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Selected problems of automatic obstacle avoiding

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Abstract. The paper presents selected problems concerning the concept of automatic controlling of motor vehicle motion in case of sudden appearance of an obstacle. If the vehicle cannot be brought to a halt before hitting the obstacle and the adjacent lane is clear, circumvention of the obstacle is the only way to avoid a collision. In the concept of the vehicle control system, elements of general control theory and simplified models of longitudinal and lateral vehicle dynamics have been used. The vehicle controlling process consists of two stages: braking and then changing the lane at a speed determined by the braking stage. The first stage is implemented with using standard mechatronic systems that automatize the braking process, while the second stage requires the use of a special controller coupled with the steering system. The controller generates a "bang-bang" reference signal and corrects it by means of regulating systems that minimize the deviations of the actual (measured) signals describing vehicle's trajectory from the reference signal. The control algorithm developed has been based on very simplified and, thanks to that, efficient reference models. The algorithm was validated by simulation tests, where a model of a medium-size truck was used as the virtual controlled object. In the model (3D, nonlinear, MBS type, experimentally verified), a very detailed description of vehicle motion, even in boundary conditions, can be taken into account. The paper presents fragments of the research work, including unpublished results of computational tests.

1. Introduction

Works on the automatic controlling of motor vehicle motion have for many years been conducted at numerous research centres. At present, the automatization of motor vehicle motion is chiefly focused on the mechatronic active safety systems that assist the vehicle driver in braking (such systems as ABS, BAS, or ACC), stabilizing the direction of vehicle motion (ESP), keeping the vehicle moving within a specific lane (Lane Assist systems), or parking (Park Assist systems). Some (although very few) examples of autonomous (driverless) vehicles can be met on roads already now. This, however, applies to motor vehicles moving with low and medium speeds in normal (i.e. far from boundary) conditions, where no risk of loss of the stability of motion may be encountered. In such cases, the automatization is actually limited to navigation and slow-changing follow-up controlling processes. The known attempts to build a vehicle that would be fully autonomous in a wide speed range show

how much complicated this problem is; they also show that this problem still has not been completely solved.

Usually, the automatic controlling of the motion of a motor vehicle driven with a high speed merely covers fragmentary issues, to which solutions (although partial) were already sought (more or less successfully) when mechatronic active-safety driver assistance systems were designed. At some research centres, projects have also been developed to automatize the manoeuvres related to lane change, which takes place at e.g. overtaking or obstacle avoidance; the automatization of such manoeuvres is indispensable in the case of an autonomous vehicle operated in a wide range of speeds and road conditions [2, 3, 14]. The problem of controlling a vehicle in the situation that an obstacle has suddenly appeared, the vehicle cannot be brought to a halt before hitting the obstacle, and the only way to avoid a collision remains a circumvention of the obstacle, was already addressed in other authors' works, e.g. [6, 7, 8, 9, 10, 11]. In those works, attention was exclusively focused on the lane-change manoeuvre. Here, more attention has been devoted to the problem of braking, which usually precedes the manoeuvre of dodging the obstacle that has suddenly sprung up.

2. Problem of controlling vehicle motion in case of sudden appearance of an obstacle, from the point of view of drivers' practice and control theory

When preparing a concept of automatic controlling of vehicle motion, one should have in mind both the known methods of defensive actions taken by experienced drivers (e.g. [12,13]) and the considerations arising from the general control theory applied to the models of dynamics of motor vehicle motion (e.g. [1]).

The controlling of motion of a fast-moving motor vehicle after noticing an obstacle that has suddenly appeared is an extremely difficult road situation. Experienced drivers control their vehicles according to the following scenario: having noticed the obstacle, the driver fully applies vehicle's brakes and if the vehicle cannot be stopped before hitting the obstacle and there is a chance of circumventing the obstacle in a safe way, then he/she gives up braking and changes the lane by rapid turning the steering wheel (with arresting it for a while) once to the one side and then to the other side. If this is the case, the vehicle controlling process consists of two stages, i.e. first braking without turning the steering wheel and then a lane-change manoeuvre with a stable vehicle speed (Fig. 1).

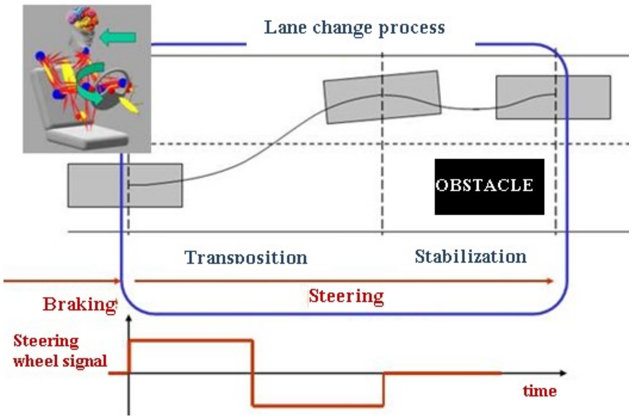


Figure 1. Two-stage process of the vehicle being controlled by the driver

Of course, an extremely difficult combined manoeuvre can also be imagined, where both the vehicle speed and angular position would be simultaneously changed. However, only specially trained rally drivers may boast adequate skills to perform a manoeuvre of this kind.

Let us consider, from the model analysis point of view, the scenario of controlling the motion of a fast-moving motor vehicle after sudden appearance of an obstacle. If the vehicle moves with a stable speed and the driver suddenly notices an obstacle present before the vehicle front at a distance considered by the driver dangerous, then the braking process is started (with some delay); after a time resulting from the inertia of the braking system, the braking efficiency rises to its full value, with the braking deceleration being only limited by the threat of loss of vehicle stability due to full tyre slip. If the minimum braking distance in the existing conditions exceeds the distance between the vehicle and the obstacle, then the only solution available is to terminate braking and to start the process of turning the steered wheels at an appropriate instant. Now, a reasonable question arises, whether the most appropriate instant of changing the vehicle control mode can be determined by the optimization method. A natural criterion of optimization of the vehicle control process is the total time of duration of the two process stages. The finding of an analytical solution of this problem seems to be crucial for the synthesis of automatic vehicle control. For an analytical formula to be obtained in result of the said optimization in order to determine the instant of switchover from the first to the second stage (defined by the vehicle speed at the end of the braking process), the elementary vehicle motion models to be used, i.e. the model representing the process of hard braking in rectilinear motion and the model representing the process of a rapid lane change at a constant speed, must be very simplified.

In the elementary model of hard braking, an assumption may be made that the braking process is run at a constant deceleration (depending on the tyre-road adhesion coefficient). In such a case, the longitudinal vehicle velocity in the elementary model of a rapid lane change is assumed as constant. To simplify the calculations, it is worth assuming that the elementary model of a rapid lane change is applied to a vehicle with neutral steer and that the steady state is achieved almost immediately after the "bang-bang" turning of the steered wheels is completed. Then, the lateral vehicle displacement required is represented by a simple quadratic function of the time of controlling the process and of the vehicle speed [11]. Fig. 2 shows the approximate longitudinal vehicle velocity vs time curve for the braking stage and the stage of "bang-bang" turning of the steered wheels.

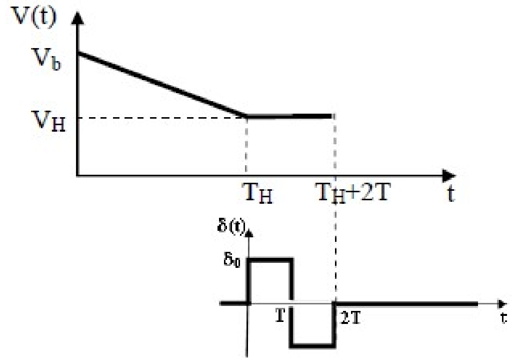


Figure 2. Longitudinal vehicle velocity vs time curve V(t) for both stages of controlling the vehicle motion

Notation:

t	–	time
T_S	–	total control process duration time
T_H	–	time of duration of the braking process
T	–	half of the time of the "bang-bang" steered wheels turning process
a_H	–	maximum braking acceleration acceptable at the actual tyre-road adhesion coefficient
$V(t)$	–	instantaneous vehicle velocity value
V_b	–	vehicle velocity at the instant of achieving the deceleration of a_H
V_H	–	vehicle velocity at the instant of the end of the braking process
$\delta(t)$	–	instantaneous value of the steering angle
δ_0	–	steering angle amplitude necessary to avoid the obstacle in the "bang-bang" process

The task to minimize the control process duration time T_S is reduced to determining the vehicle velocity V_H at which the braking stage should be terminated.

Based on Fig. 2, the following equations may be formulated:

$$T_S = T_H + 2T \tag{1}$$

$$V_H = V_b - a_H T_H \tag{2}$$

The assumption of neutral vehicle steer makes it possible to formulate the following equation [11]:

$$T^2 \left(\frac{V_H^2}{L} \right) \delta_0 = Y_0 \tag{3}$$

where:
Y_0 – lateral vehicle displacement necessary to avoid the obstacle;
L – vehicle wheelbase.

By using equations (1-3), the following functional dependence may be formulated:

$$T_S(V_H) = \frac{V_b - V_H}{a_H} + 2\sqrt{\frac{Y_0 L}{\delta_0}} \cdot \frac{1}{V_H} \tag{4}$$

The optimization task may be written as follows:

$$\min_{V_H} \left(T_S(V_H) = \frac{V_b - V_H}{a_H} + 2\sqrt{\frac{Y_0 L}{\delta_0}} \cdot \frac{1}{V_H} \right) \tag{5}$$

Unfortunately, the equation for $T_S(V_H)$ is a hyperbolic function (monotone, with no local minimum) and its minimum value is achieved for

$$V_H = V_b \tag{6}$$

The concept of the automatic control system was prepared without excluding the possibility of braking within the vehicle motion control process. Quite the opposite, an assumption was made a priori that the vehicle motion control process would be run in two stages. This was because of several reasons:

1. The braking stage is necessary when the adjacent lane is occupied by another vehicle and a lane-change manoeuvre cannot be carried out.
2. The braking stage may turn out to be sufficient for avoiding a collision, when the distance to the obstacle is long enough.
3. The braking stage (short-lasting) is very helpful in identifying current parameters of the reference model representing the dynamics of vehicle motion (e.g. in determining current parameters of the tyre-road adhesion characteristics and, in consequence, the cornering stiffness of the tyres), which is indispensable for automatic controlling of the lane-change manoeuvre.

The braking time T_H and, therefore, the vehicle braking distance S_H available are limited by the minimum distance S_{omin} to the obstacle necessary for obstacle circumvention with a speed of V_H in boundary conditions (with maximum lateral acceleration a_y being limited by a possibility of directional stability loss or vehicle rollover [5]). The unknowns S_{omin} and V_H may be determined by solving the system of equations (7)

$$\begin{cases} V_b^2 - V_H^2 = 2 \cdot \mu \cdot g \cdot \left(S_p - S_{o\,min}\right) \\ S_{o\,min} = \sqrt{\dfrac{4 \cdot V_H^2}{\mu \cdot g} \cdot Y_o - Y_o^2} + \Delta S \end{cases} \tag{7}$$

where:

S_p – distance between the vehicle and the obstacle at the instant when the vehicle velocity becomes equal to V_b;

ΔS – road length determined from results of simulation tests of obstacle avoidance in boundary conditions with using the control system having been developed and the virtual vehicle model;

μ – tyre-road adhesion coefficient (the system of equations (7) was derived with an assumption made that $a_H \approx a_y \approx \mu g$).

The solution of the system of equations (7) is as follows:

$$S_{o\,min} = \Delta S + 4 \cdot Y_o + 2\sqrt{15 \cdot Y_o^2 + 8 \cdot Y_o \cdot \left(\Delta S - S_p\right) + \frac{2 \cdot V_b^2 \cdot Y_o}{\mu \cdot g}} \tag{8}$$

$$V_H = \sqrt{V_b^2 - 2 \cdot \mu \cdot g \cdot \left(S_p - S_{o\,min}\right)} \tag{9}$$

Equations (8) and (9) make it possible to determine (interchangeably) the limit values of the distance to the obstacle S_{omin} and the vehicle velocity V_H at which the braking process must be terminated and the obstacle circumvention process must be started.

3. Concept of the system of automatic vehicle control during obstacle avoidance

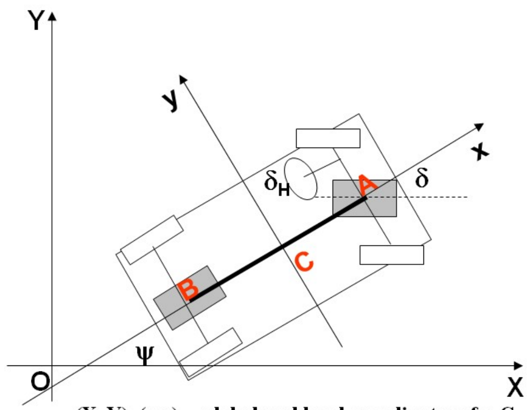
When the concept of the automatic control system was developed and then the control algorithm was synthesized, the following assumptions were adopted:

1. The motor vehicle is provided with a system of automatic control of its braking and steering systems, which includes controller with digital processor, memory, and signal transducers, electromechanical braking and steering system actuators, and standard motion sensors such as those used in the ABS, BAS, and ESP systems, as well as devices to monitor the road and vehicle surroundings, i.e. cameras, radars, and lidars, typical for the ACC and LAS systems.
2. The motion sensors provide all the data needed for determining instantaneous values of the variables that describe the vehicle motion during both the braking stage and the obstacle circumvention stage. The monitoring devices provide the processor with all the information necessary for the system to calculate the width of the roadway and the lanes available.
3. The system controller ensures complete processing of measurement signals, with identifying and storing the values of individual parameters (e.g. the tyre-road adhesion coefficient μ) present in the reference models of longitudinal and lateral vehicle dynamics.
4. The reference models of vehicle motion dynamics have very simple mathematical forms. Thanks to this, analytical forms of the reference signals generated and analytical forms of the algorithms of operation of correcting regulators can be built, which is essential for effective real-time controller operation.
5. When, in result of the automatic monitoring of vehicle surroundings, the control system detects that the vehicle is moving along a straight path in which an obstacle has appeared (at a distance shorter than the estimated necessary vehicle stopping distance) then, at first, a process of hard braking, with using the ACC, BAS, and ABS systems, is started, during which the model of vehicle motion dynamics is identified and the possibilities of stopping the vehicle

before hitting the obstacle are estimated. If a collision is found unavoidable in spite of the braking and if the adjacent lane is found to be clear, the automatic control of the steering wheel angle is started and the steering wheel is operated so that the vehicle passes by the obstacle with a constant speed (determined by the final conditions of the vehicle braking stage) along a path parallel to the initial vehicle path.

6. The lane-change process controller operates in the structure of an optimum follow-up system [1]. The generator of a signal to control the steering wheel angle sends a predetermined "bang-bang" reference signal to the steering system actuator. The signal is corrected by two Kalman regulators switched on in succession. The transposition regulator corrects the reference control signal based on the deviation of the measured lateral vehicle displacement curve from the reference displacement. The stabilization regulator corrects the reference control signal based on the deviation of the measured yaw angle curve from the reference yaw angle. The reference signals are determined from the reference model adopted.

The lane-change control system presented below has been described in detail in previous authors' publications [7, 9, 10]. An important feature distinguishing it from other similar systems is the fact that both the reference signals and the regulator algorithms are determined with taking as a basis a specially prepared reference model of lateral dynamics of a motor vehicle at a "bang-bang" type input applied to the steering system. The reference model derives from the known "bicycle model", subjected to additional mathematical operations (transformation of variables from the local to global coordinate system, linearization, Laplace transformation, determining of transmittances, and reduction of transmittances). Thanks to this, its final form enables analytical determining of the necessary reference signals and regulator algorithms. The essence of the reference model used has been expressed in Fig. 3.



(X, Y), (x,y) - global and local coordinates of p.C
U - lateral speed in local coordinate
Ω - yaw angular speed
ψ - yaw angle
δ - steering angle
δ_H - steering wheel angle
V - velocity (here constant)
m - mass
J - moment of inetia (to p.C)
a, b - distances AC and BC
k_A,k_B - yaw coefficients (to p. A, B)
p - steering system ratio

Classic „bicycle model" in local coordinates
+
Transformation to global coordinates
Standard approach

$$m\dot{U}(t)+\frac{k_A+k_B}{V}U(t)+\frac{mV^2+k_Aa-k_Bb}{V}\Omega(t)=k_A\delta(t)$$

$$J\dot{\Omega}(t)+\frac{k_Aa^2+k_Bb^2}{V}\Omega(t)+\frac{k_Aa-k_Bb}{V}U(t)=k_Aa\delta(t)$$

$$X(t)=\int_0^t\dot{X}(\tau)d\tau=\int_0^t\left(V\cos(\psi(\tau))-U(\tau)\sin(\psi(\tau))\right)d\tau$$

$$Y(t)=\int_0^t\dot{Y}(\tau)d\tau=\int_0^t\left(V\sin(\psi(t))+U(\tau)\cos(\psi(\tau))\right)d\tau$$

$$\psi(t)=\int_0^t\Omega(\tau)d\tau$$

$$\delta_H(t)=p\cdot\delta(t)$$

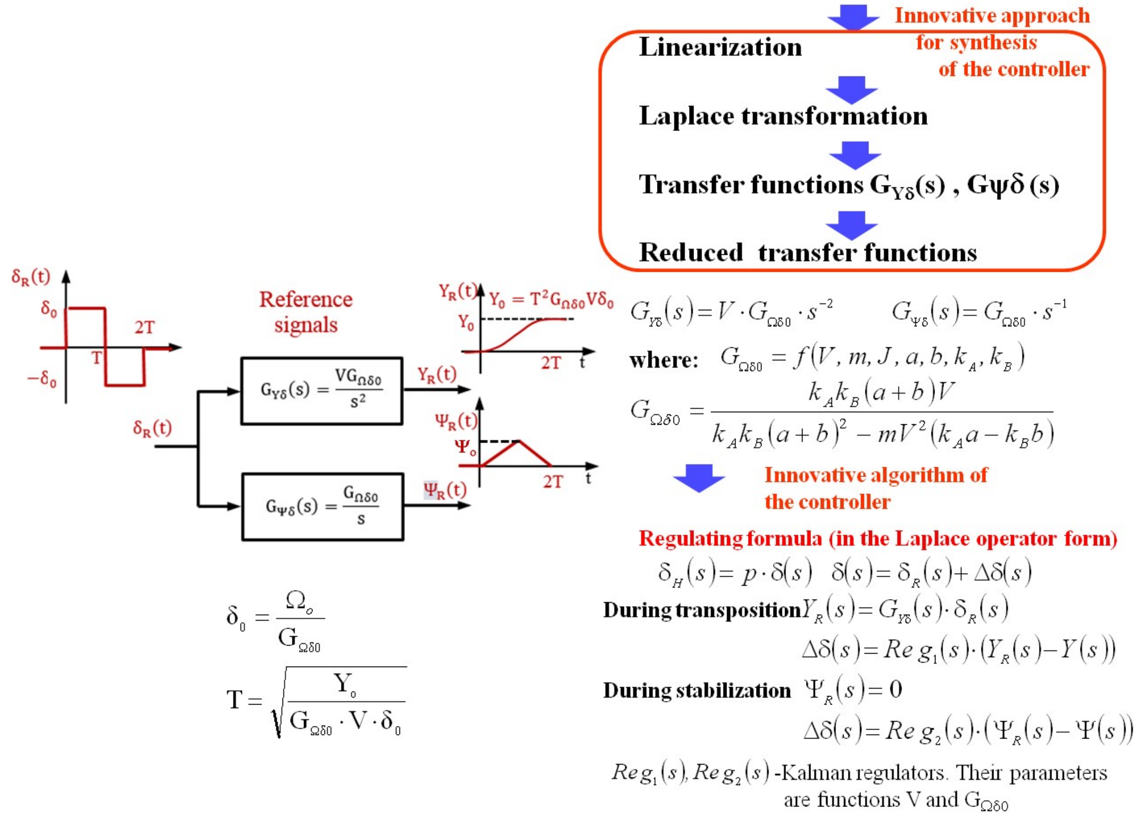


Figure 3. Concept of the synthesis of the lane change control system

The concept of the control system for the lane change stage has been depicted in the form of a schematic diagram in Fig. 4.

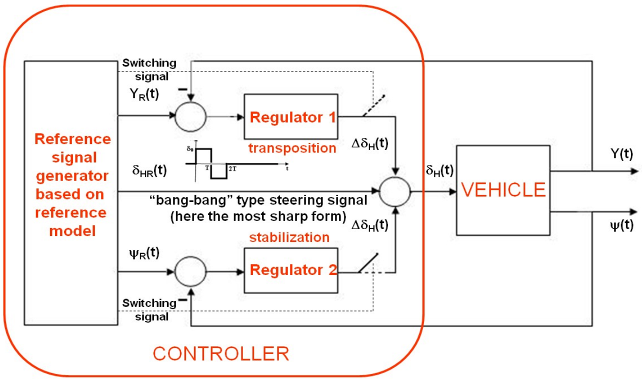


Figure 4. Schematic diagram of the lane change control system

The determination of parameters of the Kalman regulators is based on the transmittances taken from the reduced reference model. This has been described in detail in a previous authors' publication [6]. The mathematical formulas defining the parameters of these regulators (of the proportional-derivative (PD) type in this case) require that the amplification coefficient $G_{\Omega\delta0}$, which directly depends on the reference model parameters (V, m, I_z, k_A, k_B, a, b), should be known. Since a real steered object is characterized by much more complicated dynamics than the dynamics represented in the reduced model, the selection of regulator parameters must be confirmed by simulation tests.

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4. Simulation tests of the automatic lane change control system

The lane change control method developed had to be thoroughly tested. With this objective in view, a series of simulations were carried out, where a "complex model" of the dynamics of a real vehicle, extended and experimentally verified [4], was used as a virtual steered object. As the steered object, a two-axle motor truck of medium load capacity was used.

The physical model (Fig. 5) is a three-dimensional discrete dynamic system, in which all the major features of the real steered object are taken into account. It consists of seven rigid bodies (vehicle body, front axle, rear axle, and four road wheels), linked with each other by spring and damping elements having non-linear characteristics and representing the suspension system and wheel tyres. The model has 20 degrees of freedom, where the vehicle body solid has six of them, the front and rear axle beams have four degrees of freedom each, and the front and rear wheels have two and one degrees of freedom each, respectively (the rear wheels being assumed as dual wheels).

The tyre-road interaction has been described with using the known Dugoff model as a basis and with taking into account the spring and damping tyre characteristics in the radial, lateral, and circumferential direction. The tyre-road interaction model developed within this work makes it possible to simulate the vehicle motion in the conditions of full tyre slip, allows for different tyre-road adhesion coefficient values on both vehicle sides, and handles the wheel lift-off effect. The wheel driving and braking model includes simplified models of conventional ABS, ASR, and ESP systems.

The model of the vehicle steering system has been built with taking into account the geometry, kinematics, as well as spring and damping characteristics of the suspension system. In comparison with the conventional steering system, a planetary gear and an electric motor have been added, thanks to which the unit may function as an active servo, digitally controlled (e.g. in accordance with the controller algorithm proposed, where the current vehicle position measured, feedback, and regulators may be made use of). In the model of the steering system treated as a servo, not only the spring and damping effects but also the dynamic effects caused by system operation inertia are allowed for.

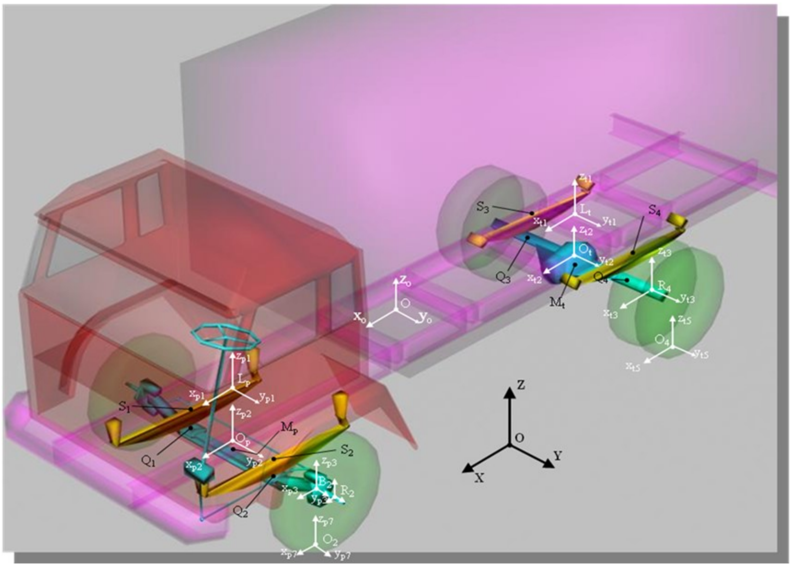

Figure 5. Idea of the model of a motor truck treated as a virtual vehicle

As it can be seen, the mathematical "complex model" of the steered object goes far beyond the simplifying assumptions adopted in the reference model, not only in the reduced version but also in the original version of the latter (the "bicycle model").

The correctness of the vehicle control concept adopted and the proper functioning of the regulators was verified by simulation tests, where an obstacle suddenly appearing in front of the vehicle forced the latter to change its lane within as short a distance as possible. Results of extensive simulation tests revealed the following:

– The control system and the regulators correcting the reference control signal functioned properly though the vehicle operation and road conditions were changed in a wide range [6, 7].
– The system was very little sensitive to the linearization of the reference vehicle model [8].
– The system showed small sensitivity to signal measurement errors (noise, offset, etc.) [9] and to disregarding low values of inertia in the control system [11].

The possibilities of functioning of a two-stage control system (that would implement the vehicle braking followed by obstacle circumvention) have been shown in this paper.

The virtual vehicle model was used to simulate, in succession, the manoeuvre of hard braking followed by the manoeuvre of obstacle circumvention. In the simulations, the following assumptions were made: a fully laden vehicle moved in the middle of the right lane (3 m wide) on a one-way two-lane road with wet surface, with a speed of V_o being slightly higher than 80 km/h. The distance needed to stop the vehicle in such conditions was estimated by the controller at $S_z \approx 90$ m. Suddenly, an obstacle occupying the whole right lane width appeared at a distance of somewhat more than 70 m from the vehicle front; the left lane remained clear. A hard braking was started; the short-lasting braking made it possible to determine the following initial parameters: vehicle velocity $V_b = 80$ km/h, distance to the obstacle $S_p = 70$ m, tyre-road adhesion coefficient value $\mu = 0.3$, obstacle width $Y_o = 3$ m. At the parameter values as above, the continuation of braking would result in a vehicle impact against the obstacle with a velocity of $V_u = 32$ km/h. The start of the obstacle circumvention manoeuvre would provide a possibility of avoiding a collision with the obstacle.

Three scenarios of the obstacle avoidance manoeuvre were analysed:

1. The control system immediately terminates the braking process and starts the obstacle circumvention with a velocity of $V_b = 80$ km/h by performing a lane-change manoeuvre (lateral vehicle displacement by $Y_o = 3$ m) within as short a distance as possible, i.e. in boundary conditions acceptable for the specific tyre-road adhesion coefficient (boundary conditions according to the reference model).
2. The control system terminates the braking process and starts the obstacle circumvention with a velocity of $V_b = 80$ km/h, but with utilizing the whole distance $S_p = 70$ m between the vehicle and the obstacle for the lane-change manoeuvre.
3. The control system continues the braking process to reduce the vehicle velocity to as low a value as possible and then starts the obstacle circumvention with a velocity of V_H within a distance of S_{omin} in boundary conditions. The V_H and S_{omin} values are calculated with using equations (8) and (9).

The predefined input conditions applied to the control system have been presented in Table 1.

Table 1. Values of the input parameters applied to the control system

	Scenario No 1	Scenario No 2	Scenario No 3
t_H [s]	0	0	1.53
T [s]	1.01	1.46	1.01
δ_{H0} [deg] $\delta_{H0} = i_l\delta_0$	44	21	63
V_b [m/s]	22.2	22.2	22.2
V_H [m/s]	22.2	22.2	18.0

S_o [m]	49.9	70	41.4

δ_{H0} – steering wheel angle amplitude necessary to avoid the obstacle in the "bang-bang" process;
i_l – steering gear ratio;
S_o – distance necessary for obstacle circumvention.

Results of the obstacle avoidance simulations have been presented in graphs in Figure 6.

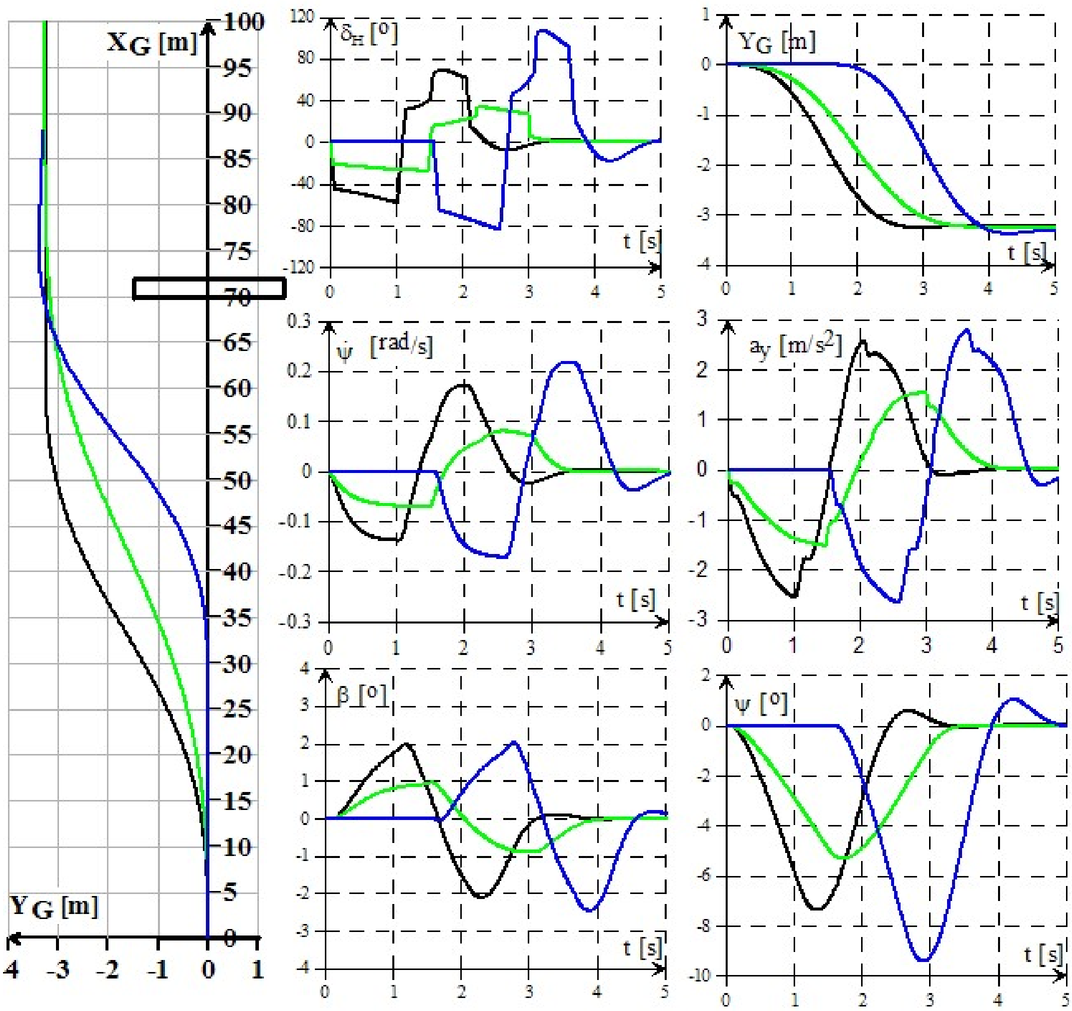

Figure 6. Comparison of results of the obstacle avoidance simulations for the three scenarios under analysis. Curve colours: black – scenario No 1; green – scenario No 2; blue – scenario No 3

Notation used in Figure 6:
X_G – longitudinal vehicle displacement
Y_G – lateral vehicle displacement
δ_H – steering wheel angle
$\dot{\psi}$ – vehicle yaw velocity
a_y – lateral acceleration of the vehicle mass centre
β – vehicle mass centre sideslip angle

ψ – vehicle yaw angle

It can be seen from the graphs presented in Fig. 6 that the control system successfully accomplished the obstacle avoidance task in each of the scenarios under analysis. In scenarios Nos 1 and 3, the obstacle avoidance manoeuvre was performed in conditions close to those defined as "boundary". In scenario No 2, the test conditions were definitely safer because the risk of exceeding the acceptable values of lateral acceleration a_y and yaw velocity $\dot{\psi}$ was much lower than those to be encountered in the other scenarios under analysis. It is important that the control system was able to generate desirable reference signals appropriate for diverse requirements in individual obstacle avoidance scenarios and then it successfully fulfilled the said requirements. Of course, the presence of interferences of various kinds (not taken into account in the simulations presented) may worsen the quality of functioning of the control system. Undoubtedly, the control system would be least sensitive to interferences if the obstacle avoidance manoeuvre were performed according to scenario No 2, in conditions far from those defined as "boundary". The sensitivity of the control system to interference is to be examined in the future, with various obstacle avoidance scenarios to be taken into account.

5. Recapitulation and conclusions

Selected problems concerning the concept of automatic controlling of motor vehicle motion in case of sudden appearance of an obstacle have been discussed. A theoretical analysis of the control process, which consists of a vehicle braking stage and a lane-change stage, has been presented. Among the conclusions drawn from the analysis, there is one quite surprisingly saying that the obstacle avoidance effect is most quickly achieved when the braking stage is shortened to the minimum, i.e. when the vehicle circumvents the obstacle with quite a high speed. The automatic vehicle control process is run with the use of standard driving aids to assist the driver in braking, such as ACC, BAS, or ABS, which make a basis for the functioning of the control system at the first stage of the process. The main part of the control process, i.e. the lane-change manoeuvre (stage 2), is run with the use of a special controller, which is based on a simplified reference model of the lateral vehicle dynamics, developed within this work. An analysis of the system concept presented shows that for the parameters of the lane-change control process to be correctly selected, the analytical deliberations should be supplemented with simulation tests. The simulation results presented, where a model of the dynamics of motor truck motion was used as the virtual object controlled, have shown that the correct selection of the steering wheel angle amplitude and of the control process time is strongly related to the velocity with which the vehicle moved at the end of the braking stage.

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