

Mathematical modelling of active safety system functions as tools for development of driverless vehicles

V Ryazantsev¹, N Mezentsev² and A Zakharov¹

¹ Active Safety Sector, FSUE “NAMI”, Moscow, 125438, Russia

² Intelligent Vehicles Department, FSUE “NAMI”, Moscow, 125438, Russia

Abstract. This paper is dedicated to a solution of the issue of synthesis of the vehicle longitudinal dynamics control functions (acceleration and deceleration control) based on the element base of the vehicle active safety system (ESP) – driverless vehicle development tool. This strategy helps to reduce time and complexity of integration of autonomous motion control systems (AMCS) into the vehicle architecture and allows direct control of actuators ensuring the longitudinal dynamics control, as well as reduction of time for calibration works. The “vehicle+wheel+road” longitudinal dynamics control is complicated due to the absence of the required prior information about the control object. Therefore, the control loop becomes an adaptive system, i.e. a self-adjusting monitoring system. Another difficulty is the driver’s perception of the longitudinal dynamics control process in terms of comfort. Traditionally, one doesn’t pay a lot of attention to this issue within active safety systems, and retention of vehicle steerability, controllability and stability in emergency situations are considered to be the quality criteria. This is mainly connected to its operational limits, since it is activated only in critical situations. However, implementation of the longitudinal dynamics control in the AMCS poses another challenge for the developers – providing the driver with comfortable vehicle movement during acceleration and deceleration – while the possible highest safety level in terms of the road grip is provided by the active safety system (ESP). The results of this research are: universal active safety system – AMCS interaction interface; block diagram for the vehicle longitudinal acceleration and deceleration control as one of the active safety system’s integrated functions; ideology of adaptive longitudinal dynamics control, which enables to realize the deceleration and acceleration requested by the AMCS; algorithms synthesised; analytical experiments proving the efficiency and practicability of the chosen concept.

1. Introduction

According to article [7], active safety is “a capability of a vehicle to prevent a road accident or to reduce its probability.” The main functional aim of the active safety systems is to prevent critical situations and maintain steerability and stability of the vehicle movement – transport task fulfilment. At the very beginning, implementation of active safety systems caused a reduction of number of road accidents and severity of their consequences. However, the feeling of being safe changed the driver’s mind and behavior, which caused stagnation and subsequent growth of number of road accidents. This unpleasant situation made engineers move to the next level of the road safety improvement – advanced driver assist systems (ADAS), semi-autonomous motion control systems (SAMCS) and tendency towards introduction of pilotless or driverless vehicles. In regulatory documents [15], there are six stages of driverless vehicle development requiring automatic vehicle acceleration and deceleration control.

However, active safety systems are and will remain the crucial element in the vehicle, because the maneuvers calculated by the AMCS cannot guarantee stable “vehicle+wheel+road” object motion.



There are papers [4, 5] dedicated to definition of limits or borders of sustainable movement in relation to the performance of the actuators. Nevertheless, the issues of autonomous driving and possibility to achieve the desired trajectories under the conditions of steerability and stability of the vehicle are still open.

2. Interface description

The authors proposed a set of rules, which provide interaction between the active safety systems and AMCS – hereinafter referred to as the universal interface – to control the longitudinal dynamics of the vehicle. The functional division of the tasks between these two systems dictates the necessity of such an interface. The AMCS task is to calculate the desired motion trajectory based on the data from computer vision and navigation systems, without taking into account the information about dynamic parameters of the vehicle, and the task of the active safety system is to provide the most efficient and safest driving along this trajectory.

Figure 1 shows the proposed interface for the acceleration control, where the primary control signal is the “required (target) acceleration” (m/s^2). According to the conditions of safe driving within the traffic, the AMCS calculates upper and lower limits of acceleration, which represent the acceptable error in the acceleration adjustment. Since, in the first approximation, the “vehicle+wheel+road” model is an inertial filter and features a transition process, its quality is set by the AMCS using a higher-order derivative – “a jerk (tug)” (m/s^3). This approach allows obtaining of the controllable transition process, which is comfortable for the user.

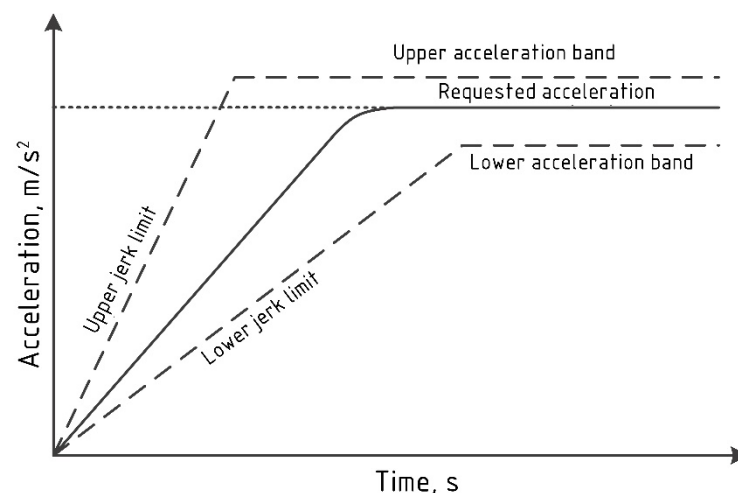


Figure 1. Universal acceleration control interface illustration.

3. Function description

Speed control, as well as realization of the acceleration or deceleration requested by the AMCS are preformed by active safety systems through the management of the engine torque or actuating fluid pressure in the brake mechanisms. Assessment of the “vehicle+wheel+road” object behavior is performed via the same information channel.

The management of the “vehicle+wheel+road” object dynamics is complicated because of the lack of prior information. Absence of initial data about the object causes the need to combine, in some ways, monitoring of the object and its management. In this case, the control actions are of a dual nature – they serve as a means of object monitoring and investigation and as a means to achieve the desired (i.e. optimal) condition – this is called “a dual control” [8-11].

Optimality of the longitudinal dynamics control can be formulated based on the primary aim of this control – ensure the vector change according to the requested values. Then, when there is no exact information, the optimum will be the minimum error between the requested and the actual realized characteristic of the phase vector change. This result can be obtained if the longitudinal dynamics control

system is implemented within the class of adaptive systems [1]. The control part of the adaptive loop (figure 2) consists of two parts or elements: consistently-correcting contour and parallel-correcting contour. The first element includes adjustable parameters, the second one – constants.

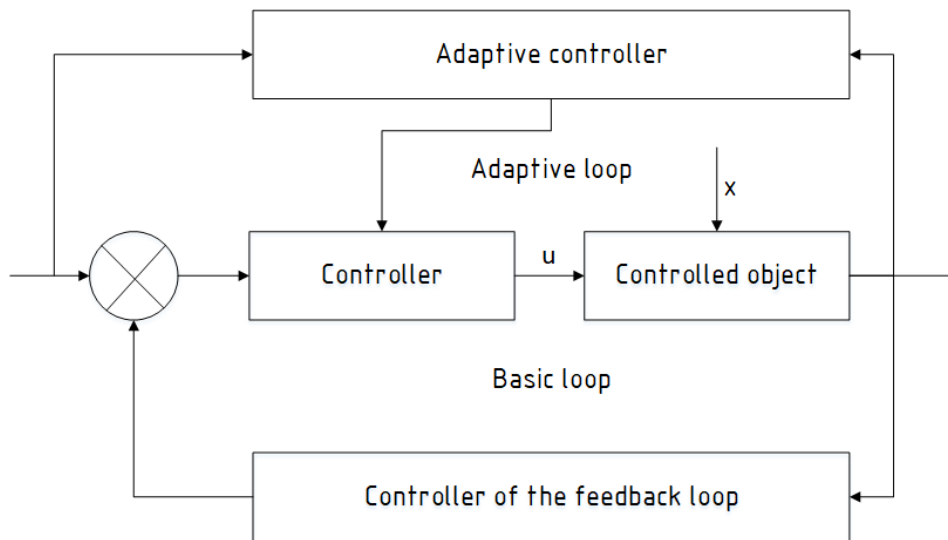


Figure 2. Structure diagram of adaptive loop.

The parallel-correcting loop is made as a program controller [2] using some basic models of the “vehicle+wheel+road” object [6, 13], which were defined by the condition of the equality of the forces applied to the vehicle.

$$m_a \frac{dV_v}{dt} = \sum_{i=1}^n R_{x_i} + W_L + W_H \quad (1)$$

where: m_a – vehicle weight;
 V_v – linear speed;
 R_x – tangential force applied to the tire-road contact area;
 W_H – uphill movement resistance;
 W_L – other movement resistances.

The consistently-correcting loop is a self-adjusting loop, which takes the minimum error of the phase vector as a qualitative criterion. The optimality based on a control error needs invariability of the parameter used. The works on the design of active safety systems [12] show that vehicle linear speed can be used as a parameter for the self-adjusting loop to analyse the vehicle motion. Then, the qualitative criterion takes the following form:

$$e = V_{st-st} - V_v \rightarrow \min \quad (2)$$

where: V_{st-st} – desired vehicle speed;
 V_v – vehicle speed.

The developed interface allows generating the signal of the desired speed (V_{st-st}) in the form of a difference equation (3). The need of a difference equation is caused by the problem of obtaining the second-order derivative in a technical system – this problem represents a separate task.

$$V_{st-st}(i+1) = \alpha(\hat{V}_e(i) + \zeta j_{req}(i)\Delta t) + (1-\alpha)V_{sens}(i) \quad (3)$$

where: $\hat{V}_e$ – vehicle speed estimation (recommended speed);
 j_{req} – requested target acceleration;
 Δt – time interval;
 α & ζ – correction coefficients;
 V_{sens} – vehicle speed based on the wheel speed sensor data.

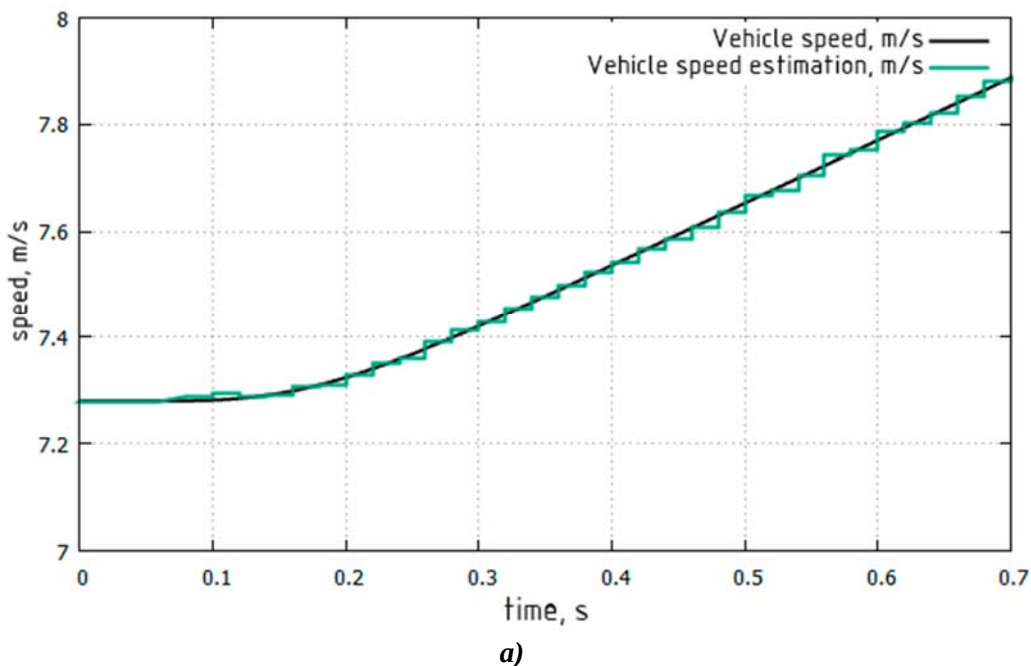
The correction coefficient α is introduced to allow usage of information from the wheel speed sensors in case of steady-state motion. The coefficient ζ is introduced based on the “jerk” parameters and is defined as follows:

$$\zeta = \begin{cases} 0, & \text{if } j_{st-st} - j_{req} \leq \varepsilon \\ \frac{j_{st-st}}{j_{req}}, & \text{if } j_{st-st} - j_{req} > \varepsilon \end{cases} \quad (4)$$

where: j_{st-st} – steady-state acceleration based on the “jerk”;
 ε – acceptable error.

4. Results

The results of the mathematical modelling (figure 3) of the function of the vehicle longitudinal dynamics control, which was performed in the MatLAB Simulink software system, show feasibility of the proposed interface. Figure 3b shows that the error between the requested and actual acceleration is 3%. Also, the vehicle speed estimation process (figure 3a) has a high convergence level.



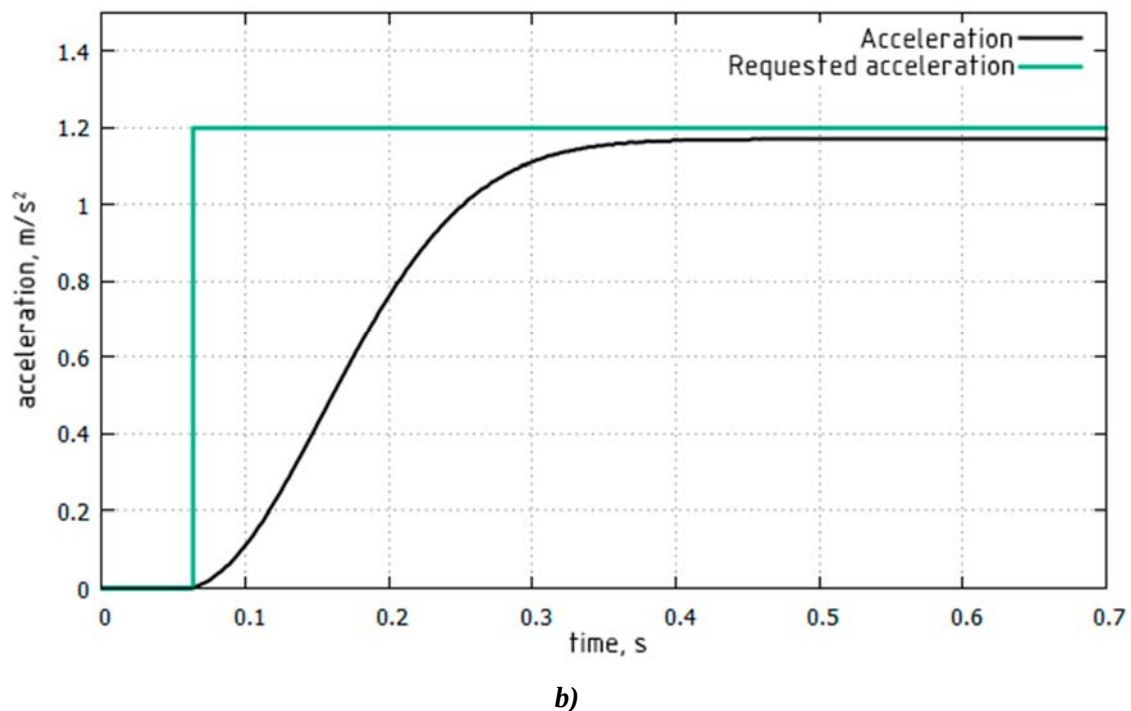


Figure 3. Results of mathematical modelling of function of vehicle longitudinal dynamics control: a) vehicle speed dynamics; b) acceleration dynamics.

5. Summary

The proposed interface allows the AMCS to use physical values with a high-order derivative – acceleration/deceleration and acceleration/deceleration change rate (“jerk”) – as the desired motion parameters, which allows the system to focus on its functional task. Conversion of the desired parameters on the part of the AMCS into the control actions for the vehicle actuators (actuating fluid pressure in the brake system and engine torque) is performed within the active safety system with ensuring the condition of vehicle stable motion based on the condition of the tire-road friction coefficient in the longitudinal direction. Technical implementation within the active safety systems requires conversion of the requested parameters into the speed vector of the vehicle and usage of adaptive control to manage the actuators. Usage of the “jerk” allows ensuring of controllable transition process, which is comfortable for the user, and preventive estimation of feasibility of the AMCS request.

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