Description and tests of a control system for automatic emergency braking of a car with an algorithm for predicting the adhesion of automobile tires to the road surface

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Abstract. Every year the number of cars in the world is steadily growing, which in turn leads to an increase in road accidents. Russia, as the largest country by area in the world, has a number of traffic-related features that are not typical for other regions, including changing road and climatic conditions. The sharp increase in the number of accidents in the first hours after precipitation is especially noticeable, that indicates the difficulty to adapt to the changing traffic situation for vehicle drivers. More than 60% of collisions, according to the traffic police databases for 2018-2019, occur due to incorrect predictions by drivers of the braking distance of their cars. As a rule, this can happen due to the inexperience of the driver, incorrect assessment of the current adhesion properties of the roadway, distraction to a mobile phone, the climate or multimedia system of the car, movement with insufficient visibility. Preventing collisions occurring in such scenarios is the main task of an intelligent driver assistance system such as the automatic emergency braking system. The main part of this system is an adequate assessment of dynamically changing road and climatic conditions and warning the driver of a possible collision hazard, as well as automatic action on the vehicle's brake drive to prevent a collision. The article describes control algorithms for assessing and predicting dangerous situations.

1. Introduction

An improvement of vehicle safety has always been critical in the design of automotive systems. One of the main tasks is to improve, increase the reliability and efficiency of vehicle braking systems. In Russia, on the topic of the effectiveness of braking, one can note the works of such scientists as A.A. Revin, A. B. Diķ, A. I. Popov, N. V. Popov, V. A. Petrov and others. In their works, they laid the fundamental and highly significant foundations of calculations and design, which currently allow the creation and improvement of complex multi-level control systems, including the system of automatic emergency braking and warning the driver of the danger of collision.

Analysis of the statistical data indicates a certain correlation between the number of accidents, the adhesion properties of the surface and unfavorable weather conditions. According to A.P. Vasiliev, a decrease in the adhesion properties of the road surface leads to a progressive increase in the average number of accidents, while the proportion of accidents which happen when the driver uses emergency braking increases significantly [1]. Under the influence of many dynamically changing factors, the driver cannot always accurately assess the current road conditions.
One of the key developments allowing the introduction of the automatic emergency braking system is the vehicle stability control system, since a typical road factor contributing to the loss of stability, especially when braking a car on a surface with low adhesion properties, is lateral slopes, which are due to the need to ensure the required intensity of water flow when exposed to precipitation and are regulated by building codes and regulations. Accordingly, in the absence of vehicle stability control system, the introduction of the automatic emergency braking system would contribute to a loss of the controllability and could lead to an accident. [2]

The main function of the automatic emergency braking system is to warn the driver of the potential danger of a collision with the front vehicle, as well as to reduce the severity of the consequences of their possible collision. In case of an inadequate assessment or ignorance by the driver of the danger of a possible collision, the automatic emergency braking system can increase the deceleration of the car, or activate braking without the driver acting on the braking system.

2. Algorithm for predicting the coefficient of adhesion of car tires to the roadway

The most important task in the development of the automatic emergency braking system is an algorithm that allows it to function effectively in various road and climatic conditions. The principle of operation of the algorithm should be made in such a way as to exclude the factor of false activations of automatic braking, but at the same time to identify the danger of a collision in a critical situation. [3]

To exclude false alarms during maneuvering, it is necessary to control the behavior of the car, below are some parameters by which you can control the driver’s behavior on the road at the moment:
- speed and percent of pressing the accelerator pedal;
- angle and speed of rotation of the steering wheel;
- the current driving mode (comfort, sport, auto, etc.);
- active mode of the dynamic stabilization system.

In this article, we will not consider algorithms for preventing false activations, but will focus on situations where the driver, for certain reasons, brought the road situation to the danger of a frontal collision with an obstacle.

The algorithm is based on the calculation of the time before collision with an obstacle, taking into account that the driver is no longer able to prevent a dangerous approach without the use of emergency braking. To do this, you need to know what distance is critical in a given situation, based on many external factors. The basic formula (1) for calculating the distance required to stop:

\[ S_o = \frac{v^2}{2\varphi g} + (v \times t_{rb}), \]  

- \( S_o \) – the calculated braking distance of the system;
- \( v \) - the current speed of the vehicle;
- \( t_{rb} \) - the brake drive response time;
- \( \varphi \) – the predicted coefficient of adhesion;
- \( g \) - the acceleration of gravity.

Since the main criterion in the operation of the system is the time intervals (time to notify the driver, the rise time of the steady-state deceleration, the time for braking), then in further calculations the main parameters lead to the time required to prevent a collision. [4]
Figure 1. Calculation of the stopping time of automatic braking.

If we write down the deceleration in a general form, then it will have the form:

$$j_{ust} = \varphi \cdot g.$$  

(2)

Below is the basic generalized formula (3) for calculations using this algorithm:

$$t_o = t_n + t_{br} + \frac{K_V}{\varphi g},$$  

(3)

$t_{br}$ – brake system response time, s;  
$K_V$ – coefficient of braking efficiency;  
$V_0$ – vehicle speed immediately before the start of braking, m / s;  
$\varphi$ – coefficient of adhesion of the vehicle wheels to the road surface;  
g – acceleration of gravity;  
t_n – deceleration rise time, s.

The main variable for calculations in all formulas for calculating the braking distance of a car is $\varphi$ - the coefficient of adhesion of the wheels of the car to the road surface. It is by predicting the current value of $\varphi$ that it is possible to calculate the braking distance of a car in various conditions of road and climatic situations. [5]

The coefficient of adhesion of the wheel to the supporting surface depends primarily on the type and condition of the coupling bodies - the tire and the supporting surface. [6]

As the speed of movement increases, $\varphi$ decreases. On wet roads, as the speed increases, the coefficient of adhesion will decrease. This can be explained by the viscoelastic deformations of the tread rubber. These changes depend on time, so at high speeds, the tread rubber does not have time to fully catch on the unevenness of the surface. The adhesion factors of the tread must be selected based on the worst operating conditions. The adhesion coefficient also changes when the ambient temperature changes.

Also, a wide spread of the braking coefficient depends on the size of the water layer on the road, and therefore the braking distance of the car changes. [7]

It is proposed to use the following sources of information for predicting the tire adhesion coefficient:

- Ambient temperature sensor;  
- Precipitation sensor;  
- Current operating mode of the wiper;  
- Actuation of the anti-lock braking system;  
- Actuation of the stability control system.

As an additional method of covering control, it was also decided to use the recognition of marking lines. In more than 90% of cases, the adhesion coefficient was better predicted by recognizing lane lines and corresponding sensor readings.

The apparatus of fuzzy logic was chosen as a mathematical tool.
Figure 2. Terms of the output variable $\varphi$.

The affiliation of the output parameter for determining the degree of truth has been designed in accordance with the table below.

Table 1. The affiliation of the adhesion coefficient.

| $t^\circ$C | Rain Detected | Rain Density | ABS | ESP | LDWS | Time (minutes) | $\phi$ |
|----------|----------------|--------------|-----|-----|------|----------------|------|
| $<0$     | +              | high         | +   | +   | -    | $>5$           | 1    |
| $<0$     | +              | high         | +   | +   | +    | $<5$           | 2    |
| $<0$     | +              | high         | +   | -   | +    | $<5$           | 3    |
| $<0$     | +              | low          | +   | +   | +    | $<5$           | 3    |
| $<0$     | -              | off          | +   | +   | +    | -              | 3    |
| $<0$     | +              | low          | -   | -   | +    | -              | 4    |
| $>0$     | -              | off          | +   | -   | +    | $<5$           | 4    |
| $>0$     | +              | low          | -   | -   | +    | $<5$           | 4    |
| $>0$     | +              | low          | -   | -   | +    | $>5$           | 4    |
| $>0$     | -              | off          | +   | -   | +    | -              | 4    |
| $<0$     | -              | off          | -   | -   | +    | -              | 5    |
| $>0$     | -              | off          | -   | -   | +    | -              | 5    |
Figure 3. Appearance of the model in Simulink.

3. Comparison of simulation results and experimental data.
To begin with, you need to determine the time interval from the submission of the request for braking to the steady deceleration. For this, a test braking request of \(-5\) m/s\(^2\) at speed of 42 km/h was carried out.

A complete set of automatic emergency braking systems was installed on the test car: a front camera for object recognition, a frontal radar, the correct operation of the standard vehicle sensors (rain sensor, wiper intensity, temperature, skid detection sensor, anti-lock braking system) was checked. The recording equipment: laptop, PCAN-Usb, Vector VN 1630.

Figure 4. Determination of the response time of the brake drive.
The graph of the recorded values clearly shows that the time from a request to a steady deceleration is of the order of 0.3 seconds. Accordingly, based on these values, a margin of time to achieve a steady-state deceleration will be calculated.

Further, a comparison of the predicted coefficient of the algorithm and its correlation with the valid experimental value are introduced.

**Experiment 1.**
Input data:
Covering: wet asphalt;
Temperature: +15 °C;
Precipitation: low intensity;
Braking request: -5 m/s²;
Result: -4.9 m/s².

Braking from 23 km/h to a full stop, experimental data:
Covering: wet asphalt;
Temperature: +15 °C;
Precipitation: low intensity;
Braking request: -5 m/s²;
Result: -4.9 m/s².

![Figure 5. Calculated adhesion coefficient.](image-url)
The result of experiment 1:
The experimental values of the adhesion coefficient $\varphi$ correspond to the predicted ones.

**Experiment 2.**
Input data:
Covering: wet asphalt;
Temperature: + 15 ° C;
Precipitation: low intensity;
Braking request: -5 m / s$^2$;
Result: -4.9 m / s$^2$;

Braking from 32 km / h to a full stop, experimental data:
Covering: wet asphalt;
Temperature: + 15 ° C;
Precipitation: low intensity;
Braking request: -5 m / s$^2$;
Result: -4.9 m / s$^2$. 

*Figure 6. Experimental values.*
The result of experiment 2:
The experimental values of the adhesion coefficient $\varphi$ correspond to the predicted ones.
Experiment 3.
The input data for this experiment were modeled according to the characteristics of the covering. The data was taken according to the recorded sensor values when testing vehicles in winter.

Input data:
Covering: snowy road;
Temperature: -5 °C;
Precipitation: low intensity;
Braking request: -5 m / s²;
Result: -4.9 m / s²;

Braking from 25 km / h to a full stop:
Covering: wet basalt covering;
Temperature: + 12 °C;
Braking request: -5 m / s²;
Result: -3.4 m / s²;

The wet basalt pavement in its properties corresponds to the coefficient of adhesion of 0.3.

Figure 9. Basalt pavement.
Figure 10. Calculated adhesion coefficient.

Figure 11. Experimental values.

The result of experiment 3: The experimental values of the adhesion coefficient $\varphi$ correspond to the predicted ones.
4. Conclusion
The collection and analysis of statistical data of accidents and road situations were carried out to select the optimal set of sensor equipment for the automatic emergency braking system. The most effective combination of sensors for the operation of the adhesion coefficient prediction algorithm was proposed. The mathematical model of the adhesion coefficient prediction algorithm has been developed. Experimental proof of the compliance of the calculated value of the adhesion coefficient with the actual value under various external conditions has been carried out.

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