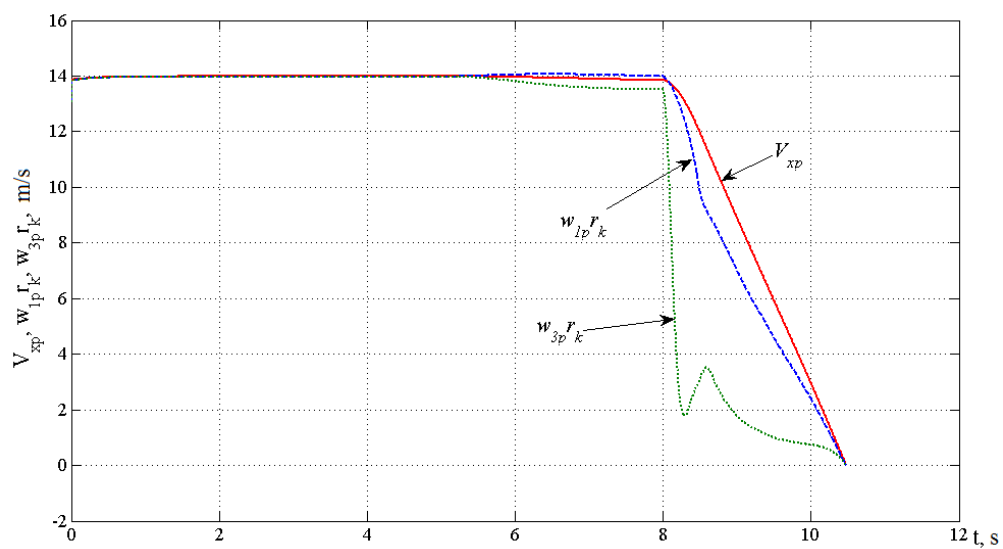
**Figure 20.** Jackknifing rate.



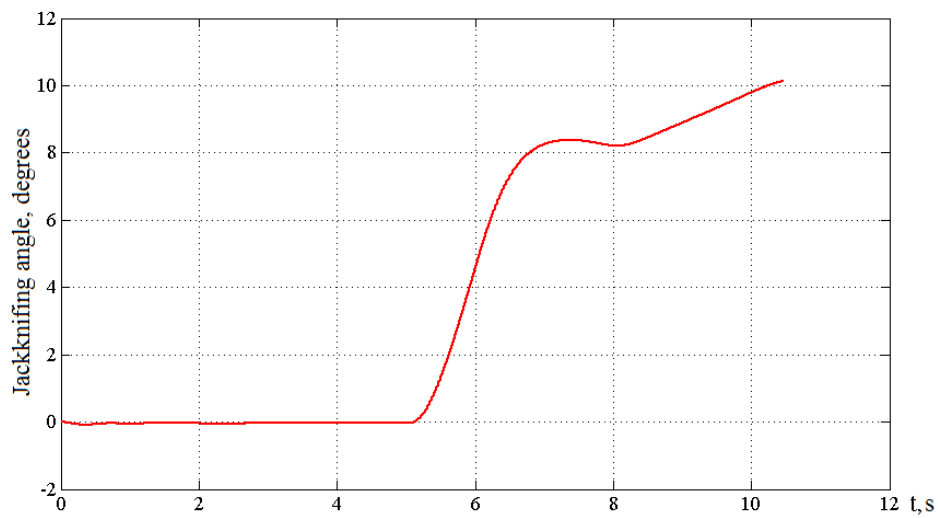
**Figure 21.** Position of the articulated lorry after a complete stop.



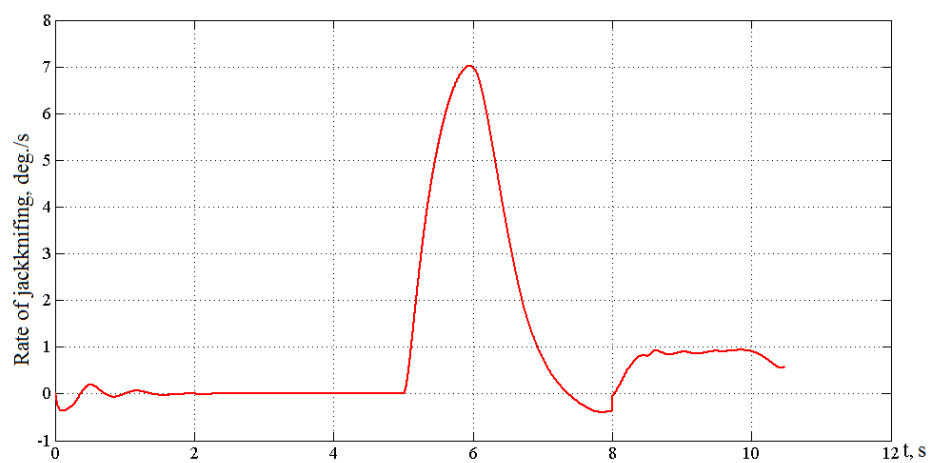
**Figure 22.** Longitudinal velocity of the tractor center of gravity and the speeds of the centers of mass of the wheels without sliding.



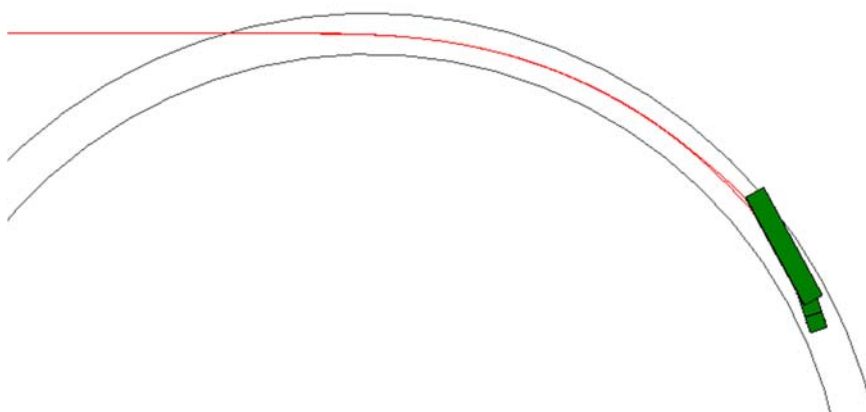
**Figure 23.** Longitudinal velocity of the semi-trailer center of gravity and the speeds of the centers of mass of the wheels without sliding.



**Figure 24.** Jackknifing angle.



**Figure 25.** Jackknifing rate.



**Figure 26.** Position of the articulated lorry after a complete stop.

## 5. Conclusion

The simulation results showed efficiency of use of the fifth wheel coupler locking device for prevention of jackknifing at braking not only on a straight line, but also on a curvilinear trajectory. With the locked fifth wheel coupler, the articulated lorry slows down in a turn practically preserving the trajectory of movement due to the fixation of the jackknifing angle that has arisen at the entrance to the turn. In the absence of locking, the vehicle folds (the jackknifing angle reaches  $100^\circ$ ) and leaves the traffic lane, thereby creating conditions for a traffic accident. It is worth noting that when braking in turn with a critical initial speed on the verge of tipping with the locked fifth wheel coupler, the trailer may skid even on the road with a high coefficient of friction. To exclude this adverse effect, it is necessary to introduce a system limiting the vehicle speed in turn thus preventing not only the drift of the articulated lorry but also the overturning.

## References

- [1] Bouteldja M Cerezo V 2011 *Jackknifing warning for articulated vehicles based on a detection and prediction system* (Indianapolis: Submitted to the 3rd International Conference on Road Safety and Simulation, September 14-16) <http://onlinepubs.trb.org/onlinepubs/conferences/2011/RSS/3/Bouteldja,M.pdf>
- [2] GOST R 41.13-99 (UNECE Regulation No. 13) *Uniform provisions concerning the vehicles of categories M, N and O with regard to braking*
- [3] Jileikin M M 2016 *Theoretical bases of increase of efficiency and controllability of the wheeled vehicle based on fuzzy logic* (Moscow: MGTU im. N.E. Bauman Press) p 238
- [4] Jileikin M M Skotnikov G I 2015 *Development of principles of increasing of stability of motion of multilink tractor trains* (Moscow: Traktory i selhozmashiny vol 10) pp 19 – 23
- [5] Ankinovich G G, Verzhbitskiy A N, Jileikin M M, Skotnikov G I 2016 *The development of principles to improve the stability of articulated lorries against roll-over in the turn* (Moscow: Izvestiya VUZov. Mashinostroenie vol 2) pp 28 – 35
- [6] Larin V V 2010 *Theory of motion of all-wheel drive vehicles* (Moscow: MGTU im. N.E. Bauman Press) p 391