Experimental system of safe distances and vehicle speed dynamic stabilization

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Abstract. One of the most promising direction for improving the level of traffic safety is various active safety systems creation. This area is intensively developed by leading foreign automakers and it is not complete. The relevance of researches aimed at effective active safety systems creating is determined by the world importance level of the traffic safety problem. Current study aims at the scientific substantiation of new technical solutions for the integrated vehicle active safety intelligent system. To conduct the research system analysis methods and modern control theory were used. The problem of structured set typical collisions prevention is reduced to the problem of vehicle state variables dynamic stabilization. The obtained result is the new technical solution scientific substantiation for the integrated intelligent system that combines the functions from several active safety systems. The high limit of the mass center velocity is defined as the minimum speed of the obstacle, wheels understeer or oversteer, turnover, slippage of the driving wheels and speed limits set by road signs, etc. To assess the control quality a modified quadratic functional is used that takes into account the operation costs as well as the software hardware initial cost. Analysis of the study results allows us to conclude that the intellectual properties developed by the system are acquired through the use of mathematical models and algorithms for indirect measurements performed in a minimal configuration of primary information sensors and actuators.

1. Introduction
One of the most promising direction for traffic safety improvement is various active safety systems creation [1]. This area is being intensively developed by leading foreign automakers. Leading foreign companies include the stabilization systems for longitudinal (ABS) and transverse (ESP) wheel slip [2, 3], turnover prevention, advanced emergency braking (AEBS), adaptive cruise control (ACC) [4], tire pressure monitoring (TPMS), position control on the lane (LDWS), etc. in the standard equipment of modern cars.

The purpose of the study is the scientific substantiation for new technical solutions of the vehicle active safety integrated intelligent system.

Based on the analysis of cars collision conditions it is possible to construct a structured set of typical collisions [5]. The problem of structured set collisions prevention is reduced to the problem of the vehicle state variables dynamic stabilization. An essential feature of the dynamic stabilization problem is the incomplete observability of the object state vector and the uncertainty of its dynamic boundaries. This feature determines the need to include the driver-operator in the control of traction loop, brakes and course.
The operator replacing at completing the unobserved state coordinates and their dynamic boundaries requires a large number of physical quantity sensors, which leads to a decrease in reliability, an increase in cost and other negative consequences [6].

The evolutionary process of automotive active safety systems improvement is built on a modular principle. This principle implies the expansion of additional functions by adding to the control system new blocks-modules that are connected to the common information bus [7], which creates a certain redundancy of technical facilities.

The integrated system involves combining the information and control functions of various active safety systems in a single control device at minimal configuration of primary information sensors and actuators.

2. Task statement
At the conceptual level, the task of adaptive cruise control is reduced to the safe distances and vehicle speeds dynamic stabilization in an automatic mode. Safe speed should be limited by the speed of oversteer and understeer, car turnover, driving wheels slippage, road signs, tire condition, etc.

The safe distances to obstacles in the front and rear hemispheres should be sufficient to prevent collisions with the stationary and passing vehicle when braking taking into account the condition of the road surface without blocking the wheels [8].

At the content level, the dynamic stabilization problem reduces to minimizing the modified quadratic control quality functional on a finite interval \( [t_2 - t_1] \) in the form:

\[
Q(t_2) = Q_1 + Q_2 \rightarrow \min
\]

at \( U \in U_{per}, R \in R_{per} \), where

\[
Q_1 = \int_{t_1}^{t_2} C_0[V_{mz}(\tau) - V_m(\tau)]^2 d\tau + \int_{t_1}^{t_2} \sum_{i=1}^{2} C_i[\Delta L_i(\tau) - \Delta L_{bound i}(\tau)]^2 d\tau;
\]

\[
Q_2 = \int_{t_1}^{t_2} \Delta C(R, \tau) d\tau + Q_2(R, t_2);
\]

\( U = (U_1, U_2, U_3)^T \) – control actions vector on the gearbox, traction and brakes;

\( U_{per} \) – permissible range of control actions;

\( R = (R_H, R_S)^T \) – technical solutions vector in the hardware (RH) and software (RS) facilities area;

\( V_{mz}(t) \) – safe vehicle speed;

\( V_m(t) \) – vehicle mass center speed;

\( \Delta L_{t1}(t) \) and \( \Delta L_{t2}(t) \) – distance to obstacles in the front and rear hemispheres on the lane;

\( \Delta L_{bound 1}(t) \) and \( \Delta L_{bound 2}(t) \) – boundary values of safe distances to obstacles in the front and rear hemispheres;

\( \Delta C(R, t) \) – intensity of the operating system costs;

The best solution of the problem (1) in the proposed statement is the traction and brakes control algorithm providing stabilization of safe distances and speeds realized in the software and hardware environment with the minimum acquisition and operation cost.

3. Research results
To implement the stabilization safe speed algorithm, a single-step traction and braking control is used.

The specified speed \( V_{mz} \) is defined as the low limit of safe speeds determined from the conditions for typical collisions of a structured set prevention.

The components of the constraint vector includes:

\( V_{mz0} \) – specified speed of movement;

\( V_{mz1} \) – given speed of obstacle approaching;

\( V_{bound 0} \) – boundary rollover speed;
\( V_{\text{bound}_1} \) — boundary speed of the front wheels understeer;
\( V_{\text{bound}_2} \) — boundary speed of the rear wheels oversteer;
\( V_{\text{bound}_3} \) — boundary speed of driving wheels slipping;
\( V_{\text{bound}_4} \) — boundary speed of tire cords rupture;
\( V_{\text{bound}_5} \) — boundary speed of movement with spare wheel;
\( V_{\text{bound}_6} \) — boundary speed specified by road signs in the their action zone;
\( V_{\text{bound}_7} \) — boundary speed of the permissible vibrations level.

The resulting value \( V_{mz} \) is defined as:

\[
V_{mz} = \min[V_{mz0}, V_{\text{bound}_1}, V_{\text{bound}_2}, ..., V_{\text{bound}_7}] 
\]  

(2)

\( V_{\text{mz}1} = \begin{cases} 
0, & \text{if } V_{ob} = 0 \text{ and } \Delta L < \Delta L_{\text{bound}}; \\
V_{ob} + k_0(\Delta L - \Delta L_{\text{bound}}), & \text{if } V_{ob} > 0 \text{ and } \Delta L > \Delta L_{\text{bound}}; \\
V_{mz0}, & \text{if } V_{ob} = 0 \text{ and } \Delta L \geq \Delta L_{\text{bound}}.
\end{cases} 
\]

\( V_{ob} \) — obstacle speed;
\( \Delta L \) — distance to the obstacle;
\( \Delta L_{\text{bound}} \) — safe distance boundary value to the obstacle in the front hemisphere;
\( k_0 \) — speed controller gain factor of approaching to the obstacle.

The quantity \( \Delta L_{\text{bound}} \) is defined as the maximum boundary distances of approaching to the obstacles during the delay time \( \tau_m \) of the deceleration \( \Delta L_{\text{bound}_1} \) and the limiting distance of the deceleration to the full stop \( \Delta L_{\text{bound}_2} \):

\[
\Delta L_{\text{bound}} = \max[\Delta L_{\text{bound}_1}, \Delta L_{\text{bound}_2}] 
\]  

(3)

\[
\Delta L_{\text{bound}_1} = 0.5\Delta a_{ob1}^2\tau_m^2; \\
\Delta L_{\text{bound}_2} = V_m \cdot \tau_m + 0.5V_{ob}^2\tau_T^{-1} - 0.5V_{ob}^2\Delta a_{ob}^{-1}. 
\]

Speed identification of the passing obstacle \( V_{ob} \) is performed from the distance measurement to the nearest obstacle on the lane \( \Delta L \) and the solution of the approach speed differential equation in discrete time with step \( \Delta T \):

\[
V_{ob}(k) = [\Delta L(k) - \Delta L(k - 1)] \cdot \Delta T^{-1} + V_m(k) 
\]  

(4)

Safe distances stabilization in the front and rear hemispheres on the lane is performed by controlling the value of the braking deceleration \( a_T \). Its value is determined from the equations of the boundary distances to the front and rear obstacles in the form:

\[
a_T = \min[a_{T0}, a_{T1}, a_{T2}] 
\]  

(5)

\[
a_{T0} = 0.5V_m^2[\Delta L_1 - \Delta L_{\text{del}} + 0.5V_{ob1}^2\Delta a_{ob1}^{-1}]^{-1}; \\
a_{T1} = 2\Delta L_2 \cdot \Delta a_{ob2}^{-2}; \\
a_{T2} = 0.5V_m^2[V_{ob2}^2\tau_{ob2} + 0.5V_{ob2}^2\Delta a_{ob2}^{-1} - \Delta L_{ob2}]^{-1}; \\
\tau_{ob1} \text{ and } \tau_{ob2} \text{ — estimates of the brake systems operation lag of the front and rear obstacles; } \\
V_{ob1} \text{ and } V_{ob2} \text{ — front and rear obstacles speed; } \\
\Delta a_{ob1} \text{ and } \Delta a_{ob2} \text{ — estimates of the front and rear obstacles maximum decelerations.}
\]

Brake deceleration value is limited by the maximum value \( a_{Tmax} \), which depends on the braking system parameters and the condition of the road surface.

The experimental intelligent active safety system includes:
- standard wheel speed sensors;
- front and rear cameras;
- video processing unit;
- three-axis solid-state accelerometers (MEMS);
• brake actuator;
• control board with software-controlled keys.

The experimental system is mounted on the "Lada Kalina" car with an electric drive and is being tested at the NAMI testing ground in Dmitrov.

The preliminary tests results confirm rather high efficiency of adaptive cruise control, automatic braking, driving stability, tire pressure and braking overheating temperatures monitoring function.

Information functions for estimating the vehicle state coordinates, such as mass center velocity, steering angle, tire pressure, brake overheating temperature, wear of tire cords, etc. are carried out using virtual sensors implemented programmatically.

Thus, the proposed technical solution is characterized by minimum hardware configuration, minimum operation and acquisition costs.

4. Conclusion
The analysis of conducted researches allows to formulate the following conclusions:
• The developed models and control algorithms for traction and brake channels are based on deterministic descriptions of traction, braking acceleration and course angle determined by control actions on the controls;
• Mathematical models are adequate in the operating range of velocities and accelerations and can be tuned to a particular model of the vehicle by introducing tuning data;
• The above control algorithms provide the solution of the vehicle state coordinates dynamic stabilization problem taking into account the extended velocity constraint vector, replacing the functions of the individual systems: ABS, ASR, ESP, ACC, AEBS and TPMS in minimal hardware configuration.

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