System analysis of vehicle active safety problem

S E Buznikov
FSUE NAMI, Moscow, Russian Federation

E-mail: sergey.buznikov@nami.ru

Abstract. The problem of the road transport safety affects the vital interests of the most of the population and is characterized by a global level of significance. The system analysis of problem of creation of competitive active vehicle safety systems is presented as an interrelated complex of tasks of multi-criterion optimization and dynamic stabilization of the state variables of a controlled object. Solving them requires generation of all possible variants of technical solutions within the software and hardware domains and synthesis of the control, which is close to optimum. For implementing the task of the system analysis the Zwicky "morphological box" method is used. Creation of comprehensive active safety systems involves solution of the problem of preventing typical collisions. For solving it, a structured set of collisions is introduced with its elements being generated also using the Zwicky "morphological box" method. The obstacle speed, the longitudinal acceleration of the controlled object and the unpredictable changes in its movement direction due to certain faults, the road surface condition and the control errors are taken as structure variables that characterize the conditions of collisions. The conditions for preventing typical collisions are presented as inequalities for physical variables that define the state vector of the object and its dynamic limits.

1. Introduction stating the purpose of the scientific work
The problem of the road transport safety affects the vital interests of the most of the population and is characterized by a global level of significance [1].

The search of ways to solve this problem is continuously conducted by the state legislative and executive bodies, public and international organizations.

However, expecting a quick solution without a clear understanding of the nature of the problem is unrealistic.

One of the conditions for improvement in the difficult economic situation is to focus on resolving the central problem of the market economy – creation of goods and services of the highest level of competitiveness.

The purpose of this scientific work is the system analysis of the issue of creation of competitive active safety systems.

One of the promising directions of resolving the problem of the vehicle traffic safety successfully developed by the leading international companies is the creation of a variety of active safety systems [2]. Such systems, including hardware and software, are designed to prevent collisions of particular types [3].

However, copying foreign technical solutions, information technologies, standards and regulations without consideration of the technological and manufacturing capabilities and without analyzing the conditions of vehicle operation in Russia will not produce a proper result.
While creation of new hardware, such as information sensors, actuators, interfaces etc. requires new materials and technologies, in the software field the range of creative activities is practically unlimited.

2. Definition of the multi-criterion optimization task in the area of technical solutions

Ensuring competitiveness of technical products is in fact directly related to solution of the problem of the multi-criterion (vector) optimization.

Competing objects are characterized by the performance vector:

\[ Q = (q_1, q_2 \ldots q_n)^T, \]

where: \( q_i(R), 0 \leq i \leq n \) – individual performance indicators whose values depend on the technical solutions vector \( R = (R_h, R_s)^T \), where \( R_h \) is the hardware vector and \( R_s \) is the software vector.

The main customer satisfaction indicators of the systems [4] in question include:

- \( q_0(R) \) – level of the external styling;
- \( q_1(R) \) – completeness of implemented functions;
- \( q_2(R) \) – level of monitoring and control errors;
- \( q_3(R) \) – level of power consumption from external sources;
- \( q_4(R) \) – degree of environmental impacts;
- \( q_5(R) \) – degree of influence on related systems;
- \( q_6(R) \) – level of failure resistance;
- \( q_7(R) \) – limitations of installation on objects;
- \( q_8(R) \) – operation costs;
- \( q_9(R) \) – system kit price.

The indicators \( q_i(R) \) will be rendered to a minimized form and are dimensionless.

The special feature of the solution of the multi-criterion optimization problem under the market economy conditions is that the choice of the best option in some sense to a large extent is done not by the developer but by the end user. This means that the demand for products that do not belong to a set of compromises naturally ends up being zero. Also the fact that a product belongs to an optimum set does guarantee its commercial success with the customers as their preferences may change in unpredictable ways.

Objective properties will be acquired by technical solutions belonging to the record systems domain (R-systems) that are subject to the system of inequalities:

\[ q_i(R) \leq q_{i_{\min}}, 0 \leq i \leq 9. \]

It is obvious that it is impossible to create systems with record performance using conventional development technologies and standard hardware and software, which inevitably leads to duplication of common solutions from the multitude of solutions that are not competitive.

The concept for creating record systems will be defined in the upstream research phase in terms of the consumer property indicator values, which specifies the coordinates of the development end target.

However, the process of moving to it takes certain time even when the developer knows how to implement the plans. This circumstance creates risks from the competitors who have the ability to stay ahead of developer and to enter the market with products of similar purpose soon.

As the direction of the search for new technical solutions that provide record performance one should consider the hardware domain \( R_h \) and the software domain \( R_s \).

The analysis of the multi-criterion optimization problem for the record systems shows that its solution lies in the field of intelligent systems that are implemented in a minimal hardware configuration.
3. The results of building a structured set of typical collisions

For assessment of the set of potential collisions and ways to prevent them, a structured set of collisions is built with the aim of decomposing the main task into groups of individual tasks.

Let us consider the conditions of the collisions \[5\] of the controlled object and the obstacle on the road surface:

\[
\begin{align*}
\{ |L_m(t) - L_{obs}(t)| &\leq E_1; \\
|H_m(t) - H_{obs}(t)| &\leq E_2,
\end{align*}
\]

where \(L_m(t)\) and \(H_m(t)\) are the coordinates of the center of mass of the controlled object in curvilinear coordinate system related to the topology of the route; \(L_{obs}(t)\) and \(H_{obs}(t)\) are accordingly the coordinates of the center of mass of the obstacle in the same coordinate system as the distance from the starting point of the route and the distance from the edge of the road surface; \(E_1 > 0\) and \(E_2 > 0\) are the constants commensurable with the dimensions of the object and the obstacle.

The collision condition (1) is the necessary and sufficient condition for the two objects to be at the moment of time \(t\) in the neighborhood of the same point on the road surface.

For the collision not to occur it is sufficient for at least one of the inequalities (1) not to hold within the travel time interval.

For solving this problem let us build a structured set of collisions. Let us assume that at moment of time \(t_0 < t\), a collision does not occur and the inequalities of system (1) are not fulfilled.

Let us define what leads to a collision of the object and the obstacle at the moment of time \(t\). For this let us put down the following system of inequalities:

\[
\begin{align*}
\{ |L_m(t_0) + \Delta L_m(t) - L_{obs}(t_0) - \Delta L_{obs}(t)| &\leq E_1; \\
|H_m(t_0) + \Delta H_m(t) - H_{obs}(t_0) - \Delta H_{obs}(t)| &\leq E_2,
\end{align*}
\]

where

\[
\begin{align*}
\Delta L_m(t) &= \int_{t_0}^{t} V_m(\tau) d\tau = \int_{t_0}^{t} [V_m(t_0) + a_m(\tau) \tau] d\tau; \\
\Delta L_{obs}(t) &= \int_{t_0}^{t} V_{obs}(\tau) d\tau; \\
\Delta H_m(t) &= \Delta \Psi_m(t) \Delta L_m(t); \\
\Delta H_{obs}(t) &= \Delta \Psi_{obs}(t) \Delta L_{obs}(t); \\
\Delta \Psi_m(t) &= b_m^{-1} \int_{t_0}^{t} V_m(\tau) \psi_{cm}(\tau) d\tau + \int_{t_0}^{t} \Delta \omega_m(\tau) d\tau; \\
\Delta \Psi_{obs}(t) &= b_{obs}^{-1} \int_{t_0}^{t} V_{obs}(\tau) \psi_{obs}(\tau) d\tau + \int_{t_0}^{t} \Delta \omega_{obs}(\tau) d\tau;
\end{align*}
\]

\(\Delta \Psi_m(t)\) and \(\Delta \Psi_{obs}(t)\) are the unpredictable changes of the course angles of the controlled object and the obstacle;

\(\Delta \omega_m\) and \(\Delta \omega_{obs}\) are the additional components of the angular velocities of the controlled object and the obstacle occurring during wheel slippage and drift;

\(b_m\) and \(b_{obs}\) are the wheelbases of the controlled object and the obstacle;

\(\psi_{cm}\) and \(\psi_{obs}\) are the steering angles of the object and the obstacle;

\(V_m\) and \(V_{obs}\) are the longitudinal velocities of the centers of mass of the controlled object and the obstacle;

\(a_m\) is the longitudinal acceleration of center of mass of the controlled object.

It should be noted that difference of the system of inequalities (2) for moment of time \(t\) from the inequalities at the moment of time \(t_0\), is availability of non-zero summands \([\Delta L_m(t) - \Delta L_{obs}(t)]\) and \([\Delta H_m(t) - \Delta H_{obs}(t)]\), which, in fact, lead to collisions.

To build a structured set of collisions we use the Zwicky "morphological box" method [6]. To simplify the problem, let us assume that \(V_m(t_0) \geq 0\), while unpredictable changes of the obstacle’s heading do not exist \(\Delta H_{obs}(t) = 0\).
We introduce three structural independent variables corresponding to driving conditions of the controlled object and the obstacle included in the equations of the additional summands $\Delta L_m(t)$, $\Delta L_{obs}(t)$ and $\Delta H_m(t)$:

$$\tilde{a}_m = \begin{cases} 
0, & \text{if } a_m = 0 - \text{driving at constant speed}; \\
1, & \text{if } a_m > 0 - \text{acceleration}; \\
2, & \text{if } a_m < 0 - \text{deceleration}, 
\end{cases}$$

$$V_{obs} = \begin{cases} 
0, & \text{if } V_{obs} = 0 - \text{stationary obstacle}; \\
1, & \text{if } V_{obs} > 0 - \text{followed obstacle}; \\
2, & \text{if } V_{obs} < 0 - \text{oncoming obstacle}, 
\end{cases}$$

$$\Delta \varPhi_m = \begin{cases} 
0, & \text{if } \Delta \varPhi_m(t) = 0 - \text{with no destabilizing facts}; \\
1, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due of asymmetry of axle pairs of wheels}; \\
2, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to tire failure}; \\
3, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to separation of wheels from hubs}; \\
4, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due of suspension or steering failure}; \\
5, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to longitudinal wheel slip}; \\
6, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to lateral wheel slip}; \\
7, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to asymmetry of brakes}; \\
8, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to road surface condition}; \\
9, & \text{if } \Delta \varPhi_m(t) \neq 0 - \text{due to driving errors}. 
\end{cases}$$

The introduction of these independent structural variables implies consideration of collisions with stationary, oncoming and followed obstacles. Collisions with obstacles at the crossroads are equivalent to collisions with stationary obstacles.

Unpredictable changes of the heading in collisions may occur or not to occur as a result of unpredictable changes of the steering angle $\psi_c \neq 0$ or an additional angular frequency of revolution of the center of mass $\Delta \omega_m \neq 0$ resulting from wheel slippage or drift.

The set of states of the variable $\Delta \varPhi_m$ corresponds to the effect of certain factors that characterize the state of the object, possible faults, the road surface condition and the driving errors.

The set of typical collisions $M_1$ built from the above variables forms a group of 90 events in total.

The set of rollovers $M_2$ includes the events that may happen both on the road surface as well as due to departure from the road.

The set of rollovers $M_2(\Delta \varPhi_m)$ contains 10 events and also forms a complete group of events for rollovers.

The total capacity of sets $M_1$ and $M_2$ is 100 events and forms a model of problem suitable for its analysis by parts.

4. Analysis of a structured set of typical collisions

Introduction of a structured set of typical collisions by the decomposition of the main problem into individual problems that are more convenient for analysis and synthesis of the control actions, allows assessing the engineering level of various technical and organizational solutions aimed at alleviating the problem.

Figure 1 shows a structured set of typical collisions $M_1$ and rollovers $M_2$.

One of directions of solving the problem of collision prevention that evolved internationally in the recent decades is the construction of highways.

A highway is a multi-lane one-way road without intersections with other roads on the same level.

The highway topology enables prevention of collisions with oncoming obstacles, stationary obstacles and obstacles assumed as stationary from intersecting directions.
In this case from the structured set of collisions $M_1$, 30 collisions with oncoming obstacles and 30 collisions with stationary obstacles are excluded. The remaining 30 collisions with followed obstacles and 10 rollovers due to driving errors, vehicle running condition and road environment stay as a potentially possible.

Implementation of this direction involves substantial costs and with current condition of the road network in Russia cannot be considered as the only possible solution.

![Figure 1. Structured set of typical collisions and rollovers.](image)

| No. | Foreign active safety systems | Limitations of functioning in full configuration |
|-----|-------------------------------|-------------------------------------------------|
| 1   | AEBS                          | Braking with activation of ABS w/o consideration for distance to vehicle that follows |
| 2   | ACC                           | Maintaining speed and distance that are not safe |
| 3   | TPMS                          | Pressure in one of four wheels at $V_m > 40$ km/h; $\Delta P_i > 0.6$ bar |
| 4   | ABS, ASR                      | Significant reduction of braking efficiency on rough surfaces, on ice and snow |
| 5   | ESP                           | Inefficient for vehicles with a high center of mass and on dirt roads |
| 6   | LDWS                          | Requires recognizable road marking and forces driving in wheel track |
| 7   | DMS                           | Requires individual driver settings |

Modern foreign systems (ABS, ASR, ESP, AEBS, TPMS, ACC, LDWS, DMS, etc.) designed to prevent certain groups of typical collisions of a structured set (see Figure 1) do not provide a complete solution of the general problem. At the same time, the existing active safety systems have a number of drawbacks that cannot be eliminated and significantly impair their effectiveness.
Table 1 shows the characteristics of foreign active safety systems that limit their application under Russian road and climatic conditions.

5. Task of dynamic stabilization of vehicles

The analysis of conditions of collisions of the controlled object with obstacles allows building a set of typical collisions, which allows decomposition of the general problem of collision prevention into subsets of individual problems. For defining typical collision groups, sufficient conditions for their prevention may be recorded in the form of inequalities for specific physical variables. Combining the groups of inequalities \( M_i \) for each of the variables \( x_i \) into one with upper and lower limits allows reducing the task of collision prevention to the problem of the dynamic stability controls stated most generally:

\[
x_{i,lim}^l(U,X,t) \leq x_i(t) \leq x_{i,lim}^u(U,X,t), 1 \leq i \leq n \quad \text{during} \quad U \in U_{adm},
\]

where \( x_i(t) \) is the \( i \)-th component of the state vector \( X \);

\( U = (U_1, U_2, ..., U_m)^T \) is the vector of control actions with components \( U_j, 1 \leq j \leq m; \)

\( U_{adm} \) is the admissible set of control actions;

\( x_{i,lim}^l(U,X,t) = \min[x_{i,lim1}, x_{i,lim2}, ..., x_{i,limr_i}] \) is the upper limit of the admissible values of \( x_i \);

\( x_{i,lim}^u(U,X,t) = \min[x_{i,lim1}, x_{i,lim2}, ..., x_{i,limr_i}] \) is the lower limit of the admissible values of \( x_i \).

The special feature of the task of the dynamic stability control for the class of objects in question is the fact that the overwhelming number of components of the state vector \( X \) are not measured and their dynamic limits \( x_{i,lim}^l \) and \( x_{i,lim}^u \) are not defined, which makes the control object not fully observable. Moreover, the dimension of the control vector \( m \ll r \) makes the object not fully controllable. These properties are crucial in construction of modern automated control systems with operator participation. The task involves augmentation of the state coordinates that are not measured and their dynamic limits based on experience, intuition, prediction and other individual characteristics of the operator.

For automatic control of the object of the given class the solution of the most comprehensively stated problem of the dynamic stability control is necessary.

From standpoint of modern control theory, the solution of the task of dynamic stability control with the finite time interval \( (t_1 + t_2) \) will be assessed by value of the quadratic functional of the control quality with the functional limitations for the technical and economic indicators of the system implementing the control taken into account:

\[
Q(t_2) = \int_{t_1}^{t_2} \sum_{i=1}^{n} C_{li} [x_i(\tau) - x_{i,lim}^l(U,X,t)]^2 \, d\tau + \int_{t_1}^{t_2} \sum_{i=1}^{n} C_{2i} [x_i(\tau) - x_{i,lim}^u(U,X,t)]^2 \, d\tau \rightarrow \min
\]

with \( U \in U_{adm}, R = (R_H, R_S)^T \in R_{adm}; q_i(R) \leq q_{i,adm}, 1 \leq i \leq l, \)

where \( C_{li} = \begin{cases} 0, \text{if } x_i(t) \leq x_{i,lim}^l; \\ \infty, \text{if } x_i(t) > x_{i,lim}^u; \end{cases} \)

\[
C_{2i} = \begin{cases} 0, \text{if } x_i(t) \geq x_{i,lim}^u; \\ \infty, \text{if } x_i(t) < x_{i,lim}^l; \end{cases}
\]

\( R \) is the vector of technical solutions; \( R_H \) and \( R_S \) are the vectors of hardware and software solutions;

\( R_{adm} \) is the admissible set of technical solutions;

\( q_i(R) \) is the \( i \)-th component of the vector of technical and economic indicators;

\( q_{i,adm} \) is the admissible value of \( i \)-th component of the vector of technical and economic indicators.

The set of the main technical and economic indicators includes the levels of power consumption, the environmental impacts, the versatility, the fault resistance, the operating costs and the cost of hardware and software.

The best solution of the problem stated as proposed is an algorithm for triggering control actions that provide dynamic stability control of the object’s state vector implemented within software and hardware environment that satisfies the system of constraints for the technical and economic indicators.
6. Conclusions
Based on the analysis performed the following conclusions can be drawn:

- Creation of active safety systems represents the most promising direction for resolving the problem of the motor vehicle traffic safety.
- Modern foreign active safety systems potentially can prevent up to 57 typical collisions out of possible 100, but this is not enough to consider the problem solved.
- The augmentation of the functions of the future systems by solutions for prevention failures of tires, steering and suspension, separation of wheels from hubs along with improvement of other solutions should allow creation of a full-featured active safety system for the road and climatic conditions of the Russian Federation.
- For achievement of a significant reduction of the accident rate all vehicle in operation, including the vehicles of lowest price segments, shout be fitted with such systems.
- Attaining a highest competiveness status by such systems is possible with a minimal configuration of technical means through the use of more advanced mathematical models and information processing algorithms.

Acknowledgments
This paper was prepared based on the results of the application research performed with the financial support of the Ministry of Education and Science of Russia. Agreement No. 14.624.21.0048, unique project identifier RFMEFI62417X0048.

References
[1] Ilarionov V A 1989 The system analysis of road traffic and road accidents Collection of Science Proc. (Moscow:MADI) p 107
[2] Davis LC Stability of adaptive cruise control systems taking account of vehicle response time and delay Physics Letters A. 2012 376 p 2658–2662
[3] Eunbi Jeong Evaluating the effectiveness of active vehicle safety systems Accident Analysis & Prevention 2017 100 p 85–96
[4] Buznikov S. E The principles of construction record information control systems for commercial purposes Materials of XIII scientific-technical Conf. “Sensor 2001” p 171-173
[5] Buznikov S E Current state and prospects of automobile active safety systems development Proc. of XV Int. Conf. “Control problems of sophisticated systems safety” (Moscow:RGGU) 2 p 207-11
[6] Zwicky F The morphological approach to discovery, invention, research and construction New methods of thought and procedure (Passadena) 1967 p 273–297