Analysis of results of investigation tests of the developed information and measuring active safety system of the vehicle

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Abstract. The research objective is the analysis of results of investigation tests of the information and measuring active safety system developed by FSUE "NAMI". The practice of operation and performed studies show that modern foreign advanced driver assistance systems do not provide appropriate functioning under severe road and climate conditions of the Russian Federation creating unjustified risks and precluding from preventing a significant number of road accidents. This statement is applicable to driving on slippery surfaces, ice and snow, to the driving mode in traffic jams, in the absence of recognizable road marking, blinding of video cameras, insufficient visibility range and road lighting, etc. In order to ensure competitive ability and commercial attractiveness of the developed domestic information and measuring active safety system, within the scope of this work additional studies were performed regarding improvement of driver status monitoring functions with an expanded vector of the state of the controls and speed range, tire pressure monitoring with an expanded speed range and start-stop driving mode, dangerous obstacle approach warning and detection of deviation from the center of the lane with unrecognizable marking. In this paper, the results of investigation tests of improved functions are considered.

1. Introduction
The need for improvement of driver awake state monitoring functions, tire pressure monitoring, dangerous obstacle approach warning and detection of deviation from the center of the lane with unrecognizable marking was caused by severe conditions of vehicle operation under road and climate conditions of the Russian Federation.

The start-stop driving mode in traffic jams with accelerations to small speeds (10–15 km/h), presence of unrecognizable road marking, poor visibility under conditions of intensive precipitation events and insufficient road lighting at night time, non-observance of road marking by other types of vehicles moving with considerable traffic overspeeding in the lanes and maneuvering between the lanes along unpredictable trajectories, as well as emergency stops in the lane because of road accidents or vehicle malfunctions resulting in congestion may be designated as the factors defining vehicle operating conditions in megalopolises.

When driving on highways and suburban roads, there are additional factors of increased rutting of the road surface, which are prerequisites to hydroplaning in a ponded rut, slippery surfaces during rain, snow and formation of ice, driving on suburban roads in one lane without barriers dividing from the oncoming traffic lane that creates prerequisites for road accidents when going around obstacles.

Under such conditions, foreign advanced driver assistance systems are insufficient.
Usage of computer vision video systems to control the vehicle position in the lane, define the distance to obstacles and recognize traffic signs is limited by lighting conditions, precipitation, fog and visible marking.

Transition of the driver from the awaken state to the sleep state is usually detected based on indirect signs demonstrating emergence of prerequisites for transition to the inadequate or inappropriate state.

Control over the driver's adequate behavior state is the main issue to ensure traffic safety under any weather and climatic conditions. The variety of foreign driver awaken state monitoring systems against the backdrop of their total absence in the domestic-made vehicles creates an issue of scientifically based selection of promising technical solutions.

When developing and studying functions of the information and measuring active safety system, the new approaches to solving the assigned issues were used with application of mathematical models and algorithms of indirect measurements, which can be performed with the minimum configuration of technical means allowing optimization of practically all technical parameters including the cost.

2. Research methods
The known approaches to solving the driver state monitoring issue reduce to equipping vehicles with a number of additional data sensors [1] and need to use interfacing equipment, algorithms and programs in order to ensure reliability and operation speed [2, 3] followed by worsening practically all consumer properties, including costs for purchasing and operation of the system.

A solution for the issue presented in this paper is implemented using virtual data sensors based on mathematical models of the object and algorithms, which allow performing indirect measurements of the state of the vehicle controls: accelerator pedal, brake pedal, gearbox, steering angle.

When motion behavior of the driver's limbs lowers to the minimum values, the derivatives of the control inputs tend to zero. A control time slot counter is used for driver awaken state monitoring. When assessing the control input derivative values exceeding the minimum threshold values, the time slot counter is reset and no control signals are generated. Under the urban driving conditions with sequential acceleration and braking intervals, control signals are generally not formed. The time slot value for giving the control signals is set by the equation:

$$\Delta T_K = 10 + V_m,$$

where $V_m$ is the vehicle center-of-mass longitudinal speed.

The linear dependence between the control interval and speed is selected based on the assumption that along with the speed increase, the level of vibration accelerations increases preventing the transition from the awaken state to the sleep state. In cases the driver does not react to the control signals, the light and sound wakening signals are activated that are switched off when the derived control inputs go beyond the threshold values.

The operating principle of the system of indirect measurement of pressure drops in vehicle tires is based on the wheels pseudo-slipping detection effect [4] in case of a pressure drop in one of the tires according to the wheel rotation rate measurement results. The implemented method of pressure drop detection based on the 1 of 4 scheme is the basis of UNECE Regulations No. 64 and 141 [5, 6] and has limited capabilities due to discretization of pseudo-slipping rating by both the lower speed threshold (40 km/h) and the pressure drop detectable threshold (0.6 bar). In case of multiple pressure drops in axial wheel pairs or in all wheels simultaneously, these drops are not detected. The essential disadvantage of such systems is the inability to function with an incomplete configuration of wheel speed sensors. The mentioned disadvantages do not allow effective use of such systems for pressure drop detection in the start-stop driving mode in traffic jams and at high driving speeds on highways and suburban roads under road and climatic conditions of the Russian Federation.

The method [7], system [8] and software [9] developed by the authors implement indirect measurements of pressure drops in tires according to the 3 of 4 scheme and detect pressure drops starting from 0.1 bar within the speed range from 4 km/h to the maximum driving speed limited by the start of
slipping of traction wheels. The system features self-diagnostics for wheel speed sensors and automatic reconfiguration of measurements according to the 2 of 3 and 1 of 2 schemes in case of failure detection.

The analysis of target determination in the problem of warning about collision with an obstacle uses the developed algorithm for determining the object (target) as true out of a finite set of targets that is in the operating area using a specialized device — Continental ARS-408 vehicle radar. In the developed algorithm, the target searching is performed in the Cartesian coordinate system with an extended vector of object parameters such as the distance to the object, the signal level of the target RCS reflectivity, the object overall dimensions along two axes (length, width), the relative speed of the object. The condition for the warning signal actuation is reduction of the distance to the obstacle below the safe level calculated by the following formula:

\[
L'_{bdr.} = V_m \tau_m + 0.5V_m^2a_T - 0.5V_{tgt}^2a_{tgt} + L_{ResDist},
\]

where \(V_m\) is the vehicle longitudinal speed, m×s\(^{-1}\);
\(\tau_m\) is the delay in the brakes control channel, s;
\(a_T\) is the vehicle maximum deceleration under current conditions, m×s\(^{-2}\);
\(V_{tgt}\) is the longitudinal speed of the obstacle in the lane, m×s\(^{-1}\);
\(a_{tgt}\) is the maximum obstacle deceleration under current conditions, m×s\(^{-2}\);
\(L_{ResDist}\) is the distance margin between the vehicle and obstacle, m.

The \(V_{tgt}\) speed of the target is calculated using the known input data on the distance to the target received from the radar and current vehicle speed:

\[
V_{tgt} = V_m + \frac{\Delta L_{dist}}{\Delta T},
\]

where \(V_m\) is the vehicle longitudinal speed at the given moment, m×s\(^{-1}\);
\(\frac{\Delta L_{dist}}{\Delta T}\) is the obstacle approach speed, m×s\(^{-1}\);
\(\Delta L_{dist}\) is the distance increment at the program execution step, m;
\(\Delta T\) is the program execution step, s.

Actuation of the driver warning about the danger of collision with an obstacle ahead allows the driver to choose a maneuver to prevent the collision, for example, avoiding or going around the obstacle or emergency stop before it.

The function of warning of deviation of the vehicle longitudinal axis from the center of the obstacle ahead under the conditions of unrecognizable marking allows controlling the vehicle position in the lane under the conditions of unrecognizable marking according to the position of the vehicle moving ahead in the same direction in the lane and warning the driver in a timely manner of the vehicle shift and lane departure for more than 0.6 meter to the left or to the right relative to the center of the vehicle ahead, as well as controlling observance of the safe boundary distance. The value of the target deviation from the radar longitudinal axis center \(\Delta H\) is calculated according to the formula:

\[
\Delta H = \alpha \times L_{dist},
\]

where \(\alpha\) is the angle from the radar longitudinal axis to the object center, rad;
\(L_{dist}\) is the distance to the target, m.

Under the conditions of urban driving in heavy traffic, repetition of the path of the vehicle ahead is a certain guarantee of safe driving with unrecognizable marking.

3. Testing results

The research testing of the information and measuring active safety system was conducted in July 2020 on the FSUE "NAMI" Dmitrov proving ground.

A Lada Kalina manufactured in 2008 and Lada Vesta manufactured in 2018 were used as the test vehicles.

The photos of the mentioned vehicles during the run are shown in Figure 1.
Figure 1. Lada Kalina and Lada Vesta test vehicles

The presented vehicles were equipped with the instrumentation (measurement and control equipment) for registration of the center-of-mass longitudinal speed, covered distance, coordinates of location and relative position of the vehicle and target (RACELOGIC VBOX 3i), longitudinal and lateral accelerations, as well as angular rate of rotation around the vertical axis (TANS CORRSYS-DATRON).

3.1. Testing of the improved driver awaken state monitoring function

The testing of the driver awaken state monitoring function was aimed at checking the correct functioning of the algorithm for generation of control intervals and wakening signals under the real road conditions of driving at different speeds, in the acceleration and braking modes including under the reduced speed conditions imitating driving in traffic jams. The function was tested on straight sections of special roads at the proving ground. The control wakening signals were actuated due to the absence of motion in the vehicle controls, i.e. the controls were fixed during vehicle movement (driving).

Figure 2 shows time diagrams of the driver awaken state monitoring function test run on a straight road section with interruption of the actuated warning by changing the control input to the accelerator, steering wheel and brakes with subsequent stop respectively.

A series of similar runs was performed within the speed range from 5 to 28 m×s$^{-1}$ for no more than 300 seconds. During each run, the control time interval was reset on the time diagrams by means of changing the input to the vehicle controls in the following order or sequence: gearbox shifting (U1), accelerator pedal pressing (U2), steering wheel turning (DC) and, in completion, stop with an input to the brake pedal (U3). In the acceleration mode, the counter was interrupted by gear shifting.

Interruption of the first control time interval caused by driving with constant input to the controls was performed by a short-term pressing of the accelerator pedal until the moment when the value of derivative $U2$ exceeded the threshold level. Change of the steering angle to the right and to the left by 0.022 rad caused a reset of the second control time interval and cancellation of the driver warning signals. The third control interval was reset by a single control input to the brake pedal – the value of derivative $U3$ exceeded the threshold level, then the vehicle was brought to the full stop.

Runs imitating driving in traffic jams within the speed range not exceeding 5 m×s$^{-1}$ were also performed. Formation of the control time intervals was reset by frequent control input to the accelerator pedal. Short-term inputs to the brake pedal and full stop of the vehicle also caused reset of the control interval counter.

Figure 3 shows time diagrams of the test run for the driver awaken state monitoring function in the start-stop driving mode imitating driving in a traffic jam, at a low speed of about 3.5 m/s (12.6 km/h).
Figure 2. Time diagrams of driver awake state monitoring function test run on straight road section.

Figure 3. Time diagrams of test run for driver awake state monitoring function in driving mode imitating driving in traffic jam.
During the test run, the average driving speed was 3.5 m/s (12.6 km/h); such speed is characteristic of driving in the start-stop mode in a traffic jam. Driving in this mode for a long time significantly raises driver drowsiness, especially in the evening, when returning home being tired after a working day. Such driver state is dangerous and may result in a collision with a vehicle ahead. The developed improved driver awaken state monitoring function allows monitoring such states, also at low speeds, if motion behavior in the vehicle controls does not exceed the threshold values. On the given time diagrams, the light and sound warnings were actuated 1 time and lasted for several seconds, which would allow the driver not to pass from the awaken state to the sleep state.

3.2. Testing of the improved tire pressure monitoring function

Figure 4 shows time diagrams of the tire pressure monitoring function test under pressure drop conditions in three wheels at the speed changing from 18 to 22 m×s\(^{-1}\) and a schematic distribution of tire pressure between the vehicle wheels.

A series of test runs for the tire pressure monitoring function was carried out at the speed ranging from 1.8 to 30 m×s\(^{-1}\) with different variations of wheels deflated (one, two or three) by 0.2, 0.5 and 0.8 bar. The rated or nominal standard pressure in the inflated tires amounted to 2.0 bar (without regard to thermal components).

In the presented time diagrams, the pressure drop was revealed in three tires out of four. The acceleration to the speed of 20 m×s\(^{-1}\) was performed and then the speed varied from 18 to 22 m×s\(^{-1}\) during the run. The presented time diagrams showed the revealed pressure drop in the fourth wheel 20 seconds after the driving start, and at the 110th second the value settled at the level of 1.3 bar. The pressure drop in the first wheel was identified at the 46th second, and at the 120th second the pressure level settled at 1.5 bar. At the 92nd second, the pressure drop in the third wheel was recorded, and after the 110th second it settled at the level of 1.8 bar. All the revealed pressure drop values were determined with regard to the thermal component of tire pressure.

The test runs for the tire pressure monitoring function in the start-stop traffic jam driving simulation mode were carried out at the speeds not exceeding 3 m×s\(^{-1}\) with different variations of wheels deflated (one, two or three) by 0.2, 0.5 and 0.8 bar.

Figure 5 shows the time diagrams of driving in the start-stop mode with the pressure drop in the first tire.
Figure 5. Time diagrams of driving in start-stop mode under pressure drop conditions in the first tire.

The runs were carried out in the traffic jam driving simulation mode with an abrupt start, subsequent continuous speed change and periodic stops. The average speed during similar runs amounted to 1.85 m×s$^{-1}$. The presented time diagrams show that pressure drop in wheel 1 was recorded 27 seconds after the driving start and lasted until the 72nd second. After that, the pressure value settled at 1.6 bar, which corresponds to the 0.4 bar pressure drop with regard to an insignificant thermal component.

3.3. Testing of the dangerous obstacle approach warning function

A set of dangerous obstacle approach warning function operation tests for the cases of a stationary obstacle or an obstacle moving in the same direction and a pedestrian was carried out using the static simulator target (EuroNCAP Vehicle Target) (for the stationary obstacle case), the second Lada Vesta/Skoda Superb vehicle (for the case of an obstacle moving in the same direction) and involving a test person (for the pedestrian case).

Figure 6 shows the time diagrams of the dangerous stationary vehicle-type obstacle approach warning function test run.

A series of similar runs using the static simulator target (EuroNCAP Vehicle Target) at the speed ranging from 6 to 28 m×s$^{-1}$ was carried out. The stationary obstacle was detected in the operating area (range) of the used ARS-408 radar (up to 250 m). The (RL) addition to variables in the legend of the time diagrams means that the variables of the RACELOGIC VBOX 3i control and measuring device are used. In the presented run, the target was detected at the distance of ~117 m. The dangerous obstacle approach warning function was actuated at the distance of 48 m to the target with the vehicle moving at the speed of ~18 m×s$^{-1}$. The vehicle deceleration to a full stop before the stationary obstacle started at the distance of 31 m to the target. The braking distance amounted to 25 m. The distance left to the target after the stop was 6 m. The measurement errors are within the range of 0.630 m maximum upper value and minus 0.350 m minimum lower value and do not exceed the acceptable error value of 1.0 m in modulus.
Figure 6. Time diagrams of dangerous stationary vehicle-type obstacle approach warning function test run.

Figure 7 shows the time diagrams of the test run for the dangerous cocurrent obstacle approach warning function.

A series of test runs on straight sections of the special roads and on the dynamometric road of the proving ground was conducted in the following modes: acceleration and target approach, braking before the target at the time of the warning system actuation, distancing from the target and maintaining the speed while keeping a safe distance. The duration of each run amounted to no more than 300 s. The presented time diagrams show the run performed at the average driving speed between 4 and 19 m s$^{-1}$.

The dangerous approach warning function was actuated when the vehicle moving in the same direction was approached and the distance to it was less than that determined by safe boundary distance value $L_{gr}$. The maximum and minimum values of target approach were determined based on the run results. The reaction of the controlled vehicle driver to the warning light and sound signals was supported by the control input to the brake pedal for setting safe distance $L_{gr}$ to the vehicle being followed.
Figure 7. Time diagrams of test run for dangerous cocurrent obstacle approach warning function.

Figure 8 shows the run time diagrams obtained during the tests of the dangerous obstacle approach warning function for the pedestrian cases.

Within the series of similar tests, it was defined that the pedestrian (actual person) was found by the radar in the front hemisphere at the distance of ~ 100–110 m. The vehicle driving speed averaged ~ 3.7 m/s (but no more than 5 m/s) before actuation of the warning of dangerous approach to a pedestrian subject to the condition of $DL < Lgr$. The distances to the pedestrian amounted to 7–10 meters when giving the collision warning. The braking with deceleration to a full stop of the vehicle lasted ~ 3 seconds. The distances to the pedestrian after the stops ranged from 2.0 to 4.5 meters.
3.4. Tests of the function of warning of deviation of the vehicle longitudinal axis from the center of the obstacle ahead under conditions of unrecognizable marking

The function of warning of deviation of the vehicle longitudinal axis from the center of the obstacle ahead under the conditions of unrecognizable marking was tested in the static and dynamic modes on special road sections of the proving ground and in the territory of FSUE "NAMI". The condition for control of lane departure by the test vehicle with respect to the axis of the vehicle moving ahead amounted to 0.5–0.6 m with safe boundary distance observance.

Figure 9 shows fragments of tests of the function with different positions of the test vehicle with respect to the vehicle moving ahead.

On the indication device, the information on vehicle position control with respect to the vehicle moving ahead is displayed in the form of the arrow symbol indicating the corresponding direction of deviation in order to return to the lane if such deviation exceeds 0.6 m.

Figure 8. Test run time diagrams for dangerous pedestrian approach warning function.
Figure 9. Fragments of tests of function with different positions of test vehicle with respect to vehicle moving ahead.

4. Conclusion

Based on the results of the analysis of the performed investigation tests of the improved functions of driver awaken state monitoring, tire pressure monitoring, dangerous obstacle approach warning and detection of deviation from the center of the lane with unrecognizable marking, the following conclusions can be formulated:

— lowering of driver's mobility preceding transition from the awaken state to the sleep state is adequately and truly detected within the speed range from 10 to 120 km/h and in the start-stop driving mode in traffic jams;

— confirmation of the driver awaken state is provided based on the data about changes in the state of the controls for the traction, brakes, gearbox and direction in all the driving modes including cruise control;

— pressure drops in one, two and three tires are adequately and truly detected in the speed range from 4 to 120 km/h on straight lines and when turning, as well as in the start-stop driving mode in traffic jams;

— digital indication of tire air pressure values provides displaying these tire state parameters to the tolerances of no more than 0.1 bar taking into account the thermal component;

— warnings of dangerous approach to a vehicle-type stationary obstacle are adequately and truly formed within the speed range from 0 to 90 km/h;

— warnings of dangerous approach to a cocurrent vehicle are adequately and truly formed within the speed range from 4 to 120 km/h;

— warnings of dangerous approach to a pedestrian are adequately and truly formed within the speed range from 0 to 20 km/h;

— warnings of deviation of the vehicle longitudinal axis from the center of the rear end of the vehicle moving ahead by more than 0.6 m are adequately and truly formed within the speed range from 0 to 120 km/h and do not demand presence or availability of recognizable marking.

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