Development and research of adaptive control algorithm for road train lateral motion

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Abstract. In the presented work, the problem of control of a road train when it performs various maneuvers while moving along the highway is considered. An adaptive algorithm for controlling the lateral displacement of road train elements is proposed, based on the use of a PD-controller, the values of the coefficients of which depend on the current value of the longitudinal velocity. Computer simulation has been carried out, which has shown the correctness of the proposed algorithm.

1. Introduction
One of the main trends in the modern stage of development of automotive technology is the widespread introduction of various kinds of electronic driver assistance systems [1]. Such systems are intended, first of all, to increase efficiency when performing typical maneuvers while driving: ensuring directional stability, maintaining a constant speed or distance to the vehicle in front, etc. However, there are also promising developments that provide a much higher degree of automation. These include systems that provide autonomous and semi-autonomous movement along the route (including movement in a column) with automatic route selection and its rebuilding when external conditions change [2]. According to a number of experts, in the next 10-15 years there will be a significant increase in the share of vehicles that can perform transportation without a driver [3]. Moreover, from a commercial point of view, trucks and road trains are of considerable interest – their full automation will significantly reduce operating costs and increase efficiency. Thus, the development of algorithms for automatic control of vehicle traffic can be considered extremely relevant.

When building control systems for automotive equipment, as a rule, a hierarchical principle is applied, in which 3 levels are distinguished [4]. At the lower (local) level, the issue of managing individual nodes and units is being resolved; at the middle (tactical) level, the coordinated operation of subsystems and the implementation of typical maneuvers by the car as a whole are considered; at a high (strategic) level, the tasks of choosing a route and determining modes of movement are solved in interaction with third-party information systems.

In this paper one of the tasks of the tactical level of road train control is considered – the implementation of typical maneuvers when moving along the highway. It is required to develop an algorithm that would ensure a high quality of control processes in all permissible modes of motion. It should be taken into account that the dynamics of the control object changes significantly depending on its speed.
2. Calculation model used

To describe the movement of the elements of a road train, consisting of a truck and a semitrailer connected by a fifth wheel coupling, we will use the mathematical model proposed in the work [5]. It is assumed that the road train makes a flat motion, the deformations of the supporting structures of the truck and the semitrailer can be neglected, the steering angles of the steered wheels and the slip angles of each of the wheels for all axles are pairwise equal to each other (thus, each axle can be replaced by one conventional wheel, which is affected by longitudinal and transverse components of the reaction force). The corresponding calculation scheme of the model is shown in figure 1.

![Figure 1. Calculation road train scheme.](image)

Taking into account the accepted assumptions, the movement of the truck and semitrailer can be described by the following system of equations:

\[
\begin{bmatrix}
\sigma (m_1 + m_2) & 0 & 0 & -m_2d_2 \sin (\varphi_1 - \varphi_2) & 0 & 0 & 0 & 0 \\
0 & m_1 + m_2 & m_1d_1 & -m_2d_2 \cos (\varphi_1 - \varphi_2) & 0 & 0 & 0 & 0 \\
0 & m_1d_1 & J_1 + m_1d_1^2 & 0 & 0 & 0 & 0 & 0 \\
0 & -m_2d_2 & 0 & J_2 + m_2d_2^2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{\varphi}_1 \\
\dot{F}_1 \\
\dot{\varphi}_2 \\
\dot{F}_2 \\
\dot{\varphi}_3 \\
\dot{F}_3 \\
\dot{\varphi}_4 \\
\dot{F}_4 \\
\dot{\varphi}_5 \\
\dot{F}_5 \\
\dot{\varphi}_6 \\
\dot{F}_6 \\
\dot{\varphi}_7 \\
\dot{F}_7 \\
\dot{\varphi}_8 \\
\dot{F}_8
\end{bmatrix}
= \begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
F_4 \\
F_5 \\
F_6 \\
F_7 \\
F_8
\end{bmatrix}.
\]
\[
\begin{align*}
F_1 &= (m_1 + m_2) v_y \omega_{z1} + m_1 d_1 \omega_{z1}^2 - m_2 d_2 \omega_{z2}^2 \cos(\varphi_1 - \varphi_2) - F_a - R_{x1} \cos \theta + R_{x2} - R_{x1} \sin \theta - (R_{y3} + R_{y4} + R_{y5}) \cos(\varphi_1 - \varphi_2) + (R_{y3} + R_{y4} + R_{y5}) \sin(\varphi_1 - \varphi_2), \\
F_2 &= -\sigma (m_1 + m_2) v_x \omega_{x1} + m_1 d_1 v_x \omega_{x1} \sin(\varphi_1 - \varphi_2) - R_{x1} \sin \theta + R_{x1} \cos \theta + R_{y2} + (R_{y3} + R_{y4} + R_{y5}) \sin(\varphi_1 - \varphi_2) + (R_{y3} + R_{y4} + R_{y5}) \cos(\varphi_1 - \varphi_2), \\
F_3 &= (\sigma - 1)(m_1 + m_2) v_x v_y - m_1 d_1 v_x \omega_{x1} - R_{x1} \sin \theta + R_{y1} \cos \theta - R_{y2} / 2, \\
F_4 &= m_2 d_2 v_x \omega_{z1} - R_{y1} \omega_{z1} - R_{y4} \omega_{z4} - R_{y5} \omega_{z5}, \\
F_5 &= v_x \cos \varphi_1 - v_y \sin \varphi_1, \\
F_6 &= v_x \sin \varphi_1 + v_y \cos \varphi_1, \\
F_7 &= \omega_{z1}, \\
F_8 &= \omega_{z2}.
\end{align*}
\]  

Here \(v_x\) and \(v_y\) – are values of the longitudinal and transverse components of the velocity of the fifth-wheel coupling in the moving coordinate system associated with the vehicle body; \(\omega_{z1}\) and \(\omega_{z2}\) – are angular speeds of rotation of the body of the truck and semitrailer; \(X\) and \(Y\) – are coordinates of the fifth-wheel coupling in immovable coordinate system associated with the road; \(\varphi_1\) and \(\varphi_2\) – are angles of rotation of the body of the truck and semitrailer; \(m_1\) and \(m_2\) – are truck and semitrailer weights; \(J_1\) and \(J_2\) – are moments of inertia of the truck and semitrailer relative to the axes passing through their centers of inertia perpendicular to the road plane; \(\sigma\) – is rotational inertia coefficient; \(d_1\) and \(d_2\) – are distances from the fifth-wheel coupling to the centers of inertia of the truck and semitrailer; \(R_{x1}\) and \(R_{x2}\) – are longitudinal and transverse components of the reaction force acting on the \(i\)-th axle; \(F_a\) – is aerodynamic resistance force; \(\theta\) – is steering angle of the front wheels of the truck; \(l_1\) and \(l_2\) – are distances from the fifth-wheel coupling to the front and rear axles of the truck; \(l_3, l_4, l_5\) – are distances from the fifth-wheel coupling to the corresponding axles of the semitrailer.

When solving the system of equations (1) – (2) it is assumed that the value of the longitudinal component of the reaction force is directly proportional to the rolling resistance coefficient of the \(i\)-th axle, and the transverse component of the reaction force is directly proportional to the side-slip angle of the \(i\)-th axle.

It is shown [5], that the presented model is relatively simple, but at the same time it allows to describe with a sufficiently high accuracy the behavior of the road train elements when performing typical maneuvers while moving along the highway.

To ensure the desired dynamics of the road train, it is proposed to use a control system, the block diagram of which is shown in figure 2. It includes a longitudinal velocity controller and a lateral displacement controller. The longitudinal velocity controller determines the required torque depending on the difference between the required and the actual value of the longitudinal velocity component. The lateral displacement controller determines the required steering angle of the front wheels of the truck depending on the difference between the required and the actual value of the lateral displacement of the fifth-wheel coupling. Since the dynamics of a road train at different speeds can differ significantly, it is proposed to make the lateral displacement controller adaptive: its coefficients will change depending on the actual value of the longitudinal velocity, providing a higher quality of control processes.

The described control system, which includes a model of road train dynamics (1) – (2) and models of controllers, was implemented in the Simulink environment of the Matlab computer mathematics system. The numerical values of the coefficients used in the model of the dynamics of the road train were chosen close to the characteristics of a real KAMAZ truck and semitrailer KRONE SDP 27.
3. Determination of parameters of the adaptive controller

To control the value of the longitudinal velocity and lateral displacement, in this work it is proposed to use a PID-controller. Controllers of this type are widely used in practice due to their rather high efficiency combined with ease of practical implementation [2].

To determine the optimal parameters of the controller we will use the standard Check Step Response Characteristics block of the Simulink environment [6]. At the same time, we will take into account that the maximum and minimum values of the output signal of the controller are limited both from above and from below – this is due to the physical nature of the signals $M$ and $\theta$.

At the initial stage, we will adjust the parameters of the longitudinal velocity controller using the previously mentioned tools. In the course of a series of computational experiments, it was determined that the optimal settings of the PID-controller are practically independent of the current motion speed. In this case, the values of the PID-controller coefficients averaged over the operating range were: $K_p = 2.006; K_I = 1.014; K_D = 1.113$. Thus, the use of an adaptive controller to control the longitudinal velocity of a road train is not advisable.

The computer simulation showed that for the selected values of the coefficients the quality indicators of the transient process remain sufficiently high in the speed range from 5 m·s$^{-1}$ to 30 m·s$^{-1}$, which corresponds to the real modes of motion of a road train along the highway. As an example, figure 3 shows the test results corresponding to the acceleration of a road train from 5 m·s$^{-1}$ to 10 m·s$^{-1}$ and from 15 m·s$^{-1}$ to 20 m·s$^{-1}$.

**Figure 3.** Speed change during acceleration from 5 to 10 (left) and from 15 to 20 (right).
As we can see, the selected controller settings allow obtaining results similar in efficiency. When developing the lateral displacement controller, we will take into account the physics of processes occurring in the control object. Since the value of the lateral velocity component is integrated when determining the value of the lateral displacement, it is not advisable to use the integral component of the controller. To confirm this assumption, a series of optimization experiments was carried out using the capabilities of the Simulink environment for tuning P-, PD-, PI-, PID-controllers at various values of the longitudinal component of the speed. The results obtained have confirmed that the use of a PD-controller allows providing the best quality indicators of control processes over the entire operating speed range.

Table 1 shows the values of the PD-controller coefficients obtained using the Check Step Response Characteristics tool, corresponding to various values of the longitudinal velocity of motion. It can be seen that the parameters of the controller differ greatly at different speeds; therefore, averaging the settings does not allow ensuring high quality of the control processes.

Table 1. Values of the controller coefficients.

| Longitudinal velocity, m·s⁻¹ | Coefficient \( K_P \) | Coefficient \( K_D \) |
|-----------------------------|------------------------|------------------------|
| 1                           | 36.528                 | 25.845                 |
| 5                           | 12.904                 | 8.384                  |
| 10                          | 3.278                  | 2.568                  |
| 15                          | 0.524                  | 0.485                  |
| 20                          | 0.296                  | 0.402                  |
| 25                          | 0.223                  | 0.364                  |

As an example, figure 4 shows the results of tests simulating the motion of a road train to an adjacent traffic lane at longitudinal velocities of 2 m·s⁻¹ and 20 m·s⁻¹. In this case, the parameters of the controller were determined by averaging the optimal values tuned for the reference speeds of the specified range.

As we can see, with the selected values of the coefficients at high speeds oscillations occur that are unacceptable in driving conditions on a real highway. Later a series of computational experiments was carried out for other ranges of speeds and values of the controller coefficients. The analysis of its
results showed that the high quality of lateral displacement control processes over the entire operating range of longitudinal velocities cannot be ensured using a PD-controller with constant coefficients.

Thus, to ensure the required quality indicators, it is necessary to use an adaptive controller, the coefficients of which change depending on the current value of the longitudinal velocity of the road train. To construct such a regulator, we use the previously obtained optimal values of the coefficients, an example of which is given in table 1. To calculate the values of KP and KD, corresponding to the intermediate values of the velocity, we will use the known interpolation methods.

To select the best type of interpolation, a series of computational experiments was carried out, during which the quality indicators of control processes were compared for various intermediate values of the velocity with linear, quadratic and spline interpolation. The resulting values of the coefficients and quality indicators of the transient process turned out to be quite close to each other. This can be explained by the relatively small velocity step that was used to prepare the initial data.

After analyzing the results obtained, it was decided to use the linear interpolation method for calculating the values of the coefficients in the construction of the adaptive controller, since, with a comparable quality of control processes, it is easier to implement and requires less resources of the onboard information and control system.

4. Results and discussion
To assess the quality of control using the developed adaptive controller, a series of tests was carried out that simulated typical road train maneuvers (lane change, overtaking, etc.) at different speeds. As an example, figure 5 and figure 6 show the graphs of the lateral displacement change during the lane change.

![Figure 5. Change in lateral displacement when using adaptive controller at low speeds.](attachment:image.png)

The analysis of the results obtained shows that the time of the transient process in all cases is acceptable, oscillation and overshoot are insignificant. Thus, the resulting controller makes it possible to ensure the set quality of the transient process at all speeds of the operating range.

It should be noted that in this work, a significant simplification was made regarding the nature of the road train movement: each transmission value corresponded to its own speed range, and these ranges did not overlap. Obviously, for a real car, this assumption is not fulfilled. Therefore, within the framework of further research, it is planned to improve the developed algorithm by taking into account the selected transmission when calculating the controller coefficients.
Figure 6. Change in lateral displacement when using adaptive controller at medium speeds.

5. Conclusions
In the presented work, a block diagram and algorithm for the operation of the system for controlling the motion of a road train are proposed. At the same time, it is proposed to use a classical PID-controller to control the longitudinal motion, and an adaptive PD-controller to control the lateral displacement, the coefficients of which change depending on the value of the longitudinal velocity. Computer simulation has been carried out, which has shown the high quality of the lateral motion control processes of the road train at the entire operating range of longitudinal velocities. In the future, it is planned to improve the proposed algorithm for calculating the controller coefficients, supplementing it with a dependence on the current value of the transmission gear ratio (this will allow to correctly work out situations of movement with the same speed in different transmissions).

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