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# The Design and Simulation of Adaptive Cruise Control System

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## Abstract

In this study, an Adaptive Cruise Control system is designed by using conventional Proportional Integral Controller (PID) and Model Predictive Controller (MPC). In the design, vehicle, acceleration, and deceleration models are constructed in a way to simulate the real-life environment. The design and simulation were carried out through Matlab and Simulink. In order to investigate the effects of gains in the PID controller, several values for $K_p$, $K_i$, and $K_d$ is tested. The simulation results illustrated that the gains $K_p$ and $K_d$ have negligible effects on the vehicle acceleration but the gain $K_i$ has a substantial effect on the response of the ego car. The results of PID controller were compared with the results when the controller is replaced by MPC. It has been shown that the PID controller gives better results as compared to the MPC controller independent from $K_p$, $K_i$, and $K_d$ values. Therefore, we can confidently state that the PID controller provides better responses in addition to its accessibility, simpler design, and cost advantages compared to the MPC controller.

Keywords: Adaptive Cruise Control Design; PID controller, MPC Controller; PID Parameter Tuning

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## 1. Introduction

Automobiles have become the most preferred transportation means in the world in the last century. According to the data of the Turkish Statistical Institute, the total number of vehicles in Turkey at the end of January 2021 is 24,256,741, with an average of 1 vehicle per 4 people [1]. Due to the increase in the demand for vehicles, the number of undesirable events such as accidents and deaths has also increased. The majority of these accidents are reported to be due to driver-related problems [2]. In order to prevent this adversary situation, new technologies have started to be developed. As a beginning, passive systems such as seat belts and airbags were integrated into the vehicles. Then, Advanced Driver Assistance Systems (ADAS) have been integrated into vehicles for the last 10 years [3].

The main purpose of ADAS is to improve vehicle safety by exploring objects, driver behavior, vehicle condition and using the existing human-machine interface [4]. The ADAS provides important and critical information to the driver and aims to increase driving and road safety by automating tasks that require high human precision. A cruise control system, an adaptive lighting control system, an automatic braking system, an automatic parking system, a collision-avoidance system, a GPS system, a lane following system, and an adaptive cruise control system are examples of ADAS. According to the research conducted by the Insurance Institute for Road Safety in USA in 2020, the frontal collision warning systems were observed to reduce front-to-rear collisions by 27% and this rate went up to 54% when frontal collision warning system was combined with the automatic braking systems [5]. Likewise, it has been observed that rearview cameras reduce rear-end collisions by 17%, and when this system is combined with automatic braking, collisions can be avoided by 78% [5]. The Adaptive Cruise Control system, which emerged as one of the ADAS systems, is an advanced version of the traditional cruise control system. While the conventional cruise control system maintains the speed set by the driver as the desired speed, the Adaptive Cruise Control system additionally maintains a safe distance to the vehicle in front. The task of Adaptive Cruise Control system is to change the speed of the vehicle by maintaining a safe distance to the vehicle in front and to continue on the road at a constant speed like conventional cruise control if there is no obstacle in front of the vehicle [6]. In this system, the vehicle processes the data coming from the radar or sensors and it adjusts the speed by keeping the distance to the surrounding vehicles at a safe level. In other words, if the vehicle in front is moving at a slower speed than the desired speed, the system maintains a safe distance by slowing down the main vehicle.

With the Adaptive Cruise Control system, a safe distance is maintained between the leading vehicle and the ego car by adjusting the speed of the car. Adaptive Cruise Control system greatly reduces the possibility of rear and side collisions. That is the first step for collision avoidance systems and is very useful to significantly reduce the number or severity of accidents [7].

In the first examples of Adaptive Cruise Control system, the system was only responsible for following the leading vehicle at a safe distance by adjusting the speed of the car. In 2006, Toyota combined the Adaptive Cruise Control System with Stop&Go technology so that the Adaptive Cruise Control System is able to stop the car if needed.

## 2. Related Works

In the study by Sivaji and Sailaja [8], "Stop&Go" was tried to be added to the Adaptive Cruise Control system, and the scenario in which a smart vehicle using a hybrid PID controller was examined. It was observed that the hybrid PID controller provides distance and speed tracking. Another study carried out by Luo [9] proposed an Adaptive Cruise Control algorithm in cooperation with Model Predictive Controller (MPC). In this study, the inner loop controller is assumed to be well designed and the outer loop is controlled by MPC. The distance control algorithm of the system is based on a fixed time difference. The performance of the system is evaluated by features such as comfort, safety, fuel consumption and capability to follow the vehicle in front. In the study conducted by Recepşan Günay [10], the Adaptive Cruise Control system was designed by using Matlab/Simulink programs. Two different control modes, speed control and distance control are used and the performance of the system has been evaluated with different scenarios. Kamesh, Madhusoodanan, and Gajendran [11] conducted a study in which a PID controller was used as the main controller. Jose Naranjo and Carlos Gonzalez [12] proposed an Adaptive Cruise Control system using a Fuzzy controller with Stop&Go feature. This design combines proven and previously used systems. The control mechanism used in the study ensures the coordination of throttle and brake in an adaptive way. Experimental studies of this model were carried out in a real environment by using 2 vehicles with GPS antennas. In another study, an Adaptive Cruise Control System was designed by Shakouri, Ordys, Laila, and Askari [13]. The distance between the two vehicles is checked and the vehicle's velocity is controlled according to this distance in order to satisfy the requirements of the system, PI controller was used to observe the distance between the vehicles. Mohtavipour [2] tried to increase the performance of the Adaptive Cruise Controller by using a PID controller and optimizing the gain. The proposed Adaptive Cruise Control used the reference signal provided by a sensor. The acceleration or deceleration status depends on this signal. It has been shown that the Stop&Go feature can be added to the Adaptive Cruise Control system by using high-accuracy systems such as GPS receivers. Rajamani and Zhu [14] developed a semi-autonomous Adaptive Cruise Control system in which the vehicle is equipped with a radio receiver in the front bumper and a radio transmitter in the rear bumper. In this study, only the high-end controller is designed, and the real vehicle dynamics are not taken into account.

## 3. Material and Method

Matlab and Simulink tools were used for system level design, simulation, and testing and verification purposes. In order to have results close to the real world, a vehicle model with a transfer function, a braking model for the deceleration of the car and throttle and a gear model for the acceleration of the car have been implemented.

A PID controller with several different gains $K_p$, $K_i$ and $K_d$ are used in the design. The effects of these different gains in the system performance are assessed. Furthermore, the performance of the PID controller is checked against Model Predictive Controller.

### *3.1 Vehicle Model*

It is very well known that the sum of all the forces applied to a mass is equal to the product of the mass by the acceleration of the mass. In our case, the mass is the mass of the vehicle. There are two forces exerting on the vehicle. One is the driving force; the other force is the friction force which is opposite to the driving force. Then, the dynamic of the car can be described by Eq. (1) [8].

$$u(t) - bv(t) = m\frac{dv}{dt} \tag{1}$$

Here, m, v, b and u are referring to the mass of the car, the velocity of the car, the friction coefficient and the force applied by the engine respectively. Upon the application of Laplace Transform into Eq. (1), the algebraic equations giving the relation between the force and the speed can be determined as given in Eq. (2) [8].

$$U(s) - bV(s) = msV(s) \tag{2}$$

Then, the transfer function of the system can easily be described by Eq. (3) [8].

$$\frac{V(s)}{U(s)} = \frac{1}{ms+b} \tag{3}$$

In this study, the mass of the car (m) is assumed to be 1000 kg and the friction coefficient (b) is taken as 50 N.sec/m.

The Simulink model detailed in Fig.1 is implemented in a way to simulate the real world. Since there should be at least two cars in the simulation, the same vehicle model is used for leading and ego car. The vehicle model for leading and ego car is shown in Fig.1

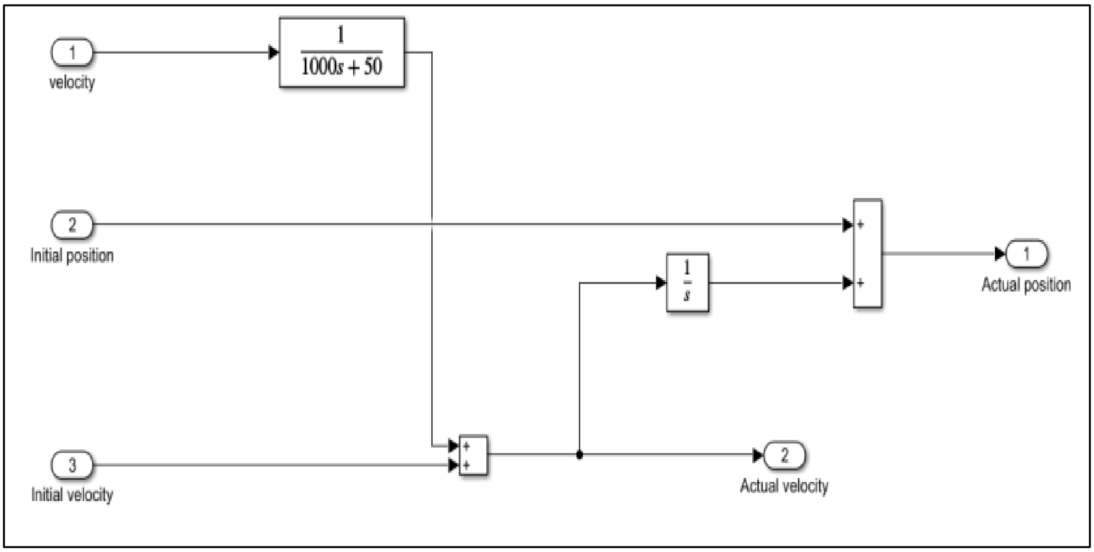

Fig. 1 Simulink Model of Leading and Ego Car

As can be seen in Fig. 1, the designed vehicle model calculates the instantaneous position and the speed of the vehicle by using the initial position and the initial speed value. The same vehicle model is used for both the leading and ego vehicles. In the vehicle model, initial velocity, initial position, and the velocity are taken as inputs to the system. The outputs of the system are the actual velocity and the actual position which are obtained by inserting the velocity into the transfer function and adding it to the initial velocity to form the actual velocity of the vehicle. At the same time, by integrating the obtained velocity, the position of the vehicle during that time is obtained. The position of the vehicle at that moment is obtained by summing the distance taken by the car and the initial position. For the ego car, the velocity input is taken from the controller and for the leading car, the velocity input is taken from signal builder block of Simulink.

### 3.2 Braking Model

In the design of the Adaptive Cruise Control system, the required braking force is dependent on the distance between the vehicles. Since the system should follow the leading car within a safe distance, which is defined as 100 meters, the ego car may need to use brakes. In today's vehicles, the braking force is determined by the applied force from the driver. In order to reflect this situation to the system, a simple brake model has been designed. In this model, the braking distance of the vehicle is determined to maintain the safe distance. The braking deceleration is a value that is calculated according to the distance between the two vehicles. During this calculation, the work done is equal to the product of the braking force and the distance [15] as defined in Eq. (4). Here, we use the kinetic energy principle.

$$W = F * d \tag{4}$$

Here, W is the work done, F is the braking force, and d is the braking distance. The kinetic energy can be defined by Eq. (5) [15].

$$KE = \frac{1}{2} * m * (v)^2 \tag{5}$$

Here, KE is the kinetic energy, m is the mass and v is the velocity of vehicle. If Eq. (4) and Eq. (5) is used together with Newton's second law, Eq. (6) can be determined as in Eq. (6).

$$a = \frac{1}{2} * \frac{(v)^2}{d} \tag{6}$$

Here, a is the braking deceleration, v is the velocity and d is the braking distance. From Eq. (6), it can be seen that the braking deceleration is directly proportional to the square of the velocity. At the same time, the braking deceleration is inversely proportional to the braking distance. In other words, as the velocity of the vehicle increases, the braking deceleration will also increase. However, as the braking distance of the vehicle increases, the braking force will decrease.

Here, an important point is that the braking model should avoid collision of the vehicles which in turn requires that the safe distance should be preserved. Therefore, the braking distance should be calculated in a way to subtract the safe distance from the distance between the two vehicles.

### 3.3 Throttle and Gear Model

Acceleration of vehicles today depends on many factors. Basically, these factors are the horsepower of the vehicle's engine, the mass of the vehicle, the radius of the vehicle's wheel, the ratio of each gear in the vehicle's transmission and the ratio of the differential used in the vehicle's transmission.

The torque produced by a vehicle on its wheels is directly proportional to its horsepower, gear ratio and differential ratio [16]. Transmission is a factor that can affect the acceleration of the vehicle. In today's vehicles, the gear ratio of each gear is different.

This causes the vehicle to have different acceleration values in each gear. As we experience while driving, as the speed of the vehicle increases, it becomes more difficult to accelerate. The reason for this is that the gear ratio decreases as the vehicles move forward. During the modeling of Adaptive Cruise Control, the gear position is also taken into account when calculating the acceleration of the vehicle. The differential ratio in this design is taken as 3.42:1 and the gear ratios are given in Table 1.

Table 1 Gear and Gear Ratio Relationship

| Gear | Gear Ratio |
|---|---|
| 1 | 2.97:1 |
| 2 | 2.07:1 |
| 3 | 1.43:1 |
| 4 | 1.00:1 |
| 5 | 0.84:1 |

It is well known that Torque is equal to the product of the applied force and the distance to which the torque is applied. In other words, it is the distance from the center of the wheel to the road. In this case, the radius of the wheel is taken into account as the distance. Therefore, the force can be determined as in Eq. (7) [16].

$$F = \frac{\tau}{d} \tag{7}$$

Here, F denotes the force, $\tau$ denotes the torque and d is the radius of the wheel. The Newton's second law applied to Eq. (8) results in Eq. (8) [16].

$$a = \frac{\tau}{m * d} \tag{8}$$

Here, a denotes the acceleration, m denotes the mass of the vehicle, $\tau$ denotes the torque and d is the radius of the wheel.

### *3.4 ACC Control System Design with PID Controller*

PID controller works on the principle of an error feedback occurred when there is a difference between the output and desired reference value [17]. The controller consists of three main blocks as proportional, integral and derivative controllers. In fact, PID control input is the sum of the proportional, integral and derivative controllers with some associated gains as given by the Eq. (9).

$$u_c(t) = k_p e(t) + k_i \int^t e(\tau) d\tau + k_d \frac{de}{dt} \tag{9}$$

The proportional part takes actions against errors at the instantaneous time. The integral part utilizes the past values of errors and the derivative part take actions for the future behavior since derivative gives a clue on how the error behavior would be.

In this study, a PID controller is used for Adaptive Cruise Control. In this design, the vehicle model, braking model, throttle and gear model described in this section above are used. Furthermore, a main distance controller is used together with PID controller. The block diagram model is depicted in Fig. 2.

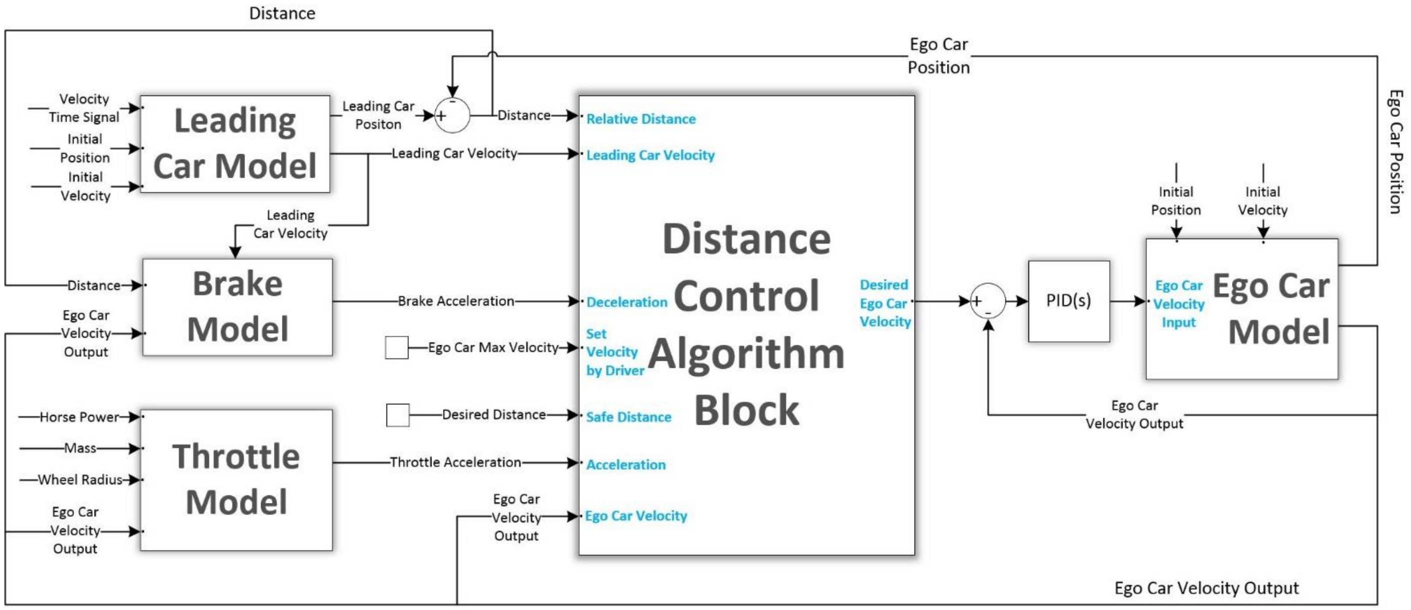

Fig. 2 Simulink Model of ACC System Design with PID Controller

Fig.2 includes front vehicle model, ego vehicle model, brake model, throttle and gear model and the main block which controls the distance algorithm. A signal builder is established for the velocity information of the leading car. The outputs of both vehicle models are velocity and position. However, the velocity input of the leading car is provided by the signal builder and the velocity input of the ego car is taken from PID controller's output. The ego car's velocity input is the input of the PID controller. As it is stated, the output of the PID controller is the velocity input for ego car.

The inputs of the main distance controller which is intended to use the distance algorithm to keep the vehicles in safe distance are the velocity of the leading car in front, the velocity of the ego car, the distance between the vehicles, the maximum velocity which is set by the driver, the acceleration obtained from the throttle and gear model, the braking deceleration obtained from the braking model and the safe distance value. The maximum velocity defined by the driver is assumed to be 36.1 m/s. This velocity will be effective when there is no leading vehicle or to limit the ego car's velocity. As stated before, the safe distance between vehicles is assumed to be 100 meters. According to the velocity of the leading vehicle, the position of leading vehicle and the distance between the vehicles, the main controller decides about the velocity of the ego car. If the vehicle needs to accelerate, it uses the acceleration that is taken from the throttle and gear model, and if it needs to slow down, it uses the deceleration from the braking model. After subtracting the output of the main controller and the feedback of the velocity information of the ego car, the value obtained is inserted into the PID controller. The output of the PID controller is the velocity input for the ego car's model.

### *3.5 ACC System Design with MPC (Model Predictive Controller)*

MPC is a type of control system which utilizes the past, present and future values and tries to follow a desired system dynamic as shown by the block diagram given in Fig.3 [10].

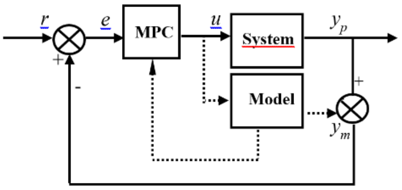

Fig. 3 MPC Block Diagram

Here, ym is the model output and yp represents the system output. MPC is capable to predict future events and take control actions accordingly. It utilizes the dynamic models of the system which is mainly an empirical model established by using system identification methods. The main principle for an MPC is to use the internal dynamic model of the system (plant), a cost function and an algorithm to minimize the cost function. Here, we see that the difference between the actual system output and the dynamic model system output is compared with the reference signal producing the error given as input to MPC. The main objective here is to minimize the error so as to achieve the desired output [18] [19].

MPC is used for Adaptive Cruise Control design in literature [10]. In this study, the MPC is used in order to check the controller with a brake, throttle, gear and car models. Therefore, the previously stated vehicle model, braking model, throttle and gear model are used. Additionally, a main distance controller is added to the Adaptive Cruise Control Block [20] together with MPC. An implementation of the Quadratic cost function for MPC is detailed in [21] The Simulink model is sketched in Fig. 4.

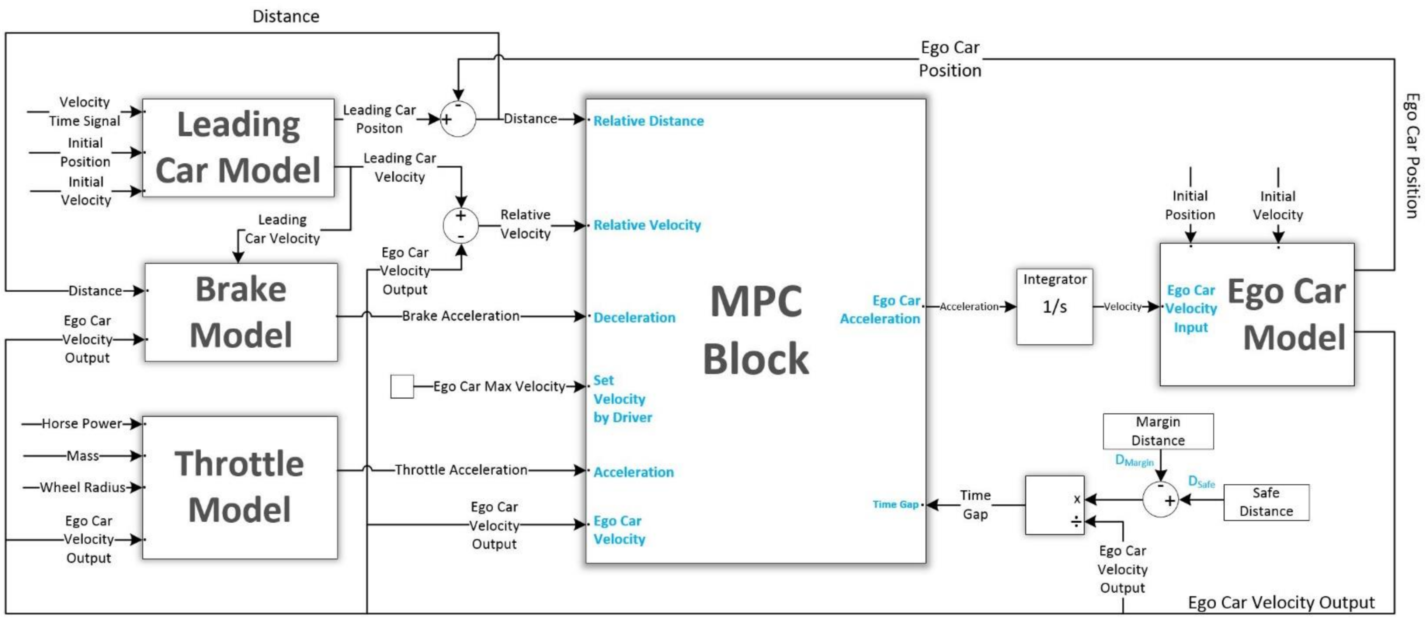

Fig. 4 Simulink Model of ACC System Design with MPC

In order to evaluate the controller performance more effectively, the same vehicle, acceleration and deceleration models are used, except that the controller is changed. There are two vehicle models which are leading and ego car. The inputs of these vehicle models are velocity, initial position and initial velocity. The velocity data of leading vehicle is provided by with the signal builder. The outputs of the vehicle models are the position and velocity data which are used in the main controller. The main controller model shown in Fig. 4 is designed by using MPC [20]. The controller uses the maximum velocity set by the driver, the time difference between vehicles, the velocity of the ego car, the distance between the vehicles, the velocity difference between the vehicles, the deceleration and the acceleration. As it is stated, the inputs of the vehicle models are the velocity, initial position and initial velocity. The output of MPC controller is the acceleration of the ego car which is integrated in order to achieve velocity to be the input of ego car.

In order to calculate the safe distance, time gap definition defined by Eq. (10) is used [20].

$$Time\ \ Gap = \frac{D_{Safe} - D_{Margin}}{V_{ego}} \tag{10}$$

Here, DSafe denotes the safe distance between the two vehicles. DMargin denotes the margin used for the safety of calculations and Vego denotes the velocity of the vehicle behind.

This model uses the safe following distance algorithm in Eq. (11) [20].

$$D_R = \ D_S + (G_T * V_E) \tag{11}$$

Here, DS denotes the default spacing parameter, GT denotes the time gap input signal and VE denotes the ego car’s velocity [20]. Initially, the velocity and the position for ego car is zero.

## 4. Results

All the simulations are based on the models given in Fig. 2 and Fig. 4. Several different values for the PID controller gains Kp, Ki and Kd are used in the simulations to see the effects on the response of the system. In this study, a lot of simulation has been done, however, in this paper, some of them are summarized.

In our study, the velocity of the leading car and the position graph is plotted in Fig. 5.

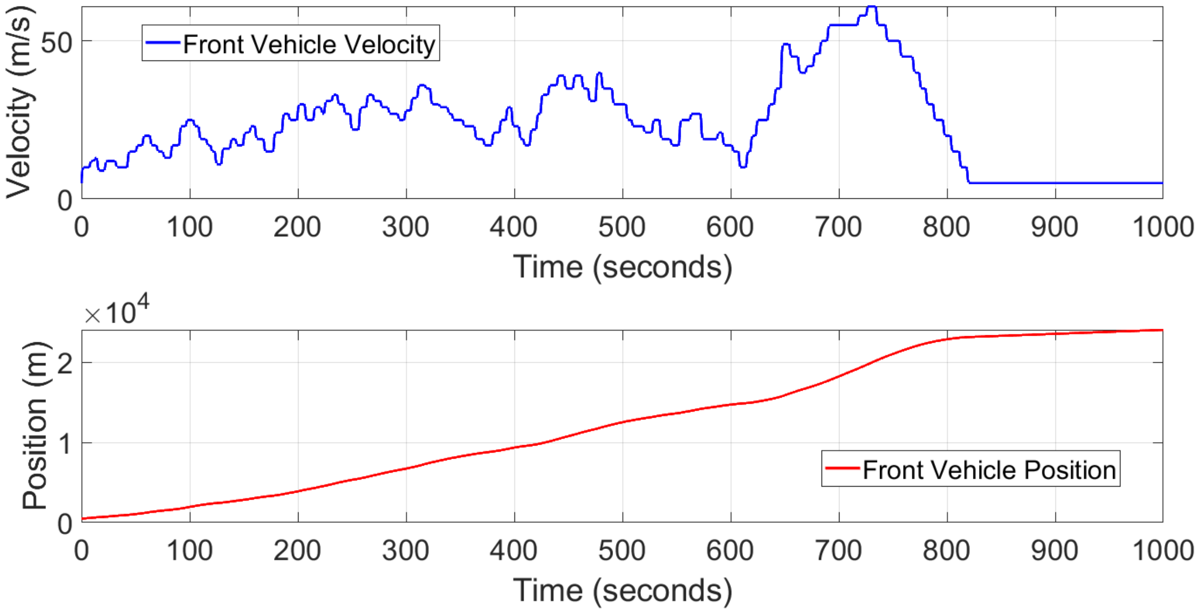

Fig. 5 The Velocity-Time and Position-Time Graphs of the Leading Vehicle

According to the velocity-time and position time graphs given in Fig.5, the simulations run on Simulink models in Fig.2 and Fig.4 shows that during the movement, there are decelerations, accelerations, and constant speed movement. It is expected to see that the ego car catches the leading car in a certain time of simulation.

For the position time graph, the distance traveled increases when the vehicle accelerates and decreases when the vehicle slows down. The distance increases linearly when the vehicle starts to move at a constant velocity.

The effects with three different PID controller gains Kp (1000, 2000, and 2500) in the velocity of the ego car can be seen in Fig. 6.

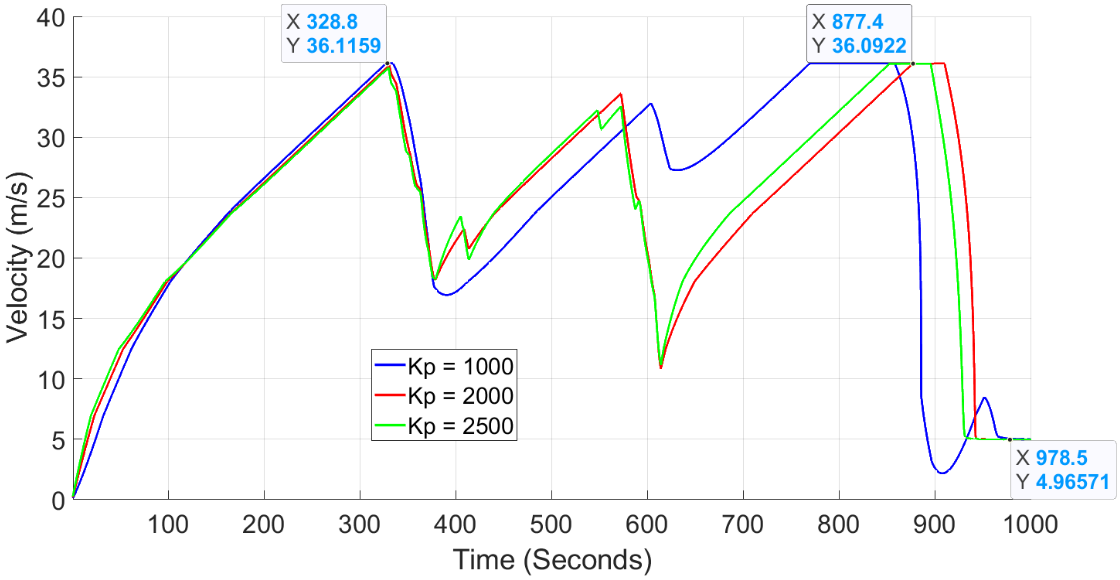

Fig. 6 The Velocity-Time Graph of the Ego Car with $K_p$ Changes

Although the velocity transitions of the vehicle are smoother and reaching to maximum speed earlier when Kp is 1000, the drive fails to obey the safe distance limitation as observed in Fig.6. For the cases where Kp is 2000 and 2500, the vehicle meets the stability and safety criteria and exhibited a very close behavior. It is observed that the speed changes are smooth and satisfactory in terms of passenger comfort when Kp is 2000. In addition to that, it is seen that the ego car can catch the leading car in a certain time independent from Kp but the Kp affects the catching time of the ego car. As a conclusion, it is an appropriate decision to use Kp as 2000.

The effects of Kp in the position of the ego car can be seen in Fig. 7.

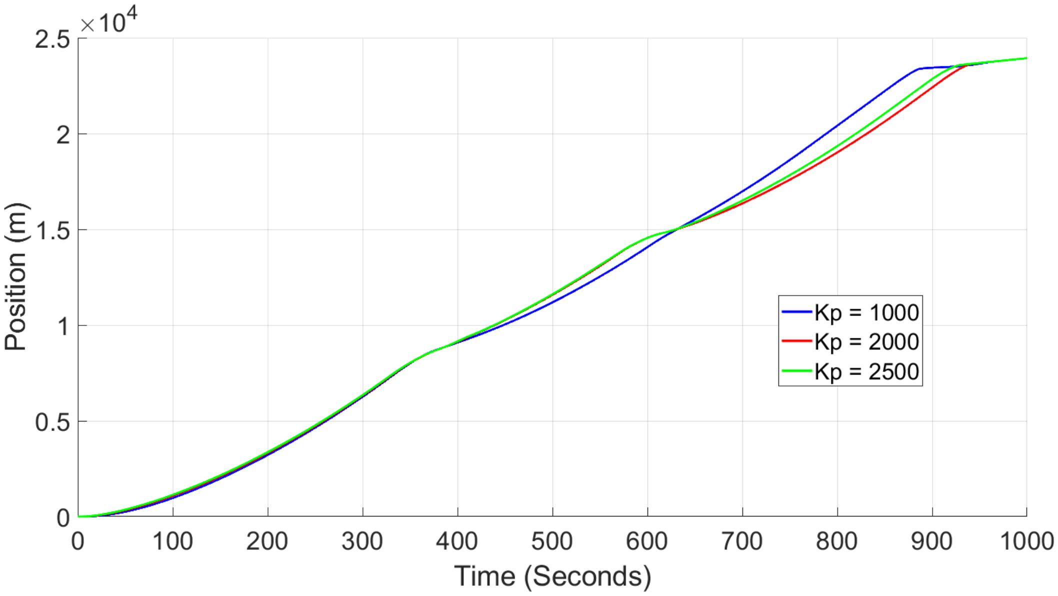

Fig. 7 The Position-Time Graph of the Ego Car with $K_p$ Changes

According to the graph in Fig.7, the vehicle has similar behavior in all cases. However, when Kp is 1000, the velocity of the vehicle reaches the maximum velocity earlier than the other two cases. Therefore, we can state that lowering the Kp value affects the acceleration of the vehicle. After the vehicle's speed remained constant at 5 m/s, the vehicle acted similarly in all cases.

The effects of Kp on the distance between the ego car and front vehicle can be seen in Fig. 8.

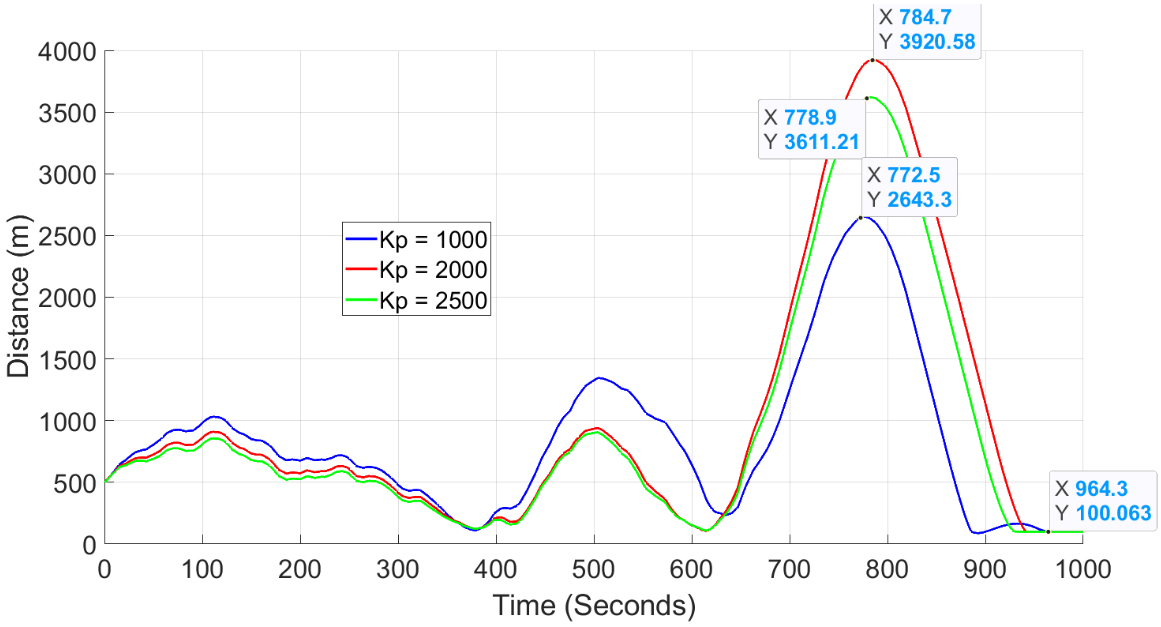

Fig. 8 The Distance Between Vehicles with $K_p$ Changes

According to Fig.8, when Kp is 1000, the maximum distance between the two vehicles is lower than other two cases. However, when Kp is 2000, the maximum distance between the vehicles is higher than other cases. When Kp is 1000, the safe distance is violated. Therefore, we can state that the Kp is effective on increasing the safety distance between the vehicles.

The effects of three different values of Ki (50, 80, and 100) in the velocity of the ego car can be seen in Fig. 9.

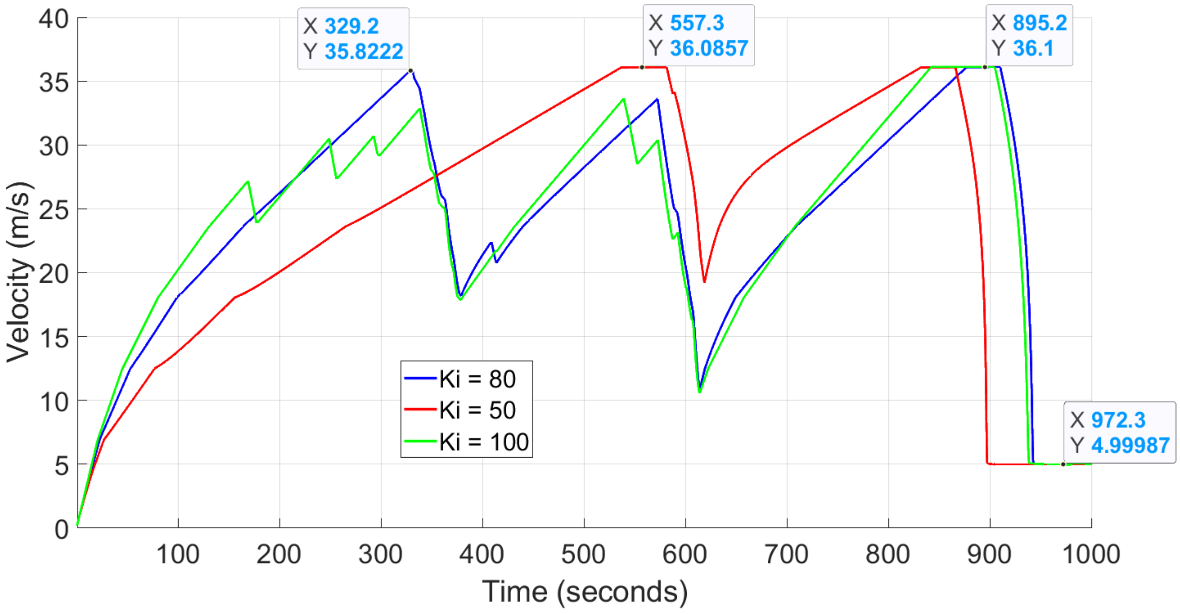

Fig. 9 The Velocity-Time Graph of the Ego Car with $K_i$ Changes

When Ki is 50, the acceleration of the vehicle is lower than the other two cases in which case the ego car increases its speed for a long time than other cases. In that time interval, the ego car has not been affected by the change of leading car’s velocity since the distance between the vehicles is much higher than the safe distance. Even though the acceleration of the ego car is comparatively higher than the previous case, when Ki is 80 or Ki is 100, the velocity changes rapidly in these two cases. When the graph is examined, there is no problem in all three cases in terms of stability and security criteria. When evaluated in terms of passenger comfort criteria, the most successful result was obtained when Ki is 50 since the vehicle moves with smoother acceleration, deceleration and also the vehicle catches the leading car before the other two cases do.

The effects of Ki in the position of the ego car can be seen in Fig. 10.

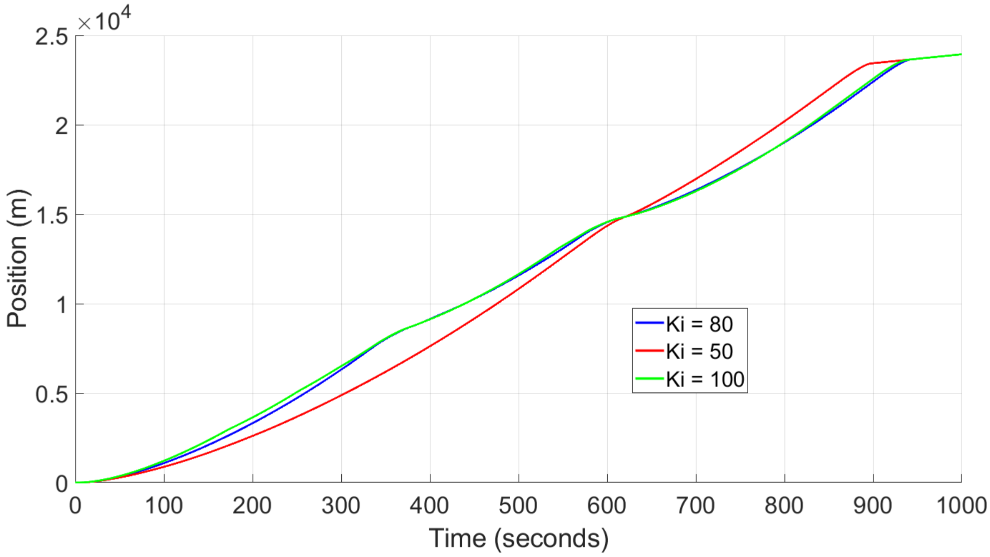

Fig. 10 The Position-Time Graph of the Ego Car with $K_i$ Changes

According to Fig.10, the vehicle has similar response in cases where Ki is 80 and 100. However, when Ki is 50, even though initially the acceleration of the vehicle is lower than the two cases, the velocity of the vehicle reaches the maximum velocity earlier than other two cases. However, seconds, when Ki is 50, the velocity of the vehicle is higher than the other two cases. After the vehicle's speed remained constant, the vehicle acted similarly in all cases.

The effects of Ki in the distance between vehicles can be seen in Fig. 11.

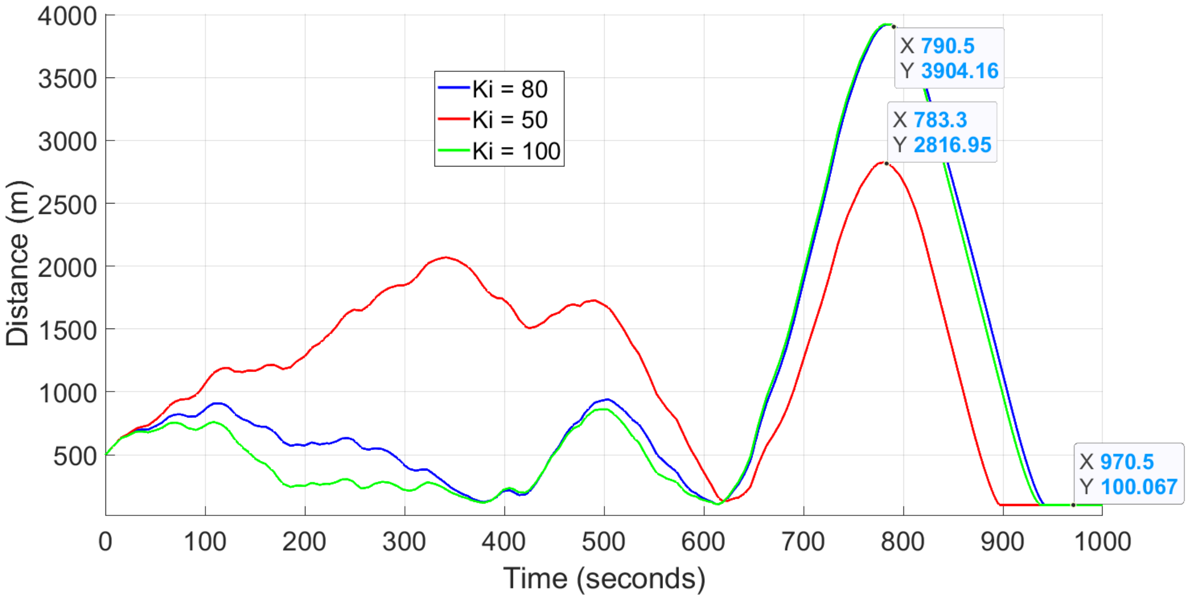

Fig. 11 The Distance Between Vehicles with $K_i$ Changes

In the beginning of the scenario, when Ki is 50, the distance between vehicles is increasing since the acceleration of the vehicle is slower than the other cases. However, when Ki is 50, the maximum distance between vehicles is lower than the other cases and the ego car catches the leading car earlier than the other ones. Therefore, we can state that decreasing the Ki is effective on lowering the maximum distance between vehicles and catching the leading car.

The effects of Kd in the velocity of the ego car can be seen in Fig. 12.

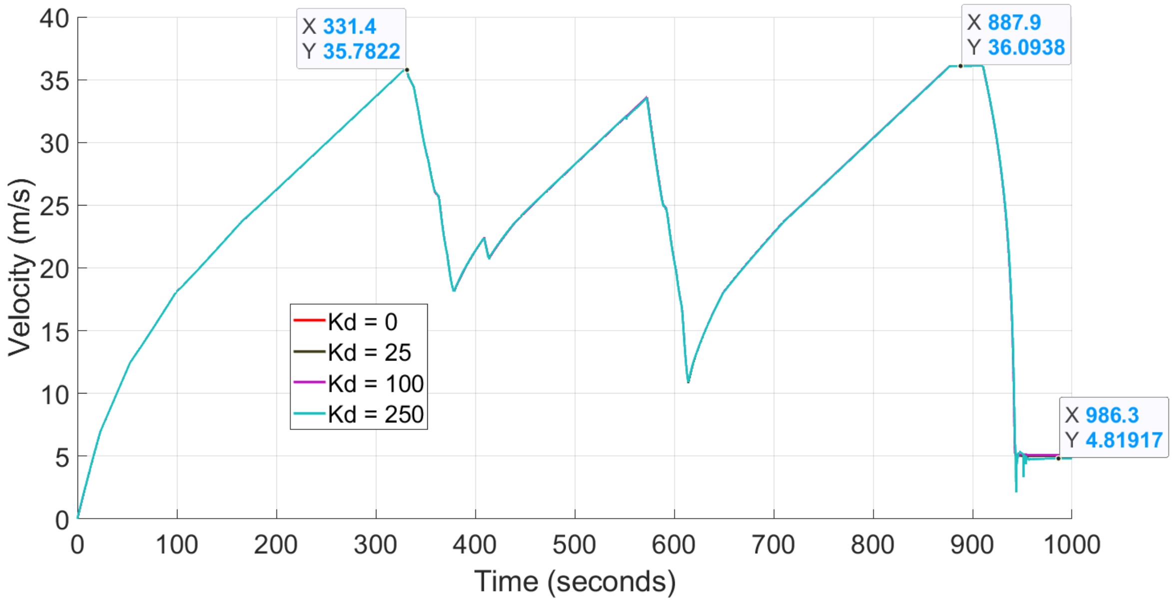

Fig. 12 The Velocity-Time Graph of the Ego Car with $K_d$ Changes

According to the Fig.12, the velocity of the ego car has not changed dramatically. Therefore, we can state that the change in Kd value changes nothing except the oscillation in the case where Kd is 250. The effects of Kd in the position of the ego car can be seen in Fig. 13.

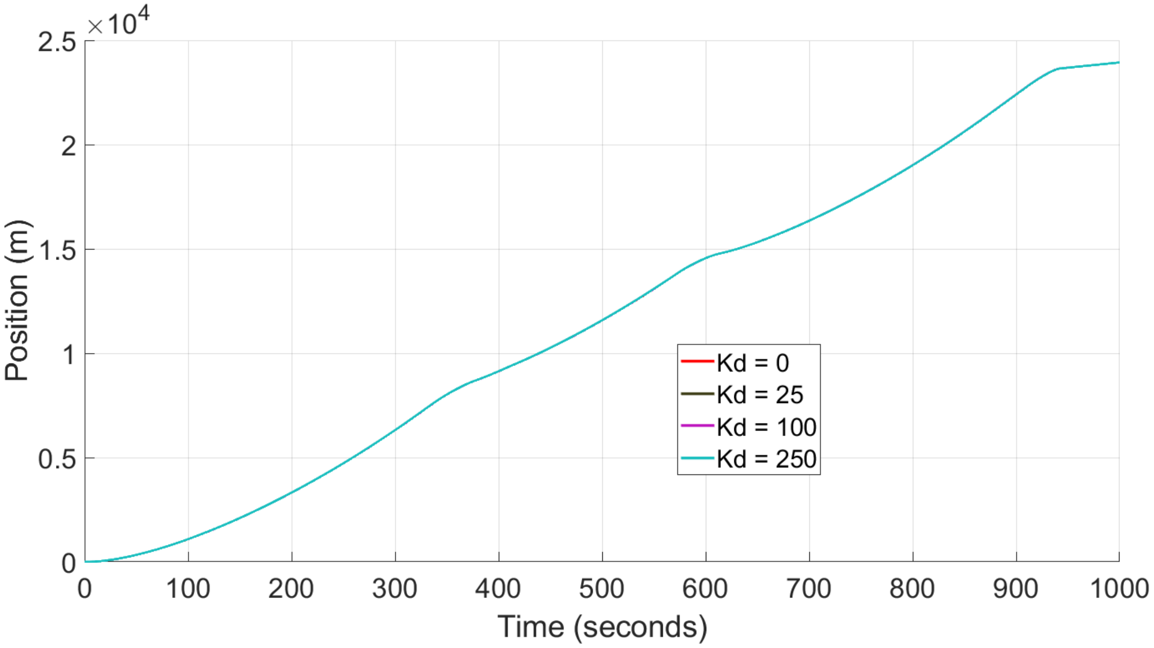

Fig. 13 The Position-Time Graph of the Ego Car with $K_d$ Changes

In Fig. 13, the position time graph of the ego car according to the change in Kd is given. As it is seen in Fig.13, there is almost no effect of Kd change in terms of the position of the ego car.

The effects of Kd in the distance between vehicles can be seen in Fig. 14.

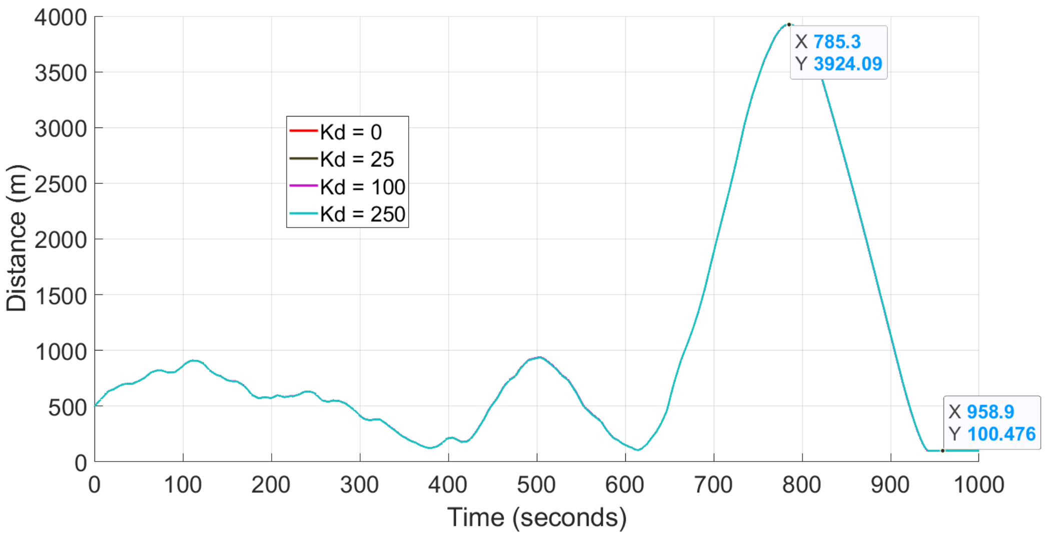

Fig. 14 The Distance Between Vehicles with $K_d$ Changes

According to the change in Kd, the distance between vehicles is given. As it is seen in Fig.14, the Kd change has almost no effect on the distance between vehicles.

Since there is no connection between the leading car and the controller, changing the controller in the system will not affect the leading vehicle's velocity and position. However, changing the controller will directly affect the velocity of the ego car since it is depending on the controller's output.

The velocity of the ego car and the position of the ego car with MPC can be seen in Fig.15.

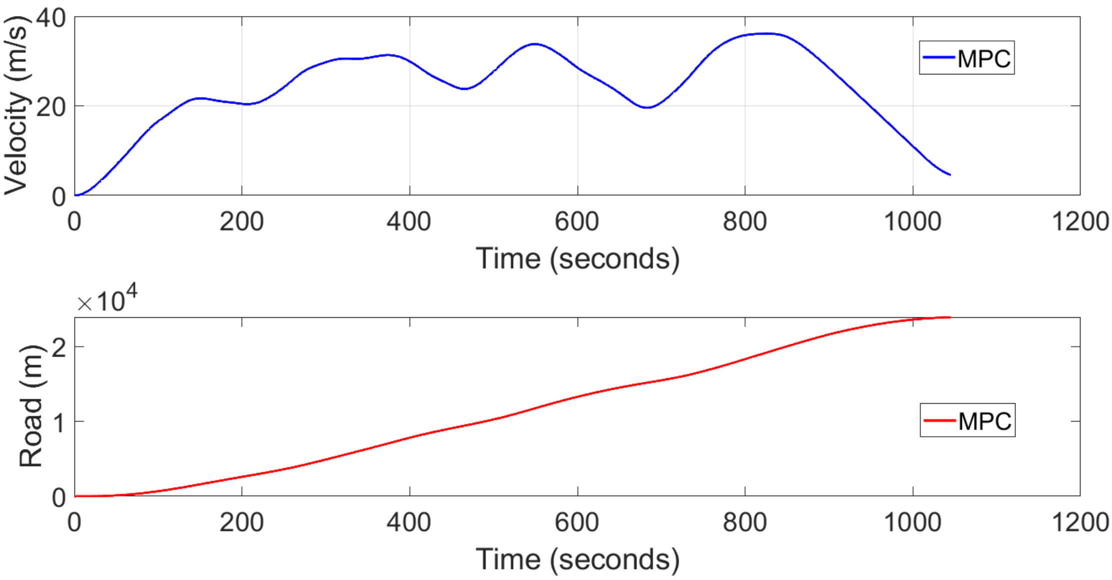

Fig. 15 The Velocity-Time and Position-Time Graphs of the Ego Car with MPC

In Fig. 15, it is seen that the vehicle reaches a maximum speed of 36.1 m/s, which is the maximum speed determined by the driver in the 820th second. After 820 seconds, the ego car slowed down to maintain a safe distance from the leading car in front. In order to prevent the safe distance between the front vehicle, the ego car should set its velocity to the velocity of leading car which is 5 m/s. The ego car could only go down to 5m/s at 1040th second. However, the ego car speed could not remain constant at 5m/s.

As can be seen in the position time graph given in Fig.15, the amount of distance traveled by the vehicle increases gradually during the acceleration time. As it is accelerated, the area under the graph is increased. In other words, the distance traveled per unit time is increased depending on the speed of the vehicle.

The comparison of PID controller and MPC in terms of ego car's velocity is given in Fig.16.

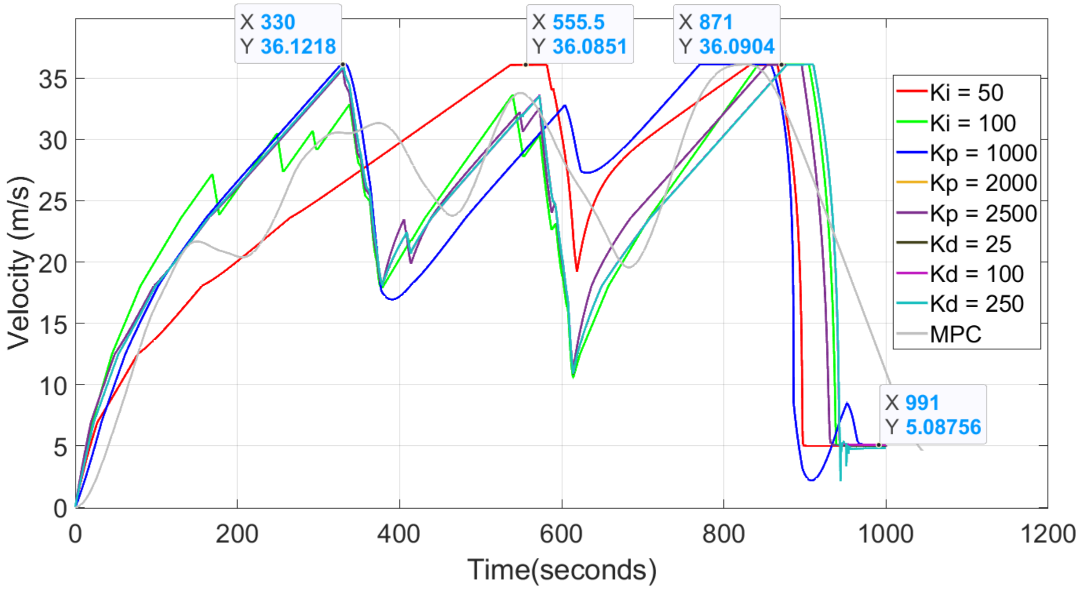

Fig. 16 The Velocity-Time Comparison Graph of PID and MPC

As it is seen from Fig.16, the ego car is not able to follow the leading car with MPC. The change in Kd gain has minimal effects on the acceleration or deceleration of the vehicle except when Kd is 250, where oscillation occurs at 5 m/s. In addition to that, when Kp is decreased considerably which is 1000 in our case, the vehicle faces with some difficulties in stabilization of the velocity at 5 m/s. Also, using Ki as 100 might cause some comfort problems for the passengers since the acceleration and deceleration occurs frequently. In terms of catching the leading vehicle and following it at a safe distance, all other cases can be used in the ACC design.

The comparison of PID controller and MPC in terms of ego car's position is given in Fig.17.

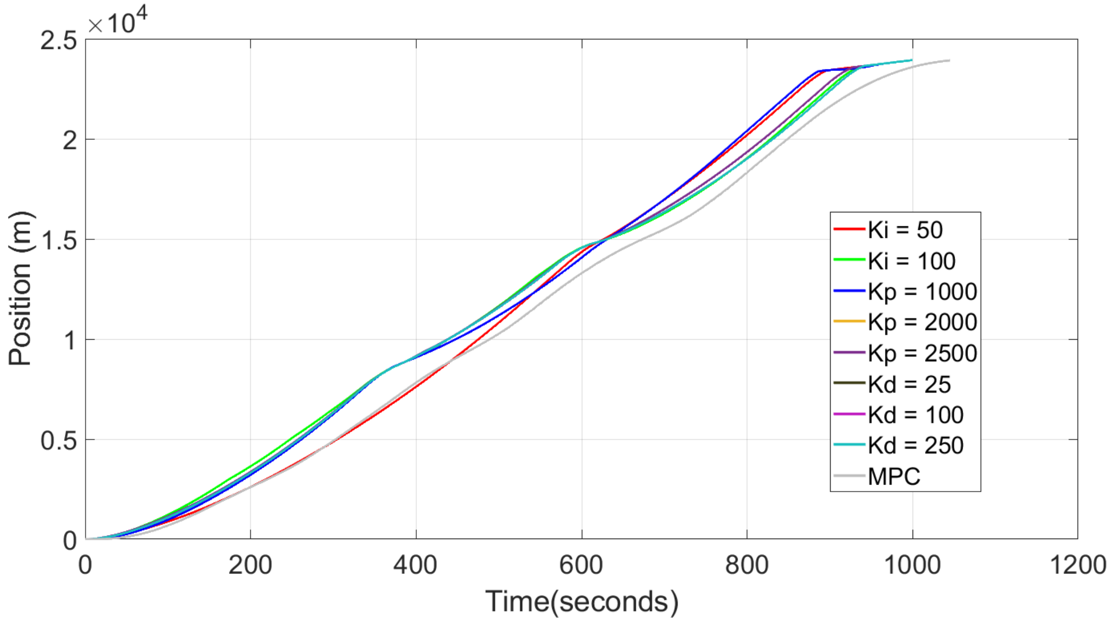

Fig. 17 The Position-Time Comparison Graph PID and MPC

As can be seen in the position time graph given in Fig.17., the amount of distance traveled by the vehicle increases gradually during the acceleration time. As it accelerated, the distance traveled per unit time is increased depending on the speed of the vehicle. In the cases where there is fast acceleration, the position taken in per unit time is also increased.

The comparison of PID controller and MPC in terms of distance is given in Fig.18.

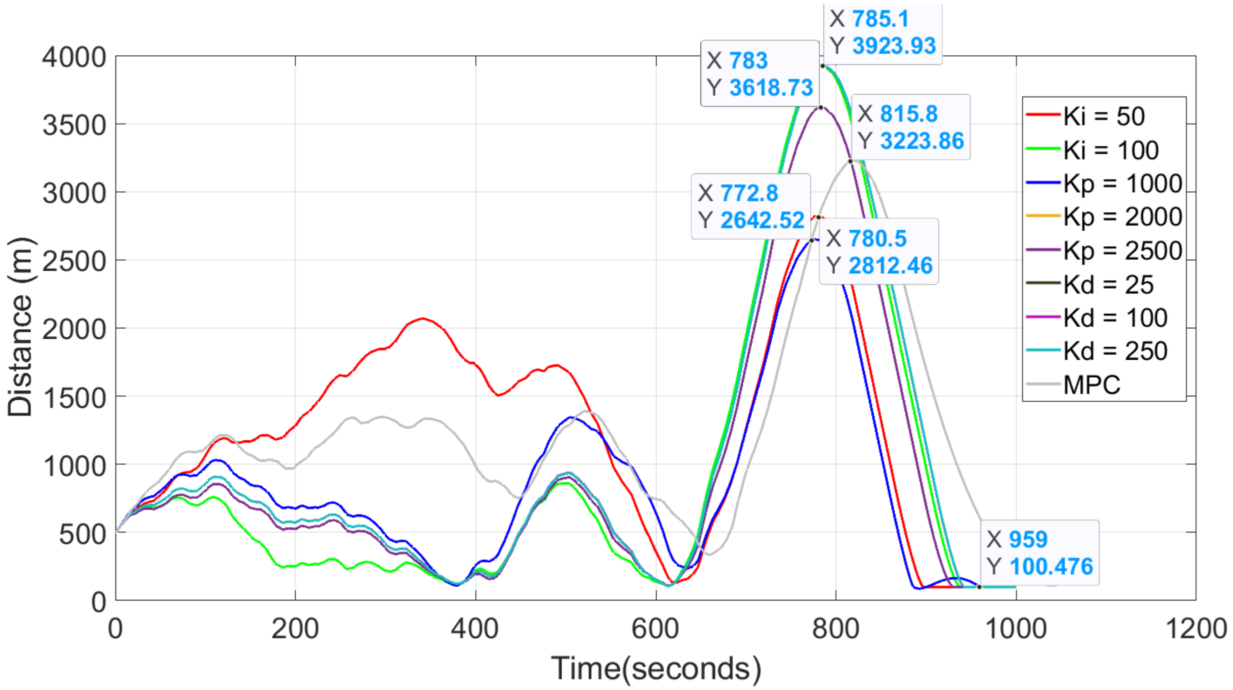

Fig. 18 Comparison of The Distance Between with PID and MPC

According to the results, it is seen that the PID controller provides better results in reaching the maximum speed than the MPC controller, except for the case in which Kp = 2000, Ki = 50 and Kd = 0 is selected as design parameters. However, in this case, the vehicle behind successfully caught the vehicle in front and succeeded in following it. As explained above, a safe distance of 100 meters could not be achieved by MPC controller. It is seen that the PID controller gives better results in terms of response time. When we look at the equalization of the speeds, it is seen that PID controller gives better results than the MPC controller, regardless of Kp, Ki and Kd. The results show that the vehicle behind caught the vehicle in front and reduced the distance between the vehicles to 100 meters when PID controller is used. After the distance between the vehicles is decreased to 100 meters, it started to follow the vehicle by equalizing the speed of the vehicle in front of it. However, in MPC controller, the vehicle behind had difficulty in catching the vehicle in front and managed to equalize their speed in the last 9 seconds of the simulation, reducing the distance between vehicles up to only 110 meters. In other words, the PID controller outperforms the MPC controller in this design.

When we examine the response for the PID controller with design parameters as Kp = 1000, Ki = 80 and Kd = 0, is reached the maximum velocity the fastest. This shows that the acceleration of the vehicle is better when these design values are used. Based on the criterion of equalization of the vehicle's speeds, the situation with Kp = 2000, Ki = 50 and Kd = 0 gives the best results. In this case, it is seen that the decrease in Kp while keeping Ki constant increases the vehicle's maximum acceleration, and the decrease in Ki while keeping Kp constant shortens the vehicle's catch-up time.

From the results of the distance between the vehicles, it is seen that the PID controller gives better results in terms of catching the safe distance, regardless of the values of Kp, Ki and Kd. When we look at the maximum distance between the vehicles, the highest distance between vehicles is observed in the case of Kp = 2000, Ki = 100 and Kd = 0. The closest distance between the vehicles, excluding the safe distance is observed when Kp = 2000, Ki = 80 and Kd = 0. In terms of capturing the safe distance between the vehicles, the PID controller provided the best performance with Kp = 2000, Ki = 100 and Kd = 0.

In addition to the advantages of the PID controller over the MPC controller in terms of accessibility, convenience, cost and usage areas, it is observed that the results obtained by using PID are more effective than the results obtained by using MPC. For this reason, it has been seen that it would be more advantageous to use a PID controller in the designed Adaptive Cruise Control system.

## 5. Conclusion

From the design of the first automobile to the present day, the automotive industry has shown a continuous development, as in every technology. With the developing automotive industry, the place and usage of automobiles in human life has increased. On the other hand, traffic accidents and loss of life, material and moral damages due to these accidents have also increased. Therefore, the automotive industry has sought solutions to reduce the loss of life and damage. Therefore, ADAS systems have been developed in accordance with the changing human needs. The purpose of ADAS systems is to support the driver to reduce loss of life, material and moral damage, and to increase driver and passenger comfort and luxury. The Adaptive Cruise Control system, which emerged as one of these systems, aims to control the accelerator and break the pedals of the vehicle and to keep the vehicle moving within a safe distance to the vehicle in front, thus minimizing the fatigue experienced by the driver. The Adaptive Cruise Control system controls the speed of the vehicle in a way that maintains a safe distance by knowing the distance between its peripheral components and vehicles.

In this paper, an Adaptive Cruise Control system, which is one of the important parts of today's automotive industry, is designed as part of Driver Assistance Systems. The designed controllers have been combined with vehicle dynamics and peripheral components and tested with various scenarios. The results obtained from these tests were evaluated.

Matlab and Simulink were used for the design within the scope of this paper. In order to verify the design, evaluations were made on criteria such as passenger safety, passenger comfort and reliability. The vehicle model, braking model and gear and acceleration model are combined with the system so that the verification processes are similar to real life.

Two controllers were designed within the scope of this paper. The first controller is a PID controller and the second controller is MPC. Both controllers have their own control algorithm. Both algorithms assume that the vehicle has environmental control systems such as radar, LIDAR or camera and use the signals from these sensors. Control systems regularly detect obstacles around the vehicle and report the distance between these obstacles and the vehicle to the controller. According to the incoming distance, the controller controls the speed of the vehicle and maintains the safe distance between the vehicles. In the controller designed by using PID controller, the effects of the gain values on the system were examined and evaluated. Kp, Ki and Kd gains were changed and their effects on the system were investigated. In the light of the simulation results, it is observed that the effect of the change in the Kp and Kd gains on the system is limited, but the increase in the Ki gain has positive effects on the acceleration of the vehicle, reaching the maximum speed and following the vehicle in front. In this case, it is observed that increasing Ki gain for the designed system has positive effects on the designed Adaptive Cruise Control system. Furthermore, it is observed that the PID controller gives better results than the system designed with MPC, regardless of Kp, Ki and Kd gains. Moreover, the simulations proved that the PID controller provides more desired results in addition to the accessibility, design and cost advantages stated in the literature as compared to the MPC controller.

The Adaptive Cruise Control system designed within the scope of this study has shown to have the traditional cruise control, vehicle tracking, “Stop&Go” and lane change features. It has also been observed that the designed system increases the speed of the vehicle so that the distance between vehicles is reduced to the defined safe distance, slows the vehicle down in a way that maintains the safe distance, detects the lane change made by the vehicle in front of it and can stop the vehicle when necessary. In the light of these results, it is proved by several simulations that the system works successfully.

As further research, different MPC parameters such as prediction and control horizon could be studied and the results are compared with PID controllers. In our study, the simulation results show that the performance of PID is superior to the performance of MPC for SISO systems. There may be further research on the comparison of the two system performances for MIMO systems.

## Nomenclature

| | |
|---|---|
| MPC | : Model Predictive Controller |
| ADAS | : Advanced Driver Assistance Systems |
| GPS | : Global Positioning System |
| USA | : United States of America |
| m | : Mass of the Car |
| v | : Velocity of the Car |
| b | : Friction Coefficient |
| u | : Force of the Engine |
| W | : Work Done |
| F | : Braking Force |
| d | : Distance |
| KE | : Kinetic Energy |
| a | : Acceleration/Deceleration |
| $\tau$ | :Torque |
| HP | : Horse Power |
| GR | : Gear Ratio |
| DR | : Differential Ratio |
| ACC | : Adaptive Cruise Control |
| Dsafe | : Safe Distance Between Vehicles |
| DMargin | : Safety Tolerance Distance |
| Vego | : Velocity of the Vehicle Behind |
| SISO | : Single Input Single Output |
| MIMO | : Multiple Input Multiple Output |
| PID | : Proportional Integral Derivative |

## Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

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