Structuring tasks of control over driverless vehicles within intelligent transport systems

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Abstract. The relevance of the research topic is defined by the global level of significance of the problem of creation and safe operation of driverless transport on public roads. The research objective was to develop a mathematical model of the problem that allows forming a scientifically grounded strategy for driverless transport progress. The Zwicky Morphological Box method was used as a research method, which allowed building a structured set of intelligent transport system variants. Variables corresponding to the hard-surfaced road types, the level of informational support in the form of digital road models and the level of control tasks with increasing complexity were used as structural variables. A complex of tasks required to control traffic or driving in closed territories, on highways, suburban motorways passing through human settlements, urban streets, and yards has been defined. The control task complexes of each consecutive level include the task complexes of all the previous levels, and the digital road models of a higher level contain the digital models of all the previous levels. The analysis of the obtained results allowed building a trajectory of progressive development of the driverless vehicle focus area within the field of control task levels, road types, and their digital models.

1. Introduction
The scientific and technical problem of creation and safe operation of driverless vehicles is in the focus of attention of the international scientific community [1] and is characterized by the global significance level. Leading foreign companies [2] and Russian organizations and enterprises are engaged in solving this problem.

From the conceptual perspective, the problem description and solutions are often limited to the number of millions of kilometers driven, detailed description of collisions caused by autopilots [3], discussion of obvious legal responsibility issues [4], ways to simulate road situations, discussion of computer vision devices’ capabilities [5] and accumulation of trial and error experience, also on public roads.

From the substantial perspective, the problem description represents a formalized model in the context of significant factors defining its essence.

An adequate model of the problem shall ensure directed search for the most rational solutions, building of well-grounded sequences of stages of development, testing and certification rules.

To build the mathematical model of the problem, the Zwicky Morphological Box method [6] was used, which is based on decomposition of an initial complex problem into independent components to generate and analyze a complete set of possible variants.

The significant factors of the problem as a research object include the levels of control tasks, types of roads and levels of infrastructure informational support.
While structuring types of roads and levels of informational support in the form of digital road models causes no difficulties, structuring the control tasks needs conducting some investigations. System analysis of the traffic safety problem [7] shows that the task of preventing collisions with obstacles reduces to the task of dynamic stabilization of the vehicle state variables with limited control inputs in terms of traction, braking and direction.

2. Research objective definition
The research objective is to develop an adequate mathematical model of the problem, which would allow forming a scientifically grounded strategy for the progress of the driverless vehicles (DLV) focus area within the intelligent transport systems (ITS).

Practical use of the research results assumes the possibility to objectively assess the relative complexity of execution of a complex of driving tasks of different levels and to define a rational sequence for solving the control tasks for DLV in the course of their development, testing and certification.

An intelligent transport system (ITS) is a control or management system integrating state-of-the-art information and telematic technologies and intended for automated search for and implementation of the most efficient scenarios for managing the road and transport complex of a region, particular vehicles or a group of vehicles in order to provide the assigned human mobility, maximize the road network use parameters, increase safety and efficiency of the transport process, vehicle driver and transport user comfort [8].

A cooperative intelligent transport system is an intelligent transport system based on V2X technologies.

A digital road model (DRM) is a part of an intelligent transport system ensuring situational awareness, notification and management of and over driverless vehicles and functioning in a fully automated mode at all stages of the technological cycle.

A fully automated vehicle is a vehicle equipped with an automated driving system working without any restrictions of an operational design domain in respect to some or all trips without the need of human intervention as a backup for ensuring traffic safety.

An operational design domain (ODD) is time of day, infrastructure, road and transport, weather, and other conditions, under which the automated driving system is intended to operate.

In general, a driverless vehicle control or driving task in a random operational design domain is rather complicated as it must ensure real-time performance of multiple control functions, state parameter measurements, communication with infrastructure, etc.

To solve the structuring tasks, the Zwicky Morphological Box method was used, which is based on conditional splitting of an initial object of investigation into independent components to generate a complete set of possible variants of the object.

An operational design domain is conditionally split into road types and used digital road models. A variety of hard-surfaced roads suitable for DLV operation can be conditionally divided into four groups:

- roads in confined company territories;
- highways with one-way multi-lane traffic without intersection with other roads on the same level;
- suburban motorway passing through human settlements;
- urban streets and yards.

Digital road models are conditionally split into three levels:

- static road maps;
- dynamic road maps;
- V2X and DLV network communication.

3. Structuring control tasks for standard roads
Many years of experience in driving vehicles under road and climatic conditions of the USSR and Russian Federation accumulated by the authors allow forming complexes of driving (control) tasks of
increasing complexity for standard hard-surfaced roads. Peculiarities of driving on dirt roads and off-
road require solving specific driving (control) tasks, including pendular swaying of a stuck or stranded
vehicle, fording, holding, and exiting a deep rut, etc., which need separate consideration.

The increase in complexity of the driving (control) task levels, starting from the initial level of driving
in confined territories, on highways with light traffic, suburban motorways passing through human
settlements and ending with urban streets and yards, essentially matches the stages of teaching and
training of young drivers aimed at safe driving on public roads.

It should be noted that the highest complexity level of driving (control) tasks related to urban streets
and yards in large megalopolises can appear difficult even for some human drivers with extensive
experience in driving on highways and suburban motorways.

The driving (control) tasks within confined territories reduce to the following:
— monitoring of traffic safety relevant parameters of the vehicle;
— emergency stop in the lane in case of detecting any dangerous malfunctions;
— braking before a static obstacle in the lane from the speeds up to 40 km/h;
— stabilizing the set driving speed (up to 40 km/h);
— stabilizing on the set driving trajectory with a deviation or offset of up to 0.5 m at the speeds up to
40 km/h.

The driving (control) tasks for highways reduce to the following:
— stabilizing minimum safe distances when driving in a platoon;
— stabilizing safe driving speeds considering the road surface condition, highway profile, road signs,
etc.;
— braking before a static obstacle in the lane from the speeds above 40 km/h;
— driving around an obstacle ahead with current lane change considering obstacles in the adjacent lanes
behind;
— driving stabilization within the set trajectory at the speeds above 40 km/h;
— emergency stop in the lane or by the roadside;
— identification of collision events by objective control data;
— yielding the right-of-way to vehicles with emergency beacons;
— recognition of road signs and zones to which they apply.

The driving tasks for suburban motorways passing through human settlements reduce to the
following:
— overtaking the preceding traffic with entering the oncoming traffic lane;
— prevention of collisions with pedestrians, cyclists, motorcyclists, animals, etc.;
— passing a signalized intersection with traffic lights and a box junction marking area;
— passing an unsignalized intersection;
— recognition of allowed driving directions for lanes;
— passing railway crossings (signalized and unsignalized);
— recognition of traffic controller signals.

The driving (control) tasks for urban streets and yards reduce to the following:
— driving control when traffic flows merge;
— adjacent lane changing under heavy traffic conditions;
— left turn at green light;
— passing pedestrian crossings (the pedestrian speed is limited to 10 m/s);
— passing a tram stop possibly giving the way to passengers;
— parking in permitted places on the streets;
— exit/departure from street parking under heavy traffic conditions;
— iterative forward and reverse parking under limited space conditions;
— iterative forward and reverse exit/departure from parking under limited maneuvering space
conditions;
— detection of marking of areas for fire fighting vehicles and equipment in the yards;
— passing by with the oncoming transport in the yards with one free lane for driving;
— iterative passing of turns in the yards with limited maneuvering space; safe exit/departure from yards into streets.

4. Structured set of ITS variants
The road types (RT), digital road models (DRM) and driving (control) task level (DTL) are considered as independent structural variables in the set of ITS variants taking on discrete values.

Thus, the variable corresponding to the road type can take on four values:
− 1 – corresponds to confined company territories (stadiums, airports, exhibition centers, railway stations, industrial enterprises);
− 2 – corresponds to highways with one-way multi-lane traffic without intersection with other roads on the same level;
− 3 – corresponds to suburban motorways, i.e. hard-surfaced roads passing through human settlements with intersections having traffic light control, pedestrian crossings and railway crossings;
− 4 – corresponds to urban streets and yards with vehicle parking places.

The variable corresponding to the digital road model takes on three discrete values:
− 1 – no infrastructure support; only on-board data sensors, static digital maps and built-in algorithms for data processing and control are used;
− 2 – dynamic digital high-resolution ground maps are used, and the DLV can predict driving parameters based on presence of objects on the map;
− 3 – the V2X network communication is provided, and the DLV obtains data from both its own sensors and road infrastructure with high accuracy positioning of the road and its current condition.

The variable corresponding to the driving (control) task level (DTL) takes on four discrete values:
− 1 – the first level tasks include the following: monitoring of safety-critical driving parameters; stabilization of driving parameters, including speed, distance to obstacles and deviations from the set trajectory; recognition and prediction of events causing road accidents; emergency stop;
− 2 – the second level tasks include the first level tasks plus the tasks of adjacent lane changing, complying with traffic signs and marking within the area to which they apply and yielding the right-of-way to vehicles with emergency beacons;
− 3 – the third level tasks include the second level tasks plus the tasks of overtaking with entering the oncoming traffic lane, passing signalized and unsignalized intersections and railway crossings, prevention of collisions with pedestrians, cyclists, motorcyclists, animals and other foreign items on the traffic way;
− 4 – the forth level tasks include the third level tasks plus the tasks of passing pedestrian crossings, tram stops, driving in yards, in traffic jams on intersections, parking in yards, reverse driving, etc.

A structured set of ITS variants for the case under study is given in Figure 1.

The number of elements of the structured set defining its potency is M=48. However, not all ITS variants are potentially operable. In particular, for the ITS variants with RT>DTL, there is a functional insufficiency area. In other words, the complex of the driving (control) tasks to be solved is insufficient for DLV control on the corresponding types of roads with any digital road models. The number of such variants amounts to 18. For the ITS variants with RT<DTL, there is a functional redundancy area. In this case, the complex of the tasks to be solved exceeds the functional needs for the corresponding road types. The number of such variants also amounts to 18.

In case RT=DTL on the diagonal plane of the cube, the complex of the tasks to be solved exactly matches the ODD road type component. The number of such variants is equal to 12.

The dynamics of development of DLV control systems is illustrated in Figure 1 with a continuous directed trajectory beginning in the point with coordinates (1; 1; 1) corresponding to the first driving (control) level in confined company territories without infrastructure support, which corresponds to the present situation in the Russian Federation.
Figure 1. Structured set of ITS variants.

The near future area corresponds to the second level of the driving (control) tasks for highways with digital static maps.

The distant future is seen as the third level driving (control) task for suburban motorways with the use of road model dynamic maps.

The farthest future for DLV on public roads is seen to be solving the fourth level tasks for urban streets and yards with the use of steady V2X.

In many respects, the rate of progress along the conditional trajectory of DLV development is determined by the results of intellectual efforts aimed at solving driving (control) tasks of all the levels, including the highest ones.

5. Conclusion
The paper contains a considered structured set of ITS variants based on a set of variables characterizing the driving (control) task levels, road types, and levels of interaction with infrastructure.

The analysis of properties of the structured set of ITS variants and the main trajectory of development of driverless vehicle control allows making the following conclusions:
— the major problem of DLV development is algorithmization of driving (control) tasks of all levels;
— the necessary condition for successful ITS functioning is creation and improvement of interaction with infrastructure;
— for DLV testing, the proving ground roads shall simulate the operational design domain conditions and be provided with the necessary equipment;
— for DLV certification, scientifically grounded regulations shall be developed according to road types, information infrastructure and driving (control) task levels.

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