Adaptive car control system based on a predictive model

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Abstract. An adaptive control is a control, which by pre-setting the parameters of the controller, enables the control of processes whose parameters are time-varying or are initially uncertain. The possibilities and benefits of adaptive control are versatile and can be best demonstrated by applying the system while driving a car, or maintaining the optimal speed and distance between cars, which is shown in this paper. As the car's weight decreases while driving due to fuel consumption, the control algorithm has to be adapted to the changed driving conditions. Accordingly, an adaptive control system using the Matlab software package, and an adaptive cruise control system (ACC) was created in this paper, which is based on a predictive model. After evaluating the developed model of adaptive car motion control, the output parameters such as speed, acceleration, and distance between the two vehicles were analyzed. In this paper a PID controller is used to reduce oscillations in the system. First, the P controller was used to reduce the rise time of the significant values, then the PI controller improved the rise time, and finally the PID controller achieved overshoot reduction performance without affecting the dynamic response system. The obtained results confirm the justified expectations for the possibility of adaptive car control utilization as one of the possible solutions to the increasing traffic incidents, as well as a measure to improve the reduction of these incidents.

1. Introduction
Nowadays, with the increase in traffic demand, there is a need for a flexible way of controlling road traffic. Adaptive control systems are made possible by the emergence of new technologies. With the increase in the number of cars on the road and the increasingly complex transport infrastructure, the need for modernization of the transport system has also increased. Accordingly, new solutions in the field of intelligent transport systems (ITS) have led to new ways of flexible controlling.

Compared to classic cruise control, Adaptive Cruise Control (ACC) contributes to improved comfort and reduced stress for drivers by maintaining tasks at a distance from the Lead Car. The ACC automatically adjusts the travel speed to keep the Lead Car according to the set distance. The system automatically decelerates the car when approaching the Lead Car, if necessary, with a slight activation of the brake, which contributes to and saves fuel consumption [2] and increases economic efficiency [3]. If the Lead Car increases speed, the ACC also increases the car speed, up to the set maximum speed. In case there are no vehicles ahead, the ACC behaves like a classic cruise control. Also, when driving downhill, the ACC brakes maintain the set speed, while a driver only needs to keep the steering wheel under control, and everything else is done by a smart ACC system. Adaptive Cruise Control has proven to be extremely useful in low visibility conditions, such as fog. In this case, the system easily recognizes the Lead Cars, even if a driver has not yet noticed them, and automatically slows down the car.
In order to understand the concept of the adaptive control in this paper, its application in car driving based on a predictive model is presented. Unlike [4] where it is assumed that the Lead Car follows the reference speed set by the driver, and the Ego Car from the ACC system follows the previous vehicle at the desired distance, in this paper the system is implemented using a PID controller was used and a comparison of the effects of P, PI and PID controllers on the dynamic car control system was performed. The simplified dynamics model for vehicle is considered in Longitudinal Vehicle Dynamics and is used in the development of the lower-level controller.

Accordingly, the first part of the paper generally considers adaptive control systems, their characteristics, areas of application, and the model of adaptive speed control and control prediction, as the main elements of an intelligent transport system. In the second part of the paper, an Adaptive Cruise Control system based on a predictive model was implemented using the example of a car control, i.e. maintaining the appropriate speed and distance between cars. In the process of simulating the behavior of this model, which is described by the dynamic behavior of the car, the Simulink tool from the Matlab software package was used. The analysis of the obtained results shows the effect of the ACC system, and the optimal parameters based on which the ACC system maintains a safe distance and appropriate speed between cars, according to their initial speed and position, as well as acceleration of the Ego Car, and how the PID controller affects the behavior of the created system.

2. Adaptive control systems

Research on adaptive steering began in the 1950s [1], which was prompted by problems in designing autopilots for aircraft operating at a wide range of speeds and altitudes. Since then, we have strongly developed adaptive control [3], which is applied in: advanced flight control systems for airplanes or spacecraft, robotic manipulators, process control, energy systems, car control and much more. An adaptive control is a systematic approach to an automatic adjustment (setting) of the controller in real time for the maintenance of the desired level of control performance when the parameters of the dynamic process model are unknown and/or change over time [1].

Characteristics of adaptive control are [1]:
- Closed loop control.
- Data on system characteristics are determined during system operation (online).
- Identification of unknown parameters or measurement and calculation of quality criteria.
- Selecting a control strategy and acting on the system by changing the signal, parameter or structure.

The Adaptive Control System is primarily oriented towards eliminating disturbances in the operation of the control system.

Disorders affecting the control system [1]:
- Disorders affecting control variables.
- Disorders affecting the control system performance.

Therefore, a flexible control system is a feedback system whose control variable is the index of performance (IP), and the control monitoring of an IP system with unknown and variable parameters representing precisely the goal of the adaptive control.

The adaptive control system measures a specific IP control system using inputs, states, outputs and known interferences, and based on a comparison of the measured IP and the default set of IPs, the adjustment mechanism changes the adjustable controller parameters and/or generates an auxiliary control to maintain control the IP system of a close default set of IP addresses, as shown in this paper on the example of car control.

2.1. Adaptive Cruise Control System (ACC)

Since 1995, when the first cruise control was installed in a car, it has become an almost inevitable in cars, and without it, long journeys would be much more tiring. Nowadays, when traffic is heavier, a conventional cruise control is no longer applicable as it was before. However, instead of becoming obsolete, it has evolved and adapted to new circumstances. For this reason, a cruise control is becoming
more adaptable, with the possibility of automatically adjusting the speed in relation to the Lead Car and acceleration when there are no cars ahead. An Adaptive Cruise Control (ACC) is a function of the advanced driver assistance system in the longitudinal dynamics of the car maintaining the desired distance and safe speed from a preceding car [4].

Car speed control is a classic application of the control theory system. Cruise control maintains the speed of a car by adjusting the position of the throttle, which means that sensors are necessary to determine the speed and position of the throttle.

Adaptive Cruise Control in the rear of the car detects the Lead Car and keeps the Lego Car at a safe distance from the Lead Car by controlling its accelerator and brake [5].

When overtaking a slower vehicle, Adaptive Cruise Control uses a radar signal to estimate the distance to it and automatically maintains the distance according to one of three selected settings, such as:

a) Supervision of constant velocity
b) Automatic deceleration
c) Automatic acceleration

The principle of the Adaptive Cruise Control is based on the fact that after setting the desired cruising speed, the system will monitor the traffic in front and automatically adjust the speed to the current situation, while maintaining a safe distance from the Lead Car and those we approach while driving. A driver does not have to brake or depress the accelerator pedal later on. After bypassing a slower car, i.e. crossing the overtaking lane, the car continues to accelerate to the set driving speed.

Reducing traffic congestion and increasing traffic capacity can benefit the environment. Research has shown that ACC systems actually contribute to the environment by reducing fuel consumption and car emissions [6]. Bose and Ioannou [7, 8, 9] suggest that some of the characteristics of ACC-equipped cars (such as accurate car tracking, position error mitigation generated by an armored car during smooth transients, and a smooth response to filtering caused by traffic disturbances) may benefit from air pollution and fuel consumption.

2.2. Model Predictive Control (MPC)
The development of Model Predictive Control (MPC) began in the late 1970s. The Model Predictive Control uses the known dynamics of the process model to calculate a control signal that will achieve the minimum of a given control criterion. Although initially the application was tied exclusively to slow industrial processes, today MPC controllers are used to control a diverse range of systems.

MPC uses a future prediction strategy in order to calculate the input. To ensure that the output of the plant follows the target reference output, the MPC controller uses what is called an optimizer, which comes to the picture by determining the best scenario which achieves the minimum error between the reference and the predicted trajectory. The prediction strategy is based on the use of a plant model, in this case car control by the MPC controller to simulate the car’s path in the next P time steps, where P is the prediction horizon which represents the time, the MPC controller looks forward in the future to make the prediction [10].

Thus, the Model Predictive Control (MPC) is an advanced process control method used to control a process satisfying a number of limitations.

3. Application of Adaptive Cruise Control System in a car based in the MPC model
Recently, many topics in Intelligent Transportation System (ITS) are researched. One of the topics is Adaptive Cruise Control (ACC). The Adaptive Cruise Control Systems should be designed such that string stability can be guaranteed in addition to that every vehicle in a string of ACC vehicles which use the same control law must track any bounded acceleration and velocity of its preceding vehicle with a bounded distance and velocity error [11]. On the example of maintaining speed between vehicles shows the application of the use of the adaptive control system block in Matlab Simulink and shows the objectives and limitations of managing this block.
Figure 1. Block diagram of Adaptive Cruise Control Systems

Figure 1 shows a block diagram of an Adaptive Cruise Control System. As can be seen the input signal of the regulator is an error that represents the difference between the desired and actual speed, or the distance between the cars. In accordance with this error, the controller will give a gas control signal that adjusts the valve angle. The accelerator pedal opening range changed by the controller will change the engine speed. Cruise control regulates the vehicle speed \( v \) based on the desired speed and distance, and the actual speed and distance come from the sensor from the feedback branch. The short time-gap gives the driver or system less time to react if the previous vehicle has to slow down very quickly, increasing the possibility of an accidental accident.

A vehicle (Ego Car) equipped with Adaptive Cruise Control (ACC) has a sensor, such as radar, that measures the distance to the preceding vehicle in the same lane (Lead Car), \( D_{rel} \). The sensor also measures the relative velocity of the Lead Car, \( V_{rel} \). The ACC system operates in the following two modes:

1. **Speed control**: The Ego car travels at a driver-set speed.
2. **Distance control**: The Ego car maintains a safe distance from the Lead car.

The ACC system decides which mode to use based on real-time radar measurements. For example, if the Lead Car is too close, the ACC system switches from speed control to distance control. Similarly, if the Lead Car is further away, the ACC system switches from distance control to speed control. In other words, the ACC system makes the Ego Car travel at a driver-set speed as long as it maintains a safe distance.

The following rules are used to determine the ACC system operating mode:

- If \( D_{rel} \geq D_{safe} \), then speed control mode is active. The control goal is to track the driver-set velocity, \( V_{set} \).
- If \( D_{rel} < D_{safe} \), then distance control mode is active. The control goal is to maintain the safe distance, \( D_{safe} \).

Figure 2. Speed control

Figure 3. Distance control
Therefore, depending on the safe and relative distance between the cars, the Adaptive Control System decides whether to use the appropriate mode, speed control or distance control.

3.1. Simulink Model for Lead Car and Ego Car

Automatic cruise control is an excellent example of a feedback control system found in many modern vehicles. The purpose of the cruise control system is to maintain a constant vehicle speed despite external disturbances, such as changes in wind or road grade. This is accomplished by measuring the vehicle speed, comparing it to the desired or reference speed, and automatically adjusting the throttle according to a control law.

Figure 4. Mechanical car control system

Figure 4 shows the mechanical system of vehicle dynamics. A vehicle of mass, m is subjected to a steering force, f. The force f represents the force generated at the road/tire interface. It is assumed that the resistance forces, bv, due to rolling resistance and wind resistance, vary linearly with the vehicle speed, v and act in the opposite direction to the vehicle movement.

Based on the above, we are left with a system of first-order mass silencers. By summing the forces in the x direction and applying Newton's 2nd law, we arrive at the following system Equation (1):

\[ m \frac{dv}{dt} + bv(t) = f(t) \]  

(1)

Taking the Laplace transform of the differential Equation (1) and assuming zero initial conditions, we find the transfer function of the cruise control system to be, Equation (2):

\[ ms.V(s) + bV(s) = F(s) \]  

(2)

\[ G_o(s) = \frac{1}{ms + b} \]  

(3)

The dynamics of control for Lead Car and Ego Car are modeled in Matlab Simulink (Figure 5).

Figure 5. Simulink model of Adaptive Car Control System
To approximate a realistic driving environment, the acceleration of the Lead Car varies according to a sine wave during the simulation. The Adaptive Cruise Control System (ACC) block outputs an acceleration control signal for the Ego Car, and its complete model is shown in Figure 7.

The analysis of the system operation requires two times: sampling time ($T_s$) and simulation duration, ($T$), in seconds. In this case, for the above times it is assumed that $T_s = 0.1 \,[s]$, and $T = 80 \,[s]$.

For both, the Ego Car and the Lead Car, whose subsystem is shown in Figure 6, the dynamics between acceleration and velocity are modeled as:

$$ G(s) = \frac{1}{s(ms + b)} \quad (4) $$

which approximates the dynamics of the throttle body and vehicle inertia.

By applying the Ziegler Nichols method to equation (3), the parameters of proportional ($K_p=1.36$), integration ($K_i=5.42$) and derivative ($K_d=0.06$) gain were obtained, which were used for the application of P, PI and PID regulators.

Considering Proportional control ($K_p$), the closed loop transfer function of the cruise control system with a proportional control is obtained (P controller), Equation (5):

$$ G_c(s) = \frac{K_p}{ms + (b + K_p)} \quad (5) $$

Considering Proportional ($K_p$) and integral ($K_i$) control, the closed loop transfer function of the cruise control system with PI controller is obtained, as in Equation (6):

$$ G_c(s) = \frac{K_p s + K_i}{ms^2 + (b + K_p)s + K_i} \quad (6) $$

By considering all three control parameters i.e, proportional ($K_p$), integral ($K_i$) and derivative ($K_d$) control, the closed loop transfer function of the cruise control system with PID controller is obtained, as in Equation (7):

$$ G_c(s) = \frac{K_ds^2 + K_ps + K_i}{(m + K_d)s^2 + (b + K_p)s + K_i} \quad (7) $$

As can be seen from Figure 5, the input parameters for the Ego Car are acceleration, initial position (10 m) and initial speed (20 m/s), while the Lead Car for input parameters receives longitudinal acceleration from the ACC system, and initial position (50 m) and the initial speed (25 m/s) it has.

### 3.2. Configuration of Adaptive Cruise Control System

The ACC system is modeled using the Adaptive Cruise Control System Model in Matlab Simulink. As can be seen from Figure 7, the inputs to the ACC system block are:

![Figure 6. Subsystem of Lead car and Ego car (a) Ego Car (b)](image)
- Driver-set velocity: \( V_{set} \)
- Time gap: \( T_{gap} \)
- Velocity of the Ego car: \( V_{ego} \)
- Relative distance to the Lead car (from radar): \( D_{rel} \)
- Relative velocity to the Lead car (from radar): \( V_{rel} \)

The output for the ACC system is the acceleration of the Ego Car.

Based on the longitudinal speed of the Ego Car, the relative distance and speed between the Lead and the Ego Car, the ACC generates a longitudinal acceleration for the Ego Car.

The basic logic of an ACC system is, if the relative distance is less than the safe distance, then the primary goal is to slow down and maintain a safe distance. If the relative distance is greater than the safe distance, then the primary goal is to reach driver-set velocity while maintaining a safe distance. These design principles are achieved through the Min and Switch blocks, as can be seen from Figure 7.

![Figure 7. Adaptive Cruise Control System Model](image)

The ACC makes the Ego Car travel at a driver-set velocity while maintaining a safe distance from the Lead Car. The safe distance between lead car and ego vehicle is defined as Equation (2), which means that the safe distance between the Lead Car and the Ego car is a function of the Ego Car velocity: \( V_{ego} \):

\[
D_{safe} = D_{default} + T_{gap} \cdot V_{ego}
\]  

(8)

where:
- \( D_{default} \) – the standstill default distance
- \( T_{gap} \) – the time gap between the cars
- \( V_{ego} \) – Ego car velocity

In this particular case, the set distance between the cars is 10 meters, while the time distance between the cars is 1.4 seconds, the set car speed set by the driver is 30 (m/s).

Considering the physical limitations of the car dynamics, the acceleration is constrained to the range [-3,2] (m/s²), that represents the value of the minimum and maximum acceleration of the Ego Car.
After making the above settings, the default parameters of the Adaptive Cruise Control System block match the parametric simulations, which is shown in Section 3.4.

3.3. Configuration of Model Predictive Control (MPC)
Figure 8 shows a Model Predictive Control based Adaptive Cruise Controller, which, as can be seen, improves the performance of relative speed and distance in the ACC system by using Switch blocks. Namely, MPC controller adds the ability to react to more aggressive maneuvers by other vehicles in the environment, in the sense that MPC controller regulates the velocity of the Ego Car while maintaining a strict safe distance constraint. Therefore, the controller can apply more aggressive maneuvers when the environment changes quickly in a similar way to what a human driver would do.

Model predictive control (MPC) is a discrete-time multi-variable control architecture. At each control interval, an MPC controller uses an internal model to predict future plant behavior. Based on this prediction, the controller computes optimal control actions.

3.4. Simulation analysis
During the starting of simulation, it is necessary to convert the model to a discrete execution time, assuming that the measured output channels are added to the measured output channel # 2 into integrated white noise, and assuming no disturbance is added to the measured output channel # 1.

By simulating the created model from Figure 5, parameters such as speed, acceleration and distance between cars were observed, and the obtained of simulation results without controller action as well as with P, PI and PID controller action, as can be seen in the figures below.
As can be seen from Figure 9, in the first 3 seconds, to reach the driver-set velocity, the Ego Car accelerates at full throttle. From 3 to 13 seconds, the Lead Car accelerates slowly. As a result, to maintain a safe distance to the Lead Car, the Ego Car accelerates with a slower rate.

From 13 to 25 seconds, the Ego Car maintains the driver-set velocity, as shown in Figure 9, the Velocity plot. However, as the Lead Car reduces speed, the distance error starts approaching 0 after 20 seconds.

From 25 to 45 seconds, the Lead Car slows down and then accelerates again. The Ego Car maintains a safe distance from the Lead Car by adjusting its speed, as shown in Figure 9, the Distance between two cars plots.

From 45 to 56 seconds, the distance error is above 0. Therefore, the Ego Car achieves the driver-set velocity again. After 56 seconds, until 76 seconds, the deceleration/acceleration sequence from the 25 to 45 second interval is repeated.
Figure 10. Acceleration, Speed, Distance between two cars with the action of the regulator (P controller)

Figure 11. Acceleration, Speed, Distance between two cars with the action of the regulator (PI controller)

Figure 12. Acceleration, Speed, Distance between two cars with the action of the regulator (PID controller)
Based on Equations (5), (6) and (7) applied to the basic model, the result of which is shown in Figure 9, the operation of P, PI and PID controllers is shown, and their comparison is shown in Figure 10, Figure 11, and Figure 12.

As can be seen from Figure 10 by the action of the P controller oscillations occur in the system, which are largely eliminated by the action of the PI controller, and a faster response of the system is obtained, which can be seen from Figure 11. The best effect is achieved by the action of the PID controller, which can be seen from Figure 12 where the oscillations in the system are almost completely eliminated and a rapid response of the system to a sudden change in error is achieved.

Throughout the simulation, the controller ensures that the relative distance between the two cars is greater than the set safe distance. When the actual distance is sufficiently large, then the controller ensures that the Ego Car follows the driver-set velocity.

4. Conclusion
The autonomous car consists of several subsystems for the implementation of automotive safety, one of them is the Adaptive Cruise Control System, whose implementation is also shown in this paper on the example of control the appropriate speed and distance between cars, based on the MPC model.

In this paper, despite the relatively small number of Lead Car input parameters (acceleration, initial speed and initial position) and Ego Car output parameters (initial speed, initial position and longitudinal acceleration of the ACC system), the system responds well to changes in all observed driving conditions, especially in the case of PID controller applications. A dynamic low-order model was used to implement the Lead Car, while a higher-order model was used to implement the Ego Car.

The simulation results show that Adaptive Cruise Control based on the MPC model can reduce the number and impact of accidents based on maintaining a safe and relative or actual distance between cars. The driver was shown to ensure that the actual distance between the two cars was greater than the set safe distance. When the actual distance is large enough, then the driver ensures that the Ego Car follows the set speed of the driver, otherwise accelerates, or decelerates according to the difference between the safe and actual distance between the cars. The paper shows that the action of only the P controller on the system control dynamics leads to an increase in oscillations and even car collisions, as shown in Figure 10, Figure 11, and Figure 12 while the action of the PI or PID controllers eliminates system oscillations and increases the speed of reaction.

As the action of the PID controller led to system stabilization, it is assumed that even greater system stabilization would be achieved by using a fuzzy controller. The above indicates the possibility of improving the adaptive car control system presented in this paper, which will leave the next research, the results of which will be compared with the results obtained in this paper.

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