Simulation tests of the integrated lane change control system

M Gidlewski 1,3, L Jemioł 2 and D Żardecki 1

1 Military University of Technology (WAT), Poland
2 University of Technology and Humanities in Radom, Poland
3 ŁUKASIEWICZ Research Network – Automotive Industry Institute (ŁUKASIEWICZ-PIMOT), Poland

Abstract. This paper presents the concept of an integrated control system for lane change by a two-axle truck. In earlier works the authors used only a controller coupled to the steering system for sudden lane changes. Nowadays, the steering system controller is integrated with ESP (Electronic Stability Program) which causes momentary braking of chosen vehicle wheels when traffic destabilization threatens. A simulation study of the integrated control system operation during sudden lane change was performed for an unladen and fully laden car on a wet road in near limiting conditions. The test results were compared with those obtained when this maneuver was performed using only the steering controller.

Keywords – safety, vehicle, vehicle detection

1. Introduction
In the last twenty years, the number of road accidents and their victims in the EU (including Poland) has significantly decreased. This was despite the fact that the number of cars in operation has been increasing from year to year [1,2,3]. The decrease of the basic indicators of accident risk was influenced by many factors, including: among others, decisive improvement of passive and active car safety. The driver of a modern car is assisted passively (information systems that warn of hazards or recommend necessary actions) and actively (systems that facilitate and correct certain driving activities, especially in boundary conditions). With the increasing use of various types of driver assistance systems in cars of many brands, their alternative name „assistant systems” has become popular [4]. Passive safety systems do not directly intervene in the car's movement control process, but only provide the driver with additional information. In dangerous situations, they warn of existing danger and suggest the initiation of designated defensive maneuvers. Active safety systems participate in controlling the vehicle together with the driver. They have the capability to assess the hazards caused by the driver's actions in order to determine when and how strongly to intervene. They generally accept the driver's actions, opposing them only if they lead to a collision or loss of stability of the car. Such systems therefore intervene automatically only when necessary to correct driver actions deemed unsafe. The interventions of safety systems should maintain the necessary balance between the level and frequency of interventions, i.e. do not change the interactions with the car controls too strongly, too early or too often [5].

Currently, there is a noticeable trend towards combining passive and active safety systems (Integrated Safety Technology).
Driving a road vehicle is a complex dynamic process in which the driver carries out successive emerging tasks. These tasks result from the current driving conditions and the road situation and they are characterized by varying degrees of difficulty and different ways of implementation. The relatively easy ones include stabilization of the vehicle movement in the presence of disturbances (bumps in the road, gusts of wind, etc.) or following the trajectory set by the lines limiting the roadway. More difficult and requiring the use of more advanced steering algorithms are maneuvers (e.g. parking). The most difficult are sudden maneuvers performed at high speeds. In such extreme dynamic conditions, the vehicle is at risk of losing directional stability, and in the case of a truck, also of tipping over. Practice shows that in such critical driving situations, an experienced driver is forced to act intuitively (almost „blindly”, but according to proven and previously learned patterns). Many drivers (especially those with low experience) in critical situations are unable to correctly select and then safely and effectively execute the appropriate defensive maneuver, which in consequence leads to a collision or road accident [6]. It is therefore widely believed that the role of the driver in driving should be increasingly reduced aiming consistently at a fully autonomous vehicle in which the driver becomes unnecessary.

Today, many academic and industrial centers are conducting intensive research on autonomous vehicles. However, despite of the considerable investment in research in this field, the introduction of fully automated vehicles into general use is still an open question. Many problems remain to be solved, not only technical, but also social and legal.

The prolonged period of introduction of fully autonomous cars into service as well as the dynamic development of various types of controllers, actuators, sensors, monitoring devices, microprocessors, networks and telecommunication technologies are conducive to the emergence of more and more effective systems supporting the driver's actions related to driving the vehicle. In recent years, a significant effort has been made to develop assistant systems that are activated automatically when a critical driving situation occurs and that replace the driver in the selection and execution of an effective or at least the most advantageous defensive maneuver in the given situation. Advanced research work on such systems is carried out in many research centers, e.g. [7,8], and in the near future they will be used in serially produced cars. In December 2019, the European Parliament passed legislation mandating (as of May 2022) the mandatory equipping of new models of cars and vans with advanced safety features such as automatically activated emergency braking systems and lane-keeping systems in emergency situations.

As part of research project N N509 568439, extensive analytical work was undertaken on the application of Active Front Steering (AFS) in the automatic steering of a two-axle medium-duty truck in accident-prone traffic situations due to a suddenly appearing obstacle [9-12]. Extensive modeling studies were conducted based on avoiding a sudden obstacle in the shortest possible time and on the shortest possible path resulting from the prevailing road conditions and the traffic condition of the vehicle. This meant that the lane changes necessary to avoid the obstacle were made under extreme traffic conditions with low stability. Simulation studies were conducted for a very wide range of varying road and operating conditions, yet the obstacle avoidance maneuver was successfully completed in the vast majority of trials without the need to change previously made assumptions and established values of controller tuning parameters [13]. Only the unladen car proved to be very sensitive to changes in traffic conditions and parameters, which manifested itself as a loss of directional stability during the manoeuvre. In order to avoid this, the reserve of stability was increased by decreasing by 20% (in relation to the other considered states of car load) the value of the reference angle of steering wheel rotation given to regulators [14]. Unfortunately, this resulted in an increase in the distance required to avoid the obstacle. In the literature, e.g. in [15, 16], a thesis is presented that the steering system provides good handling properties only when the lateral acceleration is low, the vehicle drift angle is small, and the lateral tire drift characteristics are linear. However, in emergency situations accompanied by high lateral acceleration (such as occurs during sudden lane changes), the characteristics of the tires become nonlinear and the desired effect of controlling the motion of the car cannot be achieved only by steering wheel control. In this case, the additional integration of the braking system as well as the drive train (ESP or DYC - Direct Yaw Control) into the vehicle's motion control can significantly improve the driving characteristics.
It was decided to modify the developed active steering system ASF by supplementing it with an electronic trajectory control system ESP. This paper presents the concept of the integrated steering system. Simulation tests of the integrated system functioning were carried out during the execution of sudden lane change for an unladen and laden car on a wet road, in conditions close to the limit. The results of the tests were compared with the results obtained when performing this maneuver only by the ASF system.

2. Concept and mathematical model of an integrated automatic lane change assistant system

The integrated assistance system consists of the ASF active steering system inducing preset front wheel steering angles and the ESP electronic control system causing momentary braking of selected vehicle wheels. Integration of these systems allows simultaneous control of these subsystems and mutual exchange of information from individual sensors and actuators. Coordination, on the other hand, ensures harmonious functioning of the systems and synchronization of the partial actions of the individual systems, which enable proper realization of the main goal, i.e. sudden lane change. The block diagram of the integrated assistant system is shown in Figure 1.

![Block diagram of an integrated assistant system in the lane change process.](image)

The motion of a two-axle truck traveling at a fixed speed on a straight section of a one-way roadway having at least two lanes in one direction is analyzed. At some point, an obstacle appears in the vehicle’s lane at a distance less than the distance needed to stop the vehicle but sufficient to avoid the obstacle. The assistant system initiates an abrupt lane-change maneuver, initially by turning the front wheels only, so that the car is moved into the adjacent lane in the shortest possible time and over the shortest possible distance. In practice, this maneuver requires the steering wheel to be turned very quickly in either direction (the ASF is solely responsible for this), while of course maintaining traffic stability conditions.

ESP is a system that overrides the ASF, and when the vehicle approaches the limit of adhesion, brakes the appropriate wheels causing an increase in the radius of the trajectory and a reduction in speed, which further protects the vehicle. and reduce the speed of the car which additionally secures stable movement of the vehicle.

The two systems forming the assistant system use as a reference model the flat, single-track “bicycle model” of a car known from numerous publications [17, 18] (Figure 2) describing the dynamics of motion of a vehicle traveling at a constant speed under not too strong perturbations of the steady-state
motion. However, the classical „bicycle model” was modified by performing simple transformations to express the vehicle motion in the global (OXY) system and by linearizing the equations of motion. It has been shown in [10] that for small and short-lived disturbances of motion (such forcing we deal with during obstacle avoidance), linearization of the equations of motion of the vehicle is acceptable.

The equations of motion of the reference car model used are shown below:

\[ m\ddot{Y}(t) + \frac{k_A + k_B}{V} \dot{Y}(t) + \frac{k_A a - k_B b}{V} \dot{\Psi}(t) = (k_A + k_B) \dot{\Psi}(t) = k_A \delta(t) \]
\[ J\ddot{\Psi}(t) + \frac{k_A a^2 + k_B b^2}{V} \dot{\Psi}(t) = (k_A a - k_B b) \dot{\Psi}(t) + \frac{k_A a - k_B b}{V} \ddot{Y}(t) = k_A a \delta(t) \]  

(1)

There are seven parameters in the model: car speed V, mass m, moment of inertia J, wheel drift resistance coefficients of the front axle k_A and rear axle k_B, distance from the center of mass of the front axle a and rear axle b. The reference model of vehicle motion dynamics specifically has a rather simple mathematical form, which is essential for the effective operation of the real-time assistance system.

Equations (1) are linear, so they can be subjected to the Laplace transform and the corresponding transmittance binding the waveform transforms can be determined. With zero initial conditions on the variables, one then obtains an equivalent notation of the reference model in the transfer functions form (2).

\[ Y(s) = G_{Y\delta}(s) \delta(s); \quad \psi(s) = G_{\psi\delta}(s) \delta(s) = \frac{G_{\psi\delta}(s)}{s} \delta(s) \]  

(2)

The active steering ASF uses a reference model in the transmittance form (2) and operates in the structure of an optimal tracking system [19]. The operation strategy of the system is based on the time decomposition of the lane change process. The process of steering angle control is divided into two consecutive phases which carry out the task of rearranging the lateral center of mass and then the task of stabilizing the car path. The signal generator controlling the steering wheel angle sends to its actuator the set reference waveform \( \delta_{HR} \), which is corrected by a system of two successively switched Kalman regulators. An important distinction of the developed control system (in comparison with other similar studies) is that the reference signals are determined on the basis of the vehicle reference model in the transmittance form when the steering angle is forced by the „bang-bang” type (nomenclature used in automation).

The base steering angle reference signal \( \delta_{HR0}(t) \) results from rescaling the steering angle \( \delta_R(t) (\delta_{HR0}=p\delta_R, \) where \( p \) is the kinematic steering ratio) and is described by the formula:

\[ \delta_{HR0}(t) = p \delta_R(t) = p(\delta_0(t) - 2 \cdot 1(t - T) + 1(t - 2T)) \]  

(3)

where: 1(t) – Heaviside function.
The parameter values of steering angle amplitude $\delta_0$ and maximum steering angle holding time $T$ are described by the expressions:

$$\delta_0 = \frac{\Psi_{ygr}}{G_{\Psi\delta_0}} = \frac{\Psi_{ygr}}{V_{\Psi_0}}; \quad T = \frac{\Psi_{0}}{\sqrt{V_t \delta_0 \Psi_{\delta_0}}} = \frac{\Psi_{0}}{V_{\Psi_{ygr}}} \tag{4}$$

where:

$$G_{\Psi\delta_0} = \frac{k_A k_B (a+b)V}{k_B (a+b)^2 - m v^2 (k_A a + k_B b)} \tag{5}$$

is transfer function parameter

Expressions (4) and (5) were derived using the reference car model in the transmittance form [9]. They guarantee stable motion of the reference model for the given road and operating conditions. This means that for a given course of the steering angle according to (3), the transient courses of the lateral acceleration $\tilde{Y}(t)$ and the yaw rate $\Psi$ will not exceed the preset limit values $\alpha_{ygr}$ and $\Psi_{gr}$. It has been shown in [20] that the limit values of $\alpha_{ygr}$ and $\Psi_{gr}$ can be determined using the distance from the obstacle, and in a critical situation [21] using the maximum value of the coefficient of adhesion of tires to the road surface $\mu$ in specific road conditions ($\alpha_{ygr} = \mu g$) or the maximum values of the considered quantities obtained during the simulation of driving a real vehicle on a curve in steady or transient conditions. Increasing the values of $\alpha_{ygr}$ and $\Psi_{gr}$ results in an increase in the steering amplitude $\delta_0$ and a decrease in the time of holding the maximum steering angle $T$, which consequently leads to a decrease in the time and distance needed to avoid an obstacle, but also to a decrease in the stability reserve of the car during lane change.

ESP uses a vehicle reference model in the form of linearized equations of motion (1). In critical situations, ESP reduces the risk of the vehicle skidding or rolling over. ESP performs its task by braking the relevant vehicle wheels, thus generating an optimally adjusted additional torque to bring the vehicle back on track or to reduce the value of the lateral acceleration that could cause the vehicle to roll over. The course of the real steering angle $\delta_{Head}(t)$ after scaling to the steering angle $\left(\delta(t) = \frac{\delta_{Head}(t)}{p}\right)$ is the forcing acting on the equations of motion (1). Solving these equations allows us to calculate the reference signals for the ESP: yaw rate $\Psi_{ref}(t)$ and center-of-mass drift angle $\beta_{ref}(t)$.

### 3. Methodology for simulation studies

The adopted concept of car control with the use of integrated control system and the correctness of operation of controllers were verified by conducting model tests. Such tests are currently the most efficient and effective method for testing various control systems. An extensive model of a truck (24 degrees of freedom), thoroughly verified experimentally in bench and road tests, was used as a virtual control object. Simulation studies consisted in avoiding a suddenly appearing obstacle (single lane change) on the shortest possible route. This maneuver is one of the basic maneuvers used in car driving. It is particularly dangerous when performed suddenly at high speed. The automation of this maneuver is particularly important for automating car steering. Simulation test conditions:

- the car is moving in a steady, rectilinear motion on a one-way roadway having two lanes in one direction, in the middle of the right lane;
- the width of one lane is 3 m and the width of the car is d=2.4 m;
- in each test the vehicle speed and the type of road surface on which the vehicle is travelling (the value of the coefficient of adhesion of the wheel to the road surface) are known;
- an obstacle suddenly appears in the car lane blocking the whole width of the right lane, the left lane is free;
- the distance of the emerging obstacle $S_o$ from the centre of mass of the car is not sufficient to stop the car in front of the obstacle but is greater than or equal to the minimum distance $S_{o\text{min}}$ sufficient to avoid the obstacle under the current operational and driving conditions;
- the controller initiates intensive braking of the vehicle. When the vehicle reaches a distance from the obstacle equal to $S_{o\text{min}}$ the vehicle stops braking and an automatic obstacle avoidance
manoeuvre is initiated for the existing road conditions and operating conditions. The reference waveforms of the lateral displacement of the centre of mass, the car yaw angle and the steering wheel rotation angle are generated using the reference model;

- passing an obstacle is considered to be correct if, after driving a distance \( S_0 \) the lateral displacement of the car's centre of mass slightly exceeds 3m and the car passing the obstacle has an angle of deflection close to 0° (measured in relation to the road axis). In such a case, the vehicle passing the obstacle will travel in the centre of the left lane parallel to the axis of the carriageway, at a distance of \( \Delta d = 0.3 \) m measured across the carriageway both from the obstacle and from the left edge of the carriageway.

In order to assess and compare the quality of the waveforms of selected quantities (obtained during model tests, significant for obstacle avoidance), special integral indices \([22]\) were introduced, expressing the percentage discrepancy between the reference waveforms and the actual waveforms obtained as a result of simulation, which is shown in Figure 3.

\[
W_S = 100\% \frac{\int (s_1(t)-s_2(t))^2 dt}{\int (s_1(t))^2 dt} \tag{6}
\]

In the research on the accuracy of the realisation of the reference signals, the set reference waveform and the real waveform obtained as a result of the simulation were compared for several quantities. Using expression (6) the values of accuracy index \( W_S \) were calculated for:

- steering wheel rotation angle \( \delta_H \) – accuracy index \( W_{\delta_H} \);
- the lateral displacement of the centre of mass of the vehicle \( Y \) – accuracy index \( W_Y \);
- vehicle yaw angle \( \psi \) – accuracy index \( W_\psi \).

In addition, the evaluation was subject to:

- distance needed to avoid the obstacle (lateral displacement of the vehicle's centre of mass \( Y \geq 3 \) m, longitudinal axis deviation angle \( \psi \approx 0 \));
- maximum excess of lateral displacement of the vehicle centre of mass \( \Delta Y \) of the set value \( Y = 3 \) m.

An obstacle avoidance manoeuvre was considered successful in a given test only if the following conditions were met:

- the distance needed to avoid an obstacle \( S_0 \) should be less than or equal to the set distance, obviously the smallest possible values of \( S_0 \) were preferred;
- the maximum lateral displacement of the vehicle centre of mass \( \Delta Y \) shall not exceed by more than 0.3m the set reference value (\( \Delta Y \leq 0.3 \) m);
- the values of the \( W_S \) indicators should be as low as possible.
4. Results of simulation studies

Extensive simulation studies of AFS and integrated system performance were carried out under identical operating and road conditions. The behaviour of the unladen and laden car on wet road surfaces was studied. In addition, three different driving speeds of the car during obstacle avoidance were considered V=60, 70 and 80 km/h.

Figure 4 shows an example of the waveforms of quantities describing the motion of an unloaded and loaded car while avoiding a suddenly appearing obstacle on a wet pavement (µ=0.3) at a speed of V=70km/h, for the amplitude of the reference steering wheel rotation angle δHR equal to the base value (3). Only AFS was used to steer the cars. In most of the graphs shown in the figure, there are two waveforms that differ in line colours. The continuous blue line describes the responses of the reference vehicle model to „bang-bang” steering wheel rotation. The black continuous line describes the response of the virtual vehicle model to steering wheel rotation generated by the steering system controls. From the graphs shown in the left column of Figure 4, it can be seen that the AFS failed to avoid the obstacle. The unladen car lost directional stability while performing this manoeuvre. Although the trajectory of the vehicle's centre of mass crossed the reference trajectory quite quickly at a considerable distance from the obstacle, the car lost directional stability a moment later. The AFS system, in an attempt to establish a trajectory of the vehicle on the left lane (parallel to the road axis), generated excessive values of the steering wheel rotation angle to the left, which led to exhaustion of the adhesion reserve on the wheels of the rear axle of the vehicle. As a consequence, the wheels of the rear axle of the car skidded completely. The vehicle started to rotate to the right and its centre of mass moved to the left. The loss of directional stability of the unladen car controlled by the AFS was found for all analysed driving speeds (V=60-80km/h).

From the graphs shown in the right column of Figure 4, it can be seen that the loaded vehicle controlled by the AFS avoided the obstacle on the Sroad without any problems, even showing a certain reserve of lateral adhesion (course of lateral acceleration ay(t)). The tests showed that the fully loaded vehicle was a stable system in all considered and it was very difficult to make it lose directional stability even when the amplitude of the reference steering angle was increased by more than 50% compared to the base value.

Figure 5 compares the waveforms describing the movement of the unladen car steered by the AFS (left column diagrams) and by the integrated system (right column diagrams).

From the waveforms shown in the right column, it can be seen that the car steered by the integrated control system correctly avoided the obstacle without using all of its reserves of grip. Braking of the vehicle wheels indicated by the control system at appropriate moments limited the maximum values of yaw rate (graphs φ̇(t)), lateral acceleration (graphs ay(t)), yaw angles (graphs φ(t)) and centre of mass...
drift angles (graphs $\beta(t)$) in relation to the values of these quantities when the vehicle was steered by the ASF system. Therefore, the car did not lose directional stability.

**Figure 5.** Comparison of the waveforms of selected AFS-controlled and integrated control system-controlled unladen vehicle motion during obstacle avoidance on a wet road ($\mu=0.3$, $V=70\text{km/h}$).

**Figure 6.** Comparison of changes in selected quantities and values of indicators used for their evaluation for a car steered by the AFS and by the integrated steering system during avoiding a suddenly appearing obstacle on a wet road surface for different values of steering wheel rotational amplitude $\delta_{HR}$ ($\mu=0.3$, $V=70\text{km/h}$).
Figure 6 shows selected waveforms describing the motion of the car steered by the integrated control system obtained for different values of the reference amplitude of the steering wheel rotation angle \( \delta_{HR} = \delta_{HR0} \) – solid black line, \( \delta_{HR} = 110\% \delta_{HR0} \) – dashed black line, \( \delta_{HR} = 130\% \delta_{HR0} \) – dotted black line, \( \delta_{HR} = 150\% \delta_{HR0} \) – puncted black line). The waveforms are presented against the reference waveforms (continuous blue line) and the waveforms obtained during vehicle control by the AFS system \( \delta_{HR} = 80\% \delta_{HR0} \) – continuous green line. From the graphs presented in Figure 6 and the table in the figure below, it can be seen that the integrated vehicle control system controlled the vehicle much better and safer than the unladen vehicle during its avoidance of a suddenly appearing obstacle. Increasing the \( \delta_{HR} \) even by 30\% compared to the baseline value did not cause the vehicle to lose directional stability while reducing the distance needed to avoid the obstacle. For the laden car, increasing the \( \delta_{HR} \) value resulted in a reduction of the distance needed to avoid the obstacle, but, at the same time, it increased the values of the other indices used to assess the quality of the considered runs.

5. Conclusions
The paper presents an assistant integrated control system for automatic lane changing in boundary conditions. The construction and functioning of the system is described. The system proved to be particularly effective when the unladen vehicle was avoiding a suddenly appearing obstacle. It guaranteed maintenance of the vehicle’s directional stability in all considered road and operating conditions. In addition, it shortened the distance needed to bypass an obstacle by 4-7\% in comparison to the AFS system. at the same time lowering the values of most \( W_i \) indices describing the accuracy of reference course reproduction.

For a laden car, the integrated system was not as useful, as it did not have to maintain directional stability and, in addition, slightly increased the distance required to avoid an obstacle. The 7\% reduction in obstacle avoidance distance was only achieved when the amplitude of the reference steering angle was increased by 50\% compared to the base value. However, this resulted in an increase in all of the \( W_i \) indices describing the accuracy of reference course reproduction.

Works improving the functioning of the integrated control system will continue.

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