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# Implementation of the interaction of the steering wheel loader control system of the remote-controlled wheeled vehicle operator interface with a real-time simulation model

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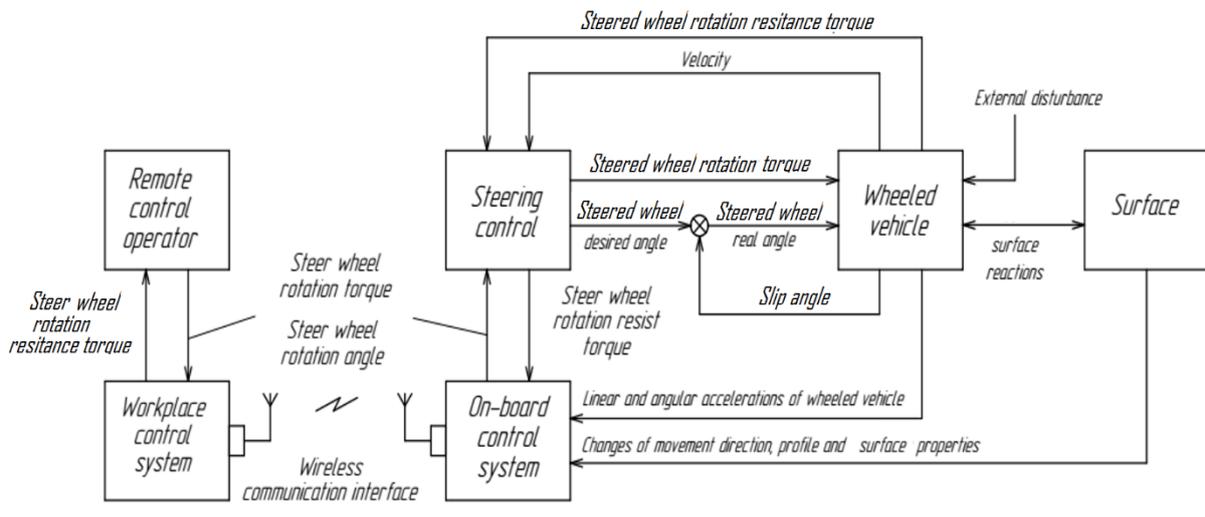
E-mail: <sup>1</sup> [buzunovnv@bmstu.ru](mailto:buzunovnv@bmstu.ru), <sup>2</sup> [kotievgo@yandex.ru](mailto:kotievgo@yandex.ru), <sup>3</sup> [gvas@mail.ru](mailto:gvas@mail.ru)

**Abstract.** A wheeled vehicle remote control workstation should include systems and devices that would provide steering feedback for the operator. The electric loader of the steering wheel with digital control can act as a system of this kind. Development and adjustment of the steering wheel loader can be performed with real-time simulation models sufficiently reflecting the behavior of the remote-controlled vehicle. The paper describes interaction of the real-time simulation model of an 8x8 wheeled chassis with the prototype of a steering wheel loader control system. The authors demonstrate compatibility of the software and hardware components in question, show adequacy of the model during interaction with the steering wheel loader control system, and propose using such models during the development of the remote control operator workstations.

When a vehicle is remotely controlled, the interface between the control object and the operator (who is located remotely) should provide the same information about the state of the vehicle and the environment as when the vehicle is locally controlled.

It is known that during a maneuver, the driver turns the steering wheel at an angle that ensures the minimum deviation of the wheeled vehicle (WV) from the desired direction. However, during the movement, the ratio between the current steering angle and the corresponding change in direction of travel is constantly changing. This occurs with the following sequence of events of the turning WV: «Turning the steering wheel (SW) – changing the angle of rotation of the steered wheels – forming lateral forces in the contact patch of the tires on the road – changing the direction of movement - adjusting the control action depending on the position of the WV» [1].





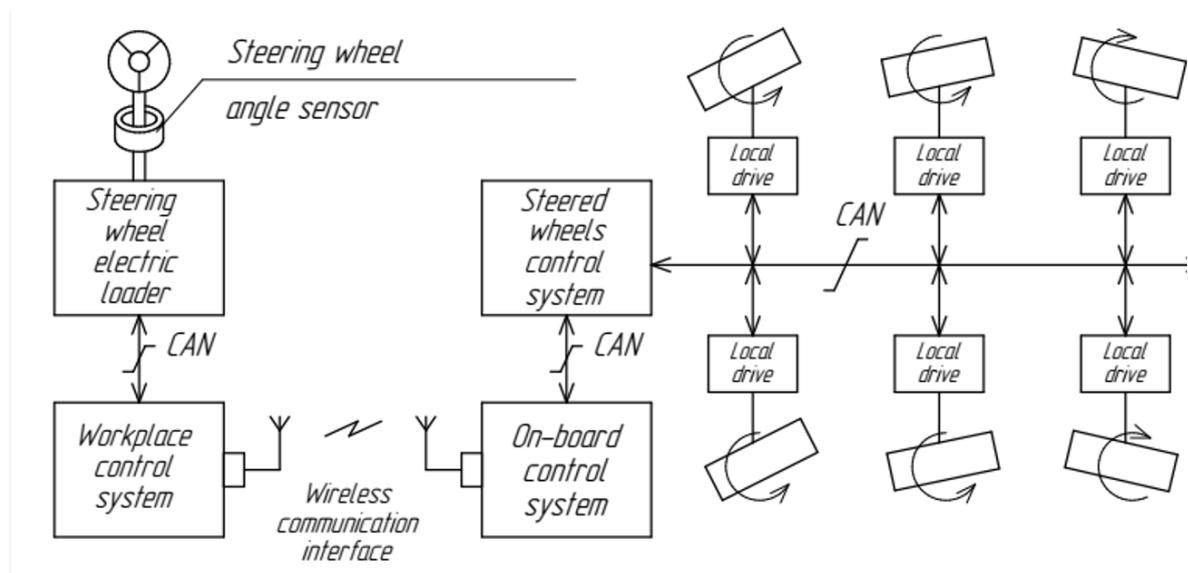
**Figure 1.** Structural scheme of interaction of the remote-controlled vehicle operator with the control object.

The visual channel for obtaining information has relatively high, but still limited possibilities. The reaction time of the driver to visual information is greater than when the information is perceived by the auditory or tactile channel. In this regard, the operator's workplace for remote control must ensure the transmission of information via both the visual, tactile, and auditory channels.

The transmission of information via a tactile channel when driving a vehicle is realized by forming the moment of resistance to steering wheel rotation in accordance with the current steering angle and the vehicle speed (figure 1) [1].

When implementing the workplace for remote control of the vehicle, the «rigid» connection between the steering and steered wheel, which is typical for local control, is absent. When working under current conditions, the operator does not feel the moment of the resistance to the steered wheels turn.

To provide feedback on the steering wheel, additional elements and systems must be introduced into the design of the remote control workstation providing the required rotation resistance. An example of such a device is the electric loader of the steering wheel (ELSW) with an electronic control system (figure 2). The steering wheel in this case plays the role of a control device without direct force transfer from the operator to the steered wheels.



**Figure 2.** Implementation of the steering system of the remote operator's workplace.

Because of the specific purpose of the ELSW, the development of such systems, the correction of the initial control laws, the adjustment of the parameters of interaction between the workplace and the control object are currently possible at all stages of design only if there is a prototype of the wheeled vehicle object. This fact, in turn, increases the cost and timing of development work.

The specified problem can be solved by performing the adjustment and debugging of the software and hardware parts of the ELSW control system using imitation mathematical models of the movement dynamics of wheeled vehicles operating in the real-time mode. With this approach to the development of a control system, there is no need for a prototype object. It is sufficient that the applied mathematical model describes the behavior of the vehicle with an accuracy sufficient to solve the problems posed.

Based on the submitted data, the following requirements can be formulated for the simulation model used in the development of remote control workstations:

- functioning in the real-time mode due to teamwork with the workplace and operator management system implemented at the physical level;
- identity to the replaced object from the point of view of the physical control system interacting with the model being developed.

The purpose of this work is to determine the possibility of the steering wheel loader control system functioning from the operator's workplace of the remote-controlled vehicle in interaction with the simulation real-time model of the plane curvilinear movement of the wheeled vehicle.

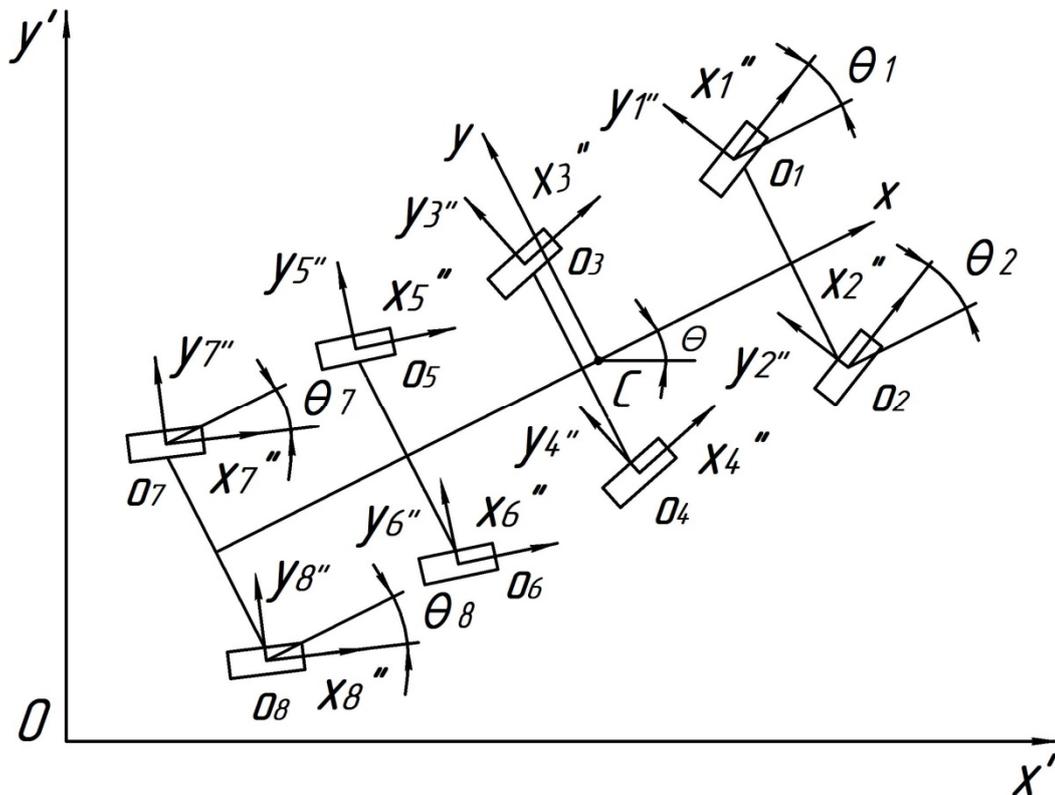
The virtual object in this study is the model of the planar curvilinear motion of the wheeled chassis along a rigid road described in [2, 3, 4]. The adequacy of this model was repeatedly confirmed by comparing its simulation results with the results obtained during test runs of prototypes of different wheeled vehicles [2, 5, 6]. In order to comply with the objects of wheeled vehicles, the remote control of which is planned using the workplace considered, this model was adapted to describe the dynamics of the chassis with the wheel formula 8x8 and the steering formula 1-2-3-4. Other parameters of the virtual chassis are presented in Table 1. In the course of this study, the model of motion dynamics of a multi-axle wheeled chassis is realized in the real-time mode to ensure joint operation with the ELSW control system.

**Table 1.** Parameters of the virtual chassis.

Parameter name	Value
Mass, kg:	29600
Length, m:	6,15
Track width, m:	2,6
Center of mass height, m:	1,38
Loaded tire radius, m:	0,725
Moment of inertia around the vertical axis, kg · m <sup>2</sup>	110106
Maximum power of the wheel hub motors, W	60000

System of equations (1) makes it possible to calculate current accelerations, based on the values of the forces and moments acting on the vehicle.

The movement of the wheeled vehicle as a rigid body is considered in a horizontal plane on an even, unreformed bearing surface and is composed of translational motion of the center of mass and rotational motion around the center of mass (figure 3) [7,8].



**Figure 3.** Coordinate systems used in modeling the curvilinear motion of the 8x8 wheeled vehicle:

$x' - O - y'$  is the fixed coordinate system (FCS);

$x - C - y$  is the movable coordinate system (MCS), associated with the object center of mass;

$x_i'' - O_i - y_i''$  is the moving coordinate system associated with the axis of rotation of the  $i$ -th wheel;

$\Theta$  is the heading angle of the wheeled vehicle model;

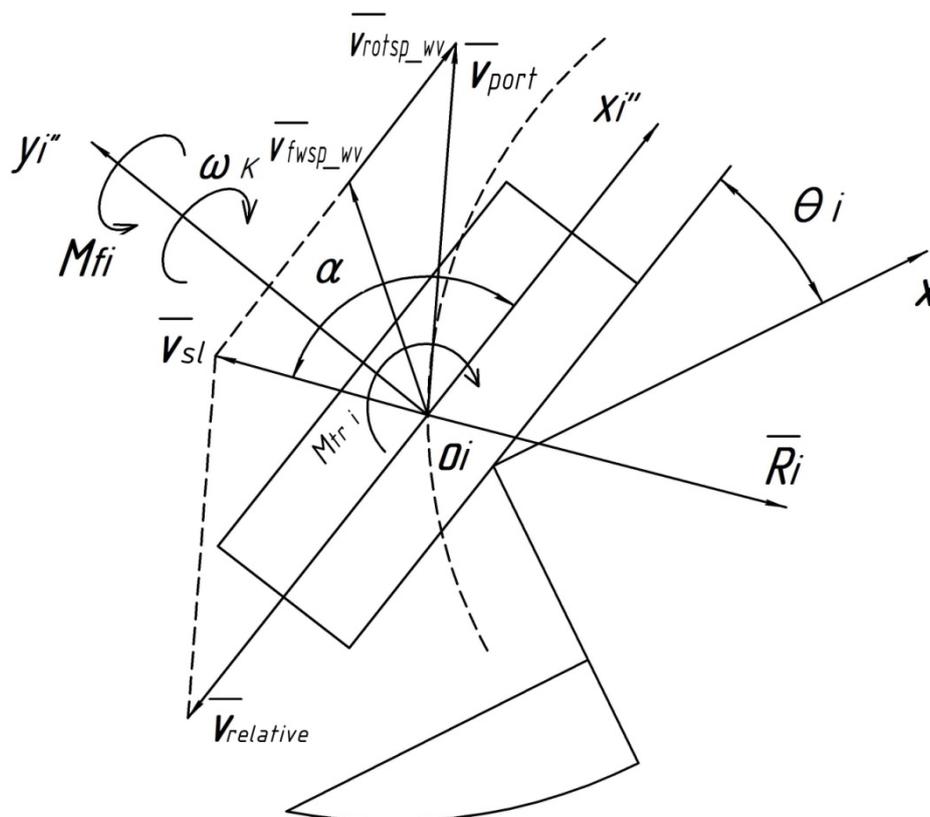
$\theta_i$  is the angle of the  $i$ -th wheel rotation.

System of equations (1) describing the vehicle motion provides calculation of the current accelerations according to the values of forces and moments acting on the wheeled vehicle from the surface and the environment [7,8,9]:

$$\left\{ \begin{array}{l} a_x = \frac{dV_x}{dt} - \omega_z \cdot V_y = \frac{1}{m} \cdot \left( P_{wx} + \sum_{i=1}^6 R_{xi} \right) \\ a_y = \frac{dV_y}{dt} + \omega_z \cdot V_x = \frac{1}{m} \cdot \left( P_{wy} + \sum_{i=1}^6 R_{yi} \right) \\ J_z \cdot \frac{d\omega_z}{dt} = \sum_{i=1}^6 M_{tri} + \sum_{i=1}^6 M(\vec{R}_i) \\ V_{x'} = \frac{dx'}{dt} = V_x \cdot \cos \theta - V_y \cdot \sin \theta \\ V_{y'} = \frac{dy'}{dt} = V_x \cdot \sin \theta + V_y \cdot \cos \theta \\ \omega_z = \frac{d\theta}{dt} \end{array} \right. \quad (1)$$

where  $m$  is the mass of the wheeled vehicle;  $J_z$  is the moment of inertia of the wheeled vehicle with respect to the  $z$  axis (center of mass);  $\vec{V}$  is the velocity vector of the center of mass of the wheeled vehicle;  $\vec{a}$  is the acceleration vector of the center of mass of the wheeled vehicle (the absolute derivative of the velocity vector of the center of mass of the car);  $\frac{d\vec{V}}{dt}$  is the relative derivative of the velocity vector of the center of mass of the wheeled vehicle;  $\omega_z$  is the angular speed of rotation of the wheeled vehicle around the center of mass;  $\theta$  is the angle of rotation of the wheeled vehicle relative to the axis  $x'$ ;  $\vec{R}_i$  is the vector of the interaction force with the support base acting on the  $i$ -th wheel;  $\vec{P}_w$  is the vector of the air resistance force;  $M_{tri}$  is the torque of resistance to the rotation of the  $i$ -th wheel.

The diagram used for calculation of the forces and velocities of an individual wheel is shown in figure 4 [6, 8].



**Figure 4.** Velocities and forces of an individual wheel.

In figure 4 the following elements are presented:

$\vec{v}_{sl}$  is the velocity vector of the sliding point of the contact of the wheel with respect to the support surface;

$\vec{v}_{relative}$  is the vector of relative wheel speed in the contact patch;

$\vec{v}_{port}$  is the vector of the transport velocity of the rotation center of the wheel  $O_i$  (velocity vector of MCS point  $x - C - y$ , with which the center  $O_i$  of MCS  $x_i'' - O_i - y_i''$  is currently connected, about FCS  $x' - O - y'$ );

$\vec{v}_{fwsp\_wv}$  is the vector of the linear velocity of the translational motion of the center of mass in the FCS  $x' - O - y'$ ;

$\vec{V}_{rotsp\_wv}$  is the vector of the linear velocity of the rotational motion of the  $i$ -th wheel center about the center of mass;

$\alpha$  is the angle of the wheel speed vector rotation relative to the axis  $x_i''$  of the system  $x_i'' - O_i - y_i''$ ;

$\omega_k$  is the angular speed of the  $i$ -th wheel rotation;

$\vec{R}_i$  is the force of interaction with the support surface of the  $i$ -th wheel;

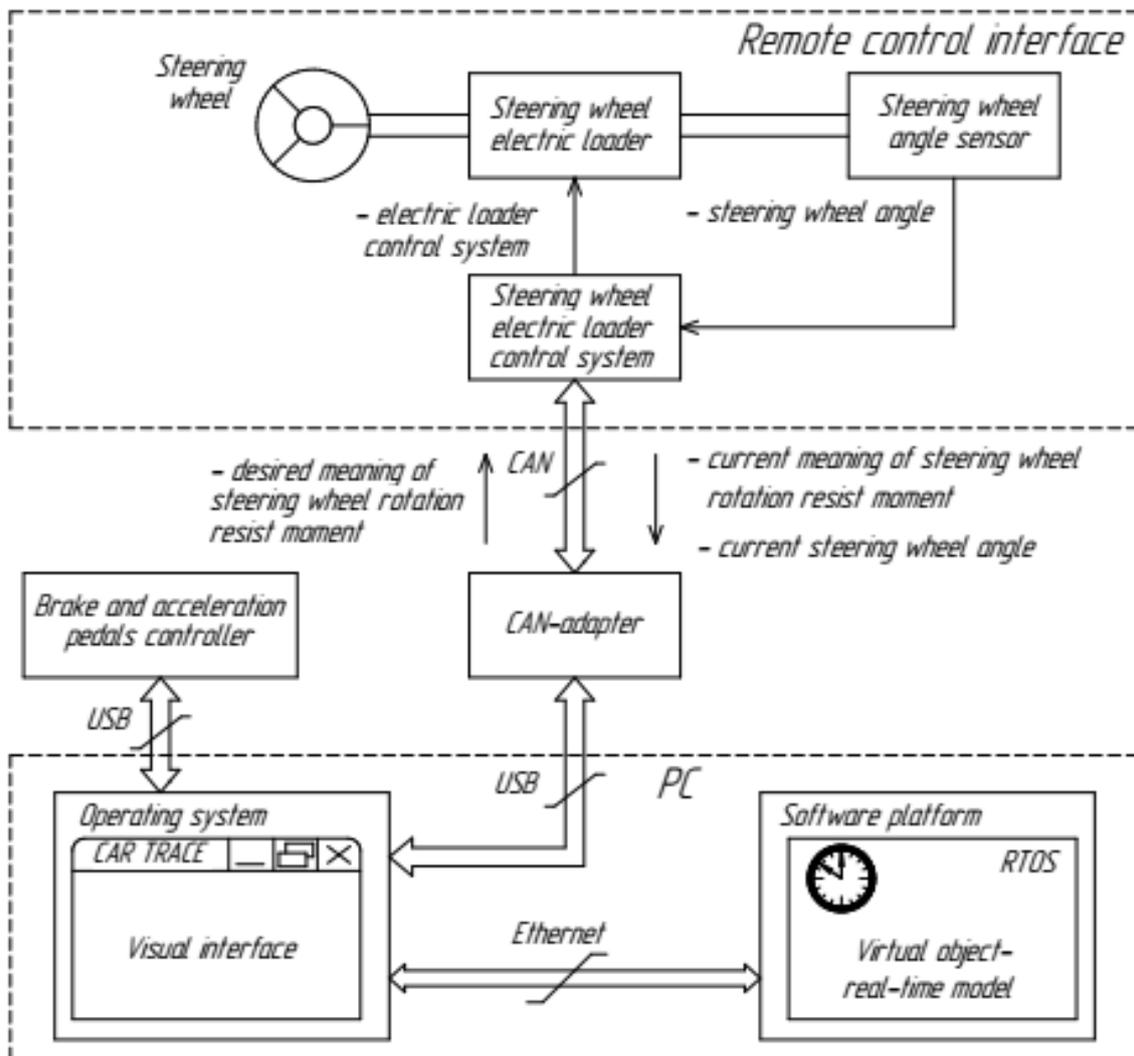
$\theta_i$  is the angle of the  $i$ -th wheel rotation;

$M_{fi}$  is the moment of the  $i$ -th wheel rolling resistance;

$M_{ri}$  is the moment of the  $i$ -th wheel resistance to the rotation.

The results of the verification of this real-time model, performed by comparison with the results of the «reference» model, showed a high degree of compliance with the replaced object of wheeled vehicles.

After confirming the adequacy, realization of the interaction of the real-time model with the control system of the steering wheel loader was carried out. The order of information exchange is presented in figure 5.



**Figure 5.** Structural diagram describing the interaction of the control system of the steering wheel electric loader with the real-time simulation model of the wheeled chassis.

When the real-time model and the steering wheel loader control system of the remote control operating station directly cooperate, the following relationship is realized as the law of forming the moment of resistance on the steering wheel:

- the value of the moment of resistance on the steering wheel depends on the angle and speed of the steering wheel rotation, as well as the discrepancy between the steering wheel angle and one of the steered wheels:

$$M_r = K \cdot \left( -k_1 \cdot \alpha - k_2 \cdot \dot{\alpha} - k_3 \cdot \left( \alpha - \frac{\theta_1}{i_{sg}} \right) - k_4 \cdot \left( \dot{\alpha} - \frac{\dot{\theta}_1}{i_{sg}} \right) \right), \quad (2)$$

where  $M_r$  is the moment of resistance on the steering wheel, N·m;  $\alpha$  is the value of the angle of rotation of the steering wheel, rad;  $\dot{\alpha}$  is the time derivative of the angle of rotation of the steering wheel, rad/s;  $\theta_1$  is the value of the angle of rotation of the front left wheel, rad;  $\dot{\theta}_1$  is the time derivative of the angle of rotation of the front left wheel, rad/s;  $i_{sg}$  is the transmission ratio of the steering gear;  $K, k_1 \dots k_4$  are the gain factors,  $k_1 = 3 \text{ N}\cdot\text{m} / \text{rad}$ ,  $k_2 = 1 \text{ N}\cdot\text{m} / \text{s}^{-1}$ ,  $k_3 = 0.2 \text{ N}\cdot\text{m}/\text{rad}$ ,  $k_4 = 1 \text{ N}\cdot\text{m}/\text{s}^{-1}$ ,  $K = 3$ .

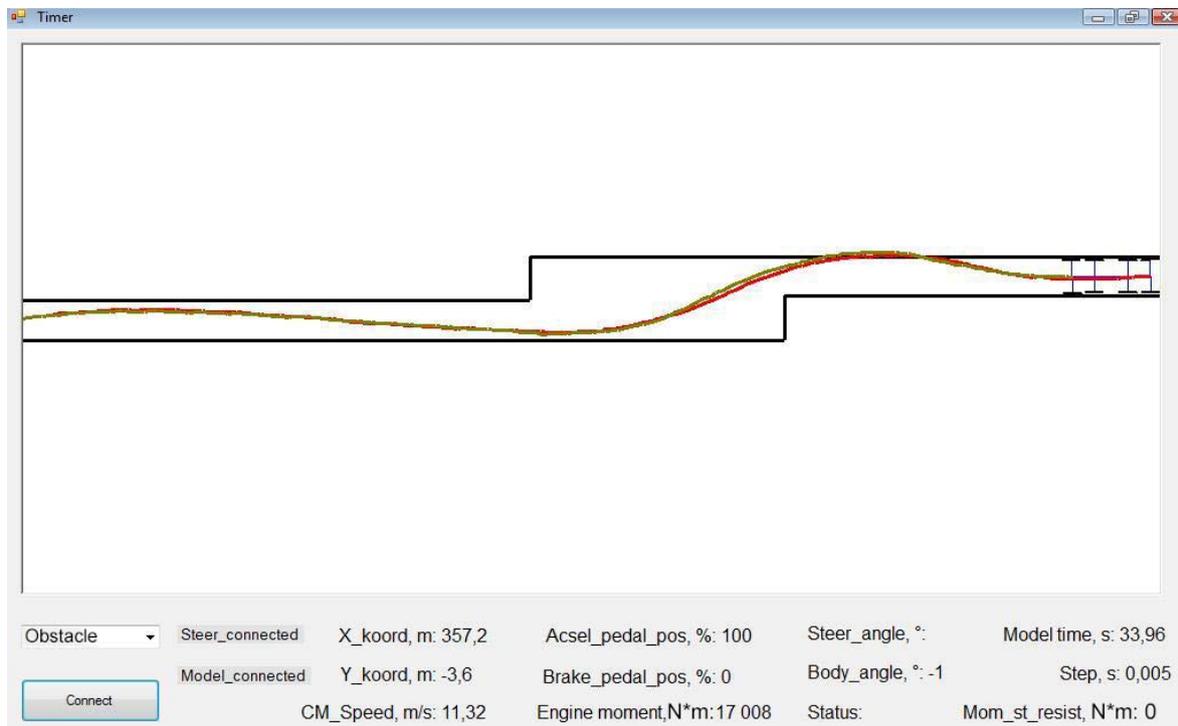
The value of the current steering angle is fed into the model from the control system of the ELSW (in accordance with figure 5), and the calculation of the steering wheel speed, the angle of rotation of the selected steering wheel and steering angle mismatch are performed while the model is running.

In order to control the rotation of the steered wheels during the implementation of the real-time model, the control law described in paper [9] was chosen. This control law is described by the following relationship:

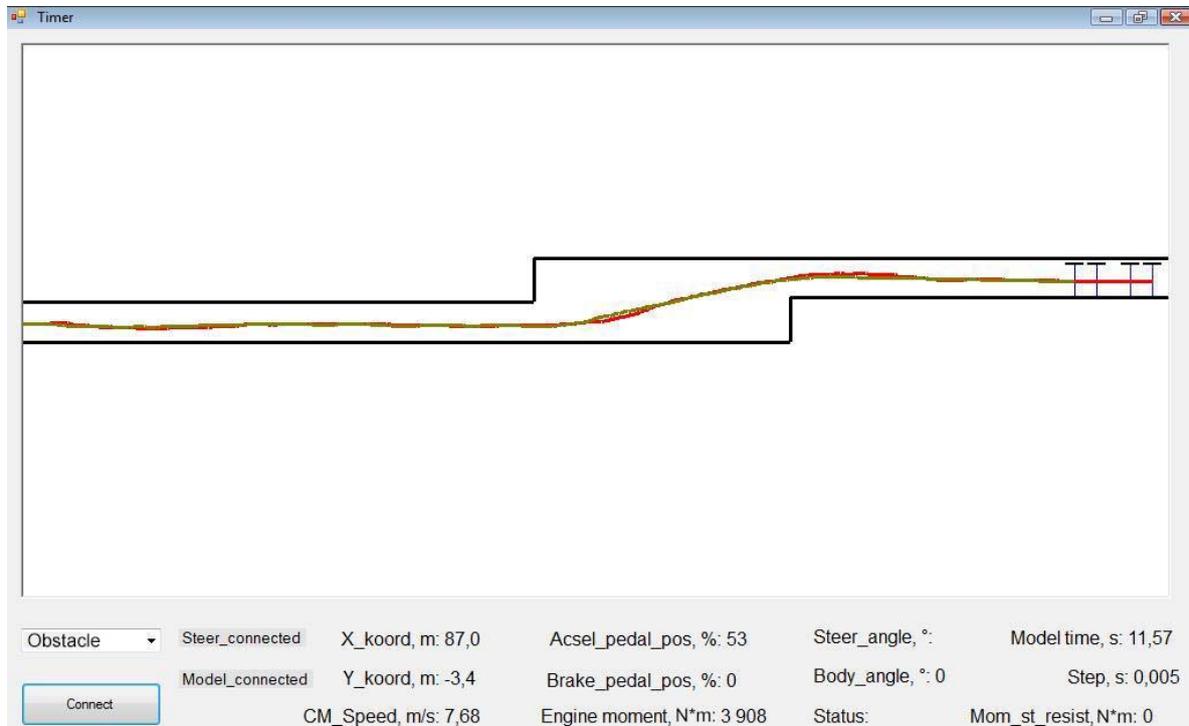
$$X_p = L/2 \cdot \left[ \frac{\theta_a - \theta_{del}}{\theta_{max} - \theta_{del}} \right]^n, \quad (3)$$

where  $X_p$  is the coordinate of the steering pole shift along the base;  $L$  is the base of the chassis;  $\theta_a$  is the average angle of the front axle, proportional to the angle of rotation of the steering wheel;  $\theta_{max}$  is the maximum angle of rotation of the steering wheel;  $\theta_{del}$  is the lag angle - the limiting angle of rotation of the front axle, within which the steering pole lies on the rear (last) axis.

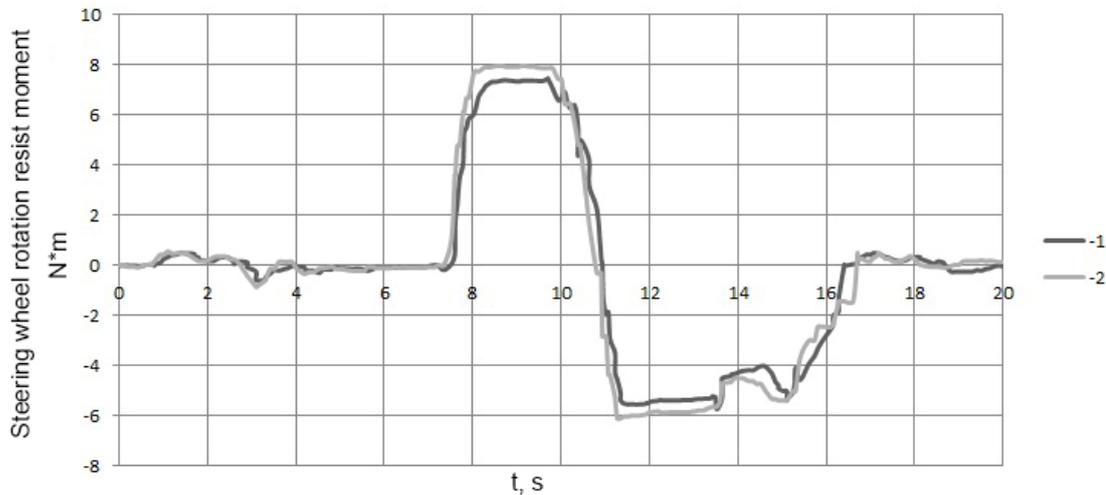
To check the correctness of the real-time model operation during interaction with the ELSW control system, two simulations of the lane change on a distance  $S_r = 20 \text{ m}$  were performed with the same parameters of motion. The first run was carried out without any moment of resistance on the steering wheel. During the second run, a resistance torque was formed on the SW, the value of which was determined in accordance with dependence (2). Figure 6 and figure 7 show the trajectories obtained at each simulation. Figure 8 shows the dependence of the required and current moment on the SW resistance.



**Figure 6.** Simulation results for the lane change without resistance on the steering wheel.



**Figure 7.** Simulation results for the lane change with the moment of resistance on the steering wheel.



**Figure 8.** Variation of the moment of resistance on the steering wheel during the lane change:  
 1 – current moment of resistance on the steering wheel;  
 2 – required moment of resistance.

According to the results of the lane change simulation it was noted that the ELSW control system correctly receives and executes the specified control action with the required resistance moment value from the real-time model. Generation of the required moment of resistance is carried out in a timely manner, without significant phase shifts, the actual value corresponds sufficiently to the specified value. When maneuvering, there was noticeable resistance on the steering wheel, as when changing the angle of rotation, and when it was held in a position other than neutral. The presented fact points to the possibility of applying real-time models of traffic dynamics in the development of remote control systems for wheeled vehicles.

The next stage of the experiment was to perform series of simulations of typical maneuvers for various parameters of the chassis movement. Lane change simulation was carried out at speeds of 15 km/h and 25 km/h; maneuver «Cornering with a radius of 35 m» was carried out at speeds of 15 km/h and 20 km/h.

Verification of the results of the real-time model when it interacts with the control system is carried out using a «reference» imitation mathematical model implemented in Matlab/Simulink. The correctness of the considered «reference» model was confirmed in the course of full-scale tests of the wheeled vehicle during typical maneuvers [2,3].

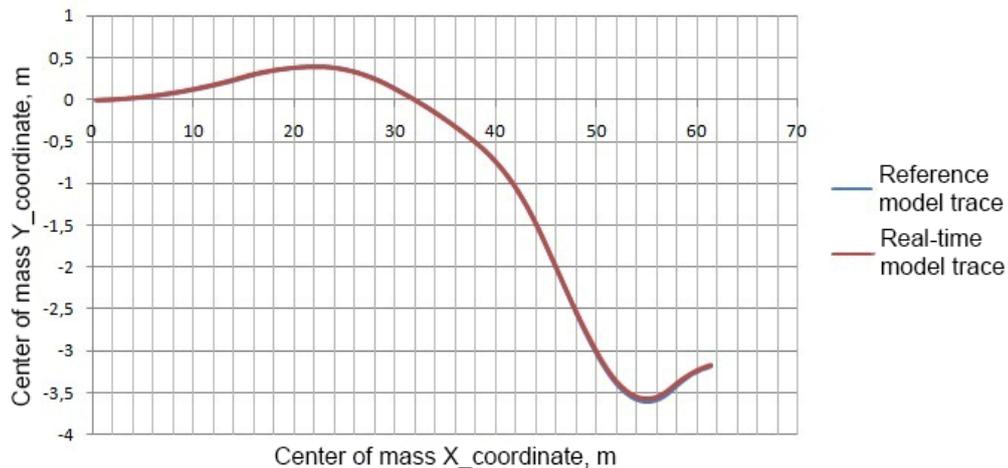
The general algorithm for verifying the real-time model consists of the following stages:

- simulation of the wheeled chassis movement in the real-time mode with recording the control actions to the file;
- modeling the movement of the wheeled chassis using a «reference» mathematical model, where the input dependencies are obtained using the dependencies of the control parameters;
- comparison of the results of mathematical modeling in real-time mode with the results of the work of the «reference» model with the purpose of estimating modeling errors in real-time;
- conclusions about the correctness of the real-time model by the results of the error estimation.
- To confirm the adequacy of the real-time model when working in conjunction with the ELSW control system of the remote control workstation, the following criteria are used:
  - the maximum value of the relative error of modeling in the real-time mode should not exceed 10%;
  - the value of the average relative error should not exceed 3%.

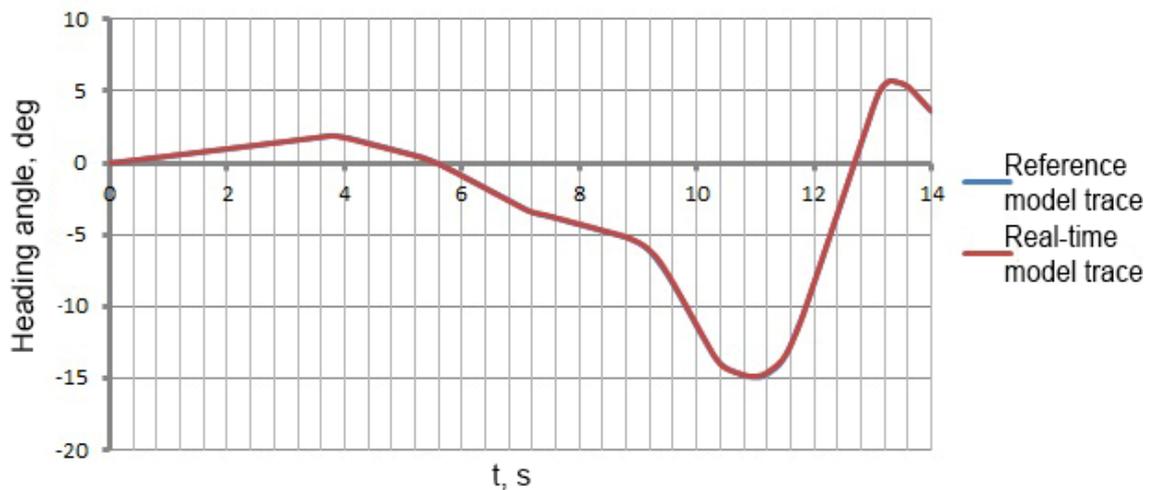
In accordance with the presented conditions, the following parameters are analyzed based on the results of the lane change and cornering simulations:

- the trajectory of the center of mass (CM);
- heading angle.

Figure 9 and figure 10 show the time histories of the parameters of the virtual chassis motion when performing the lane change with a speed of 15 km/h in real-time mode.



**Figure 9.** Centers of mass trajectories of the real-time model and the «reference» model during the lane change at speed of 15 km/h.



**Figure 10.** Heading angle of the real-time model and the «reference» model during the lane change at speed of 15 km/h.

Table 2 shows the maximum and average values of the relative errors of the output parameters obtained during simulation of typical maneuvers.

**Table 2.** Simulation errors.

Type of error	Lane Change $S_R = 20$ m, 15 km/h	Cornering $R_T = 35$ m, 15 km/h	Cornering $R_T = 35$ m, 20 km/h	Lane Change $S_R = 20$ m 25 km/h
Maximum relative error of the X-coordinate of the CM, %	0,5	0,34	0,5	0,57
Average relative error of the X-coordinate of the CM, %	0,0388	0,048	0,192	0,0388
Maximum relative error of the Y-coordinate of the CM, %	0,43	0,7	3,51	6,51
Average relative error of the Y coordinate of the CM, %	0,194	0,293	1,187	2,55
Maximum error of the heading angle, %	1,45	5,81	9,91	5,2
Average error of the heading angle, %	0,406	0,626	1,34	0,815

The presented data has proved adequacy of the real-time model on the basis of accepted criteria. This confirms the correctness of the real-time model work during interaction with the ELSW control system. The model can be used for the development of the workstations for remote control of vehicles.

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