Analysis of the Controllers for the Transitional Manoeuvres of Adaptive Cruise Control Systems

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ABSTRACT

PID (Proportional-Integral-Derivative) and MPC (Model Predictive Control) algorithms are used to synthesize the upper-level controller of a vehicle equipped with an ACC (Adaptive Cruise Control) system. Both controllers are analysed, with and without constraints, using a simple vehicle model under critical TM (Transitional Manoeuvres). A comparative analysis of both controllers' results has been conducted. The comparison gives the suitability of MPC for ACC application over PID controller. The flaws of PID control approach for the given application are highlighted. This approach can be helpful for selecting the suitable controller for the given application.

Key Words: **Adaptive Cruise Control, PID Control, Model Predictive Control, Transitional Manoeuvres, Vehicle Control.**

1. INTRODUCTION

There are many different types of controllers being used in industrial processes, chemical process systems, mechanical systems, electrical systems, and economical processes. These controllers could be anything ranging from a simple classical PID controller to the most sophisticated non-linear controllers. The challenging task for a controller is to perform well in spite of uncertainties present in a system [1].

A two-vehicle model is proposed in this study, Fig. 1, which comprises of a preceding vehicle and an ACC vehicle. The aims for the ACC vehicle are to set up and retain a SIVD (Specified Inter-Vehicle Distance) with zero range-rate behind the preceding vehicle under steady-state and TM. ACC vehicle uses range, range-rate, and its velocity and acceleration to perform the required TM in order to maintain the SIVD and avoid a collision from the preceding vehicle.

The longitudinal control of the ACC vehicle consists of two separate controllers as shown in Fig. 2. The ULC (Upper Level Controller) computes the required acceleration commands for the LLC (Lower Level Controller) to maintain the desired spacing behind the preceding vehicle. The LLC uses these required acceleration commands to generate the required throttle/braking commands for the nonlinear ACC vehicle to follow the spacing-control laws computed by the ULC [3].

In the literature, different control techniques have been proposed for the ULC, e.g. PID control [5,6], sliding mode control [3,7-11], CTG (Constant Time Gap) [2,4], and MPC [2, 12-15]. Bageshwar, *et al.* [2] made a comparison of MPC and CTG methods using a first-order ACC vehicle model. He highlighted the flaws of CTG algorithm and suggested MPC algorithm for ACC system's application. The comparison of MPC method with the other control methods

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for the ACC vehicle analysis has not been covered in the previous studies. Therefore, this paper presents a comparison of PID and MPC algorithms for ULC of an ACC vehicle.

In previous studies, different ACC vehicle models have been presented. The vehicle models used range from the simple vehicle model, which does not take into account the engine and drive-train dynamics, to the nonlinear vehicle models. The simple vehicle models used are the longitudinal vehicle model [7,8, 16-19], and first-order vehicle models [2,4]. In either case, the input to the simple ACC vehicle model is the control signal calculated by the ULC. Simple ACC-vehicle models have been used in the previous studies to analyse the performance of the ULC. In the case of a nonlinear vehicle model, the desired acceleration commands obtained from the ULC are given to the LLC which then computes the required throttle and brake commands for the nonlinear vehicle model to follow the required acceleration commands. The nonlinear vehicle model includes the engine model, transmission model, wheel model, brake model, ULC and LLC models.

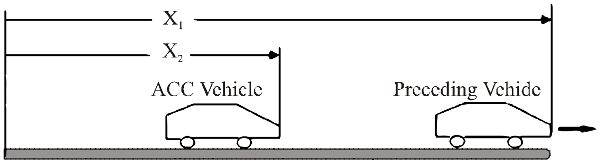

FIG. 1. A TWO-VEHICLE SYSTEM

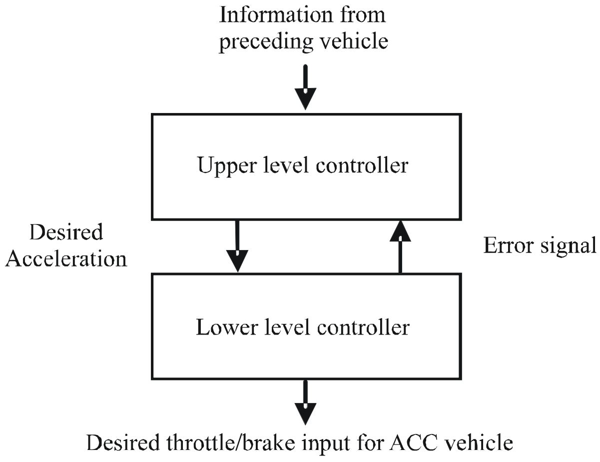

FIG. 2. ACC VEHICLE LONGITUDINAL CONTROL SYSTEM [4]

In this paper, the vehicle model used for the ACC vehicle's ULC analysis is a first-order model. A first-order is based on a first-order lag [4,13]. This lag is incorporated in the control input command calculated by the ULC. This first-order model can be defined as [4,13].

$$\tau\dddot{x}(t) + \ddot{x}(t) = u(t) \tag{1}$$

where, x is position, $\dot{x}$ is velocity and, $\ddot{x}$ is acceleration of the ACC vehicle. u represents the control input commands determined by the ULC. τ refers to the time lag equivalent to the lag in the LLC model. The value of τ recommended in the previous studies is 0.5s [4,20].

Two modes of operation of an ACC vehicle namely speed control mode and vehicle following, the switching between these two modes, the effects of transitional manoeuvres on the ACC vehicle's longitudinal dynamics when it is operating in the vehicle following mode are covered in this study.

The two control strategies used for controller synthesis are:

(1) Proportional-Integral-Derivative Control

(2) Model Predictive Control

In these controllers analysis, the preceding vehicle is based on the complex vehicle model which includes engine, torque converter, transmission, and drivetrain models [21] and the ACC vehicle model is based on the first-order vehicle model. A simple first-order ACC vehicle model is used to compare the performance of these control methods at the ULC under the same critical encounter scenarios between the two vehicles.

The main tasks for the control methods to perform on the ACC system are:

1. Track smoothly desired acceleration commands
2. Reach and maintain a SIVD in a comfortable manner and at the same time react quickly in the case of dangerous scenarios.

3. Optimize the system performance within defined constrained operational boundaries.

2. ADAPTIVE CRUISE CONTROL SYSTEM

A standard cruise control system enables a ground vehicle to control its longitudinal speed. A desired speed is selected by the driver, and a control system operates on the throttle to maintain this desired speed [3,4,8]. ACC systems have been developed as an enhancement to the standard cruise control systems. In addition to the speed control mode, an ACC-system equipped vehicle can also regulate the set speed to maintain a SIVD from a preceding vehicle [3,22,23]. This additional feature is termed as vehicle following mode. The control law for the vehicle following mode is computed using onboard radar sensors that measure the range (relative distance) and the range-rate (relative velocity) between the ACC vehicle and the preceding vehicle [2,4,23]. Therefore, both throttle input and brake input are required to control the distance and the relative velocity between an ACC vehicle and a preceding vehicle. In the vehicle following mode the SIVD is a function of the preceding vehicle's velocity [2]. In the literature [8] it is termed as headway spacing control policy.

The spacing control law is designed within the ULC model of an ACC vehicle where the kinematic relation between the range (R) and range-rate ($\dot{R}$), Fig. 3, between the two vehicles and the ACC vehicle velocity and acceleration are used to compute the desired acceleration for the LLC [2]. The error signal generated due to differences in the longitudinal motion of the preceding vehicle and the ACC vehicle is sent back to the ULC where the desired acceleration for the next time step is calculated.

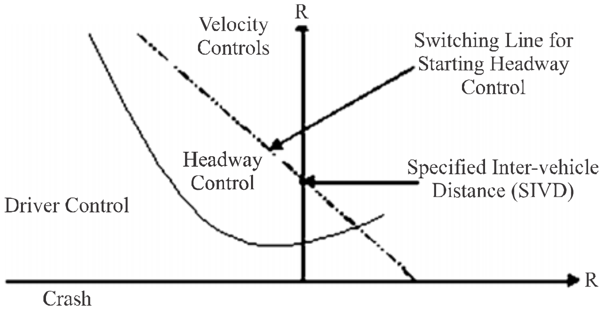

FIG. 3. RANGE VS. RANGE-RATE DIAGRAM [4]

2.1 System Limitations

An ACC system is attractive for the automobile manufacturers and most of luxurious vehicles, Mercedes, Sedans, Lexus LS340, etc, are equipped with an ACC system. Due to its advanced features, it relieves the driver of stress associated with tiresome driving tasks such as maintaining speeds on long journeys, driving behind other vehicles in congested traffic, safety assurance. Despite its advanced functions an ACC system also contains some operational and physical constraints. Two physical constraints for an ACC vehicle have to be incorporated in the formulation of the ULC, used for the vehicle-following control law. Firstly, the ACC vehicle is not permitted to have a negative velocity during a transitional manoeuvre, and secondly, the ACC vehicle is assumed to have limited accelerations: a lower limit equal to -0.5g and an upper limit equal to 0.25g [2]. Equation (2) and Equation (3) show the two physical constraints applied on this ACC vehicle model during the high deceleration (transitional) manoeuvres.

$$\dot{x}_2(t) \geq 0 \tag{2}$$

$$u_{\min} \leq u(t) \leq u_{\max} \tag{3}$$

It should be noted that the lower acceleration limit implies that the ACC vehicle cannot apply the necessary brakes to avoid the collision with the preceding vehicle. Even while providing a support for the driver, he/she still remains responsible for the vehicle handling while performing lateral manoeuvres and in a complex decision making.

3. PID CONTROL ARCHITECTURE

The PID control approach, Fig. 4, is simple and easy to implement. It is widely applied in industry to solve various control problems. It has been estimated that 98% of all control systems in the pulp and paper industries are controlled by PI controllers, and in process control applications, more than 95% of the controllers are based on PID controllers [24].

3.1 PID Control for Two-Vehicle System with Headway Spacing Policy

The PID control algorithm is applied on the ULC of the ACC vehicle to analyse the performance of the ACC vehicle. The PID control law for the follower ACC vehicle can be expressed as:

$$u = K_P(\dot{x}_1 - \dot{x}_2) + K_I(x_1 - x_2 - h\dot{x}_2) + K_D(\ddot{x}_1 - \ddot{x}_2) \quad (4)$$

where K_P, K_I, and K_D are the controller gains, x_1 and x_2 are the actual positions of the preceding vehicle and the follower ACC vehicle respectively. The term $h\dot{x}_2$ is called headway spacing policy where the spacing (SIVD) between the two vehicles varies linearly with the vehicle's speed such that the headway time (h) between the two vehicles remains constant. The headway time (h) can be defined as the time taken by the follower vehicle to reach the point where the preceding vehicle is at present speed [25]. In this study, h is assumed as 1s [2,4]. The control input (u) is the desired acceleration command applied to Equation (1) to determine the response of the first-order ACC vehicle model. The error signal to the PID controller is the difference between the velocities of the two vehicles. The PID controller gains in all scenario are obtained using the famous Ziegler-Nichols method as shown in the Table 1.

where K_u is the proportional gain at the point when the output of the system starts to oscillate while setting the integral and derivative gain to zero, and P_u is the total oscillation period. For the ACC vehicle model, K_u = 2.2 and P_u = 5s [26].

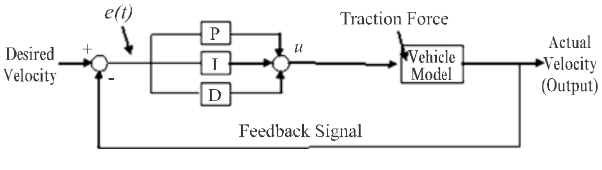

FIG. 4. BLOCK DIAGRAM FOR THE PID FEEDBACK CONTROL SYSTEM

TABLE 1. ZIEGLER-NICHOLS METHOD

Control Type	K_P	K_I	K_D
PID	$0.6K_u$	$2\,K_P / P_u$	$K_P P_u / 8$

3.2 Preceding Vehicle with throttle Input of 50 Degrees and Different Initial Conditions for Both Vehicles

In this scenario as shown in Fig. 5, both vehicles start with the different initial speeds and different initial positions while the throttle angle for the preceding vehicle is kept constant at 50 for the entire simulation time of 20s. The baseline scenario is that an ACC vehicle travelling at 30 m/s (67 MPH) in the speed control mode detects a preceding vehicle which is accelerating from 10 m/s (22.34 MPH), the ACC vehicle is 60m behind the preceding vehicle when it detects the preceding vehicle. The ACC vehicle response, using the PID control method, has been analysed for two different situations: (1) the ACC vehicle has no acceleration limits and (2) the ACC vehicle is restricted to the acceleration limits. In situation Equation (2), if the acceleration command computed by Equation (4) is less than the deceleration limit, then the acceleration command is set equal to the deceleration limit.

The velocity of the ACC vehicle for both conditions is shown in Fig. 5(a), the velocity profile, with limited acceleration, establishes first the SIVD and then maintains the zero-range-rate behind the preceding vehicle; this manoeuvre can be well understood by observing acceleration graph in Fig. 5(c). The ACC vehicle without the acceleration limits, only concerns with establishing a SIVD with zero-range-rate and is unable to meet the other requirements of the transitional manoeuvre.

Fig. 5(b) shows the corresponding positions of the two vehicles for this scenario. The initial relative distance between the two vehicles is 60m. In response to the initial deceleration commands computed using by the PID control method; the ACC vehicle decelerates and successfully establishes a SIVD with a zero range-rate behind the preceding vehicle based on the headway spacing control policy for both limited and unlimited acceleration conditions. Once the SIVD is established, the ACC vehicle maintains the steady-state operation with a SIVD, which is the function of the vehicle speed. Fig. 5(d) shows the range (relative distance) between the two vehicles. It can be seen that the ACC vehicle is smoothly establishing the desired SIVD after the transitional operation. It has been observed from this analysis that the ACC vehicle, using the PID control algorithm, has performed all the control tasks discussed in Section 1.

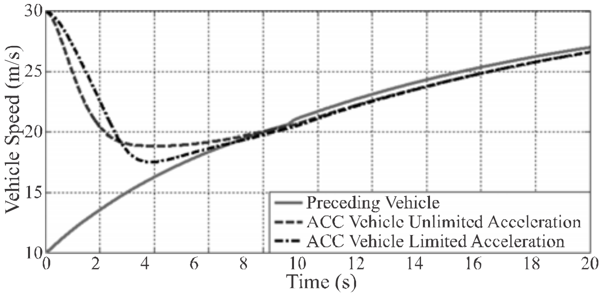

FIG. 5(A). VELOCITIES OF THE VEHICLES

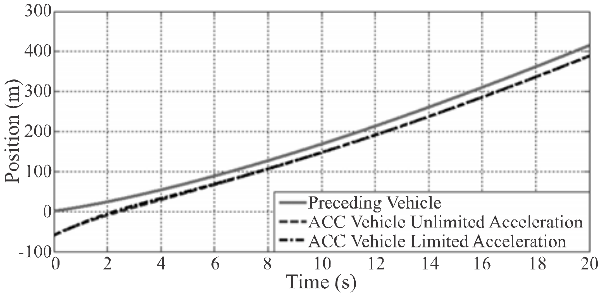

FIG. 5(B). POSITIONS OF THE VEHICLES

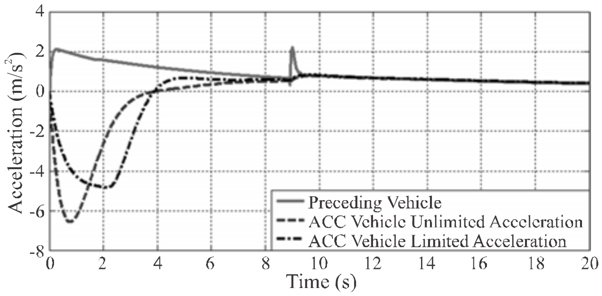

FIG. 5(C). ACCELERATIONS OF VEHICLES

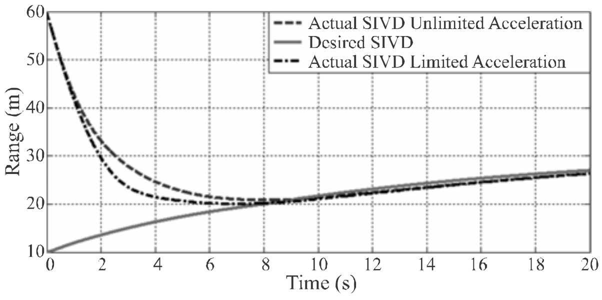

FIG. 5(D). RANGE BETWEEN BOTH VEHICLES

3.3 ACC Vehicle Response against a Halt Preceding Vehicle

In the scenario considered below, an ACC vehicle detects a halt vehicle in front of it. The initial speed of the ACC vehicle is 30 m/s, and it is 110m behind the preceding vehicle. This encounter scenario has also been analysed for two different situations; (1) ACC vehicle with unlimited acceleration, (2) ACC vehicle with limited acceleration. In situation Equation (2), if the acceleration command computed by Equation (4) is less than the deceleration limit, then the acceleration command is set equal to the deceleration limit.

The simulation results for both conditions are shown in Fig. 6. It can be seen with unlimited acceleration, the ACC vehicle successfully performs the TM (dashed line). In the case of acceleration limits (dashed-dotted line), the ACC vehicle cannot meet the required control objectives of establishing the desired SIVD with zero range-rate and collides with the preceding vehicle as shown in Fig. 6(b) (dashed-dotted black-line). During this TM, the ACC vehicle is executing a negative velocity, Fig. 6(a) (dashed-dotted black-line), which does not satisfy Equation (2) constraint. The initial commands computed by the PID control law for the ACC vehicle is to accelerate rather than to decelerate, Fig. 6(c). If the initial commands are to accelerate then the deceleration limits would not allow using the necessary brakes to prevent a crash with the preceding vehicle. It is essential that ACC vehicle must decelerate to avoid the collision. After analysing this scenario, it can be concluded that the PID control law is not feasible for these kinds of transitional manoeuvres of the ACC vehicle, because, the PID control algorithm does not include either the state constraints or the control constraints in its formulation.

4. MPC PREDICTION MODEL FOR THE TWO-VEHICLE SYSTEM

Similarly, the MPC control algorithm is applied to the two-vehicle system which consists of a preceding vehicle and a following ACC vehicle. The position of the preceding vehicle is denoted by x_1 and the position of the ACC vehicle is denoted by x_2, (Fig. 1).

The continuous-time model in Equation (1) can be re-written in a discrete-time state-space model as:

$$\begin{pmatrix} x_2(t+T) \\ \dot{x}_2(t+T) \\ \ddot{x}_2(t+T) \end{pmatrix} = \begin{pmatrix} 1 & T & 0 \\ 0 & 1 & T \\ 0 & 0 & 1-\dfrac{T}{\tau} \end{pmatrix} \begin{pmatrix} x_2(t) \\ \dot{x}_2(t) \\ \ddot{x}_2(t) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \dfrac{T}{\tau} \end{pmatrix} u(t) \qquad (5)$$

where, T is the discrete sampling time of the ACC system and assumed as 0.1s.

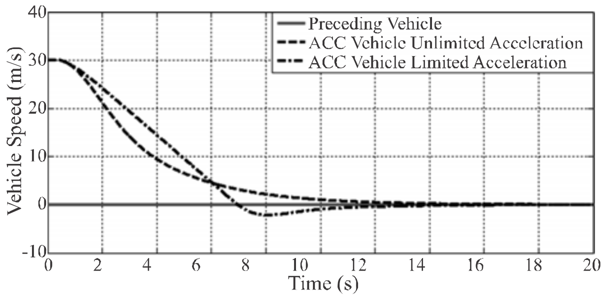

FIG. 6(A). VELOCITIES OF THE VEHICLES

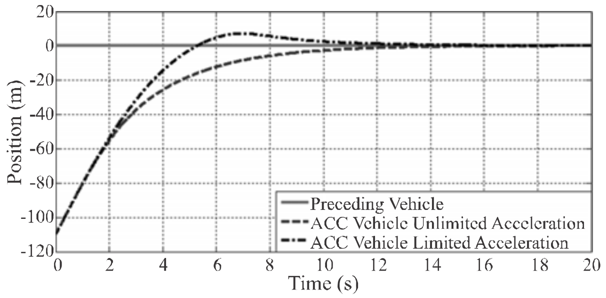

FIG. 6(B). POSITIONS OF THE VEHICLES

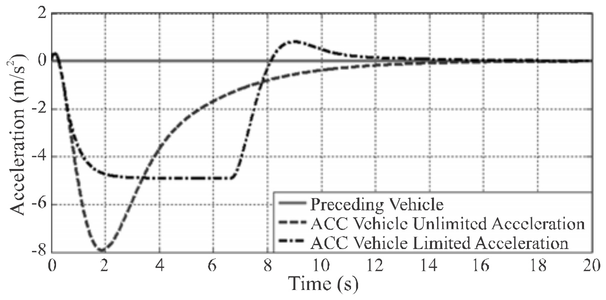

FIG. 6(C). ACCELERATIONS OF VEHICLES

4.1 Coordinate Frame for Transitional Manoeuvres

It is necessary to design and understand the mathematical link between the state variables of the ACC vehicle and the preceding vehicle. The desired SIVD between the two vehicles varies linearly with the preceding vehicle's speed such that the headway time (h) between the two vehicles remains constant (SIVD = $hv_{preceding}$).

A coordinate frame [2], as shown in Fig. 7, travels with a velocity equal to the preceding vehicle velocity. This frame is used to determine the ACC vehicle motion relative to the preceding vehicle. The origin of this frame is situated at the desired SIVD and the objective of the TM is to steer the ACC vehicle to the origin of this frame in order to set up the zero range-rate with the preceding vehicle, where, R is the range (relative distance) between the two vehicles.

Using this coordinate frame (Fig. 7) for TM, the discrete-time state-space model of the error vector between the two vehicles can be defined as:

$$e_{k+1}=Ae_k+Bu_k \qquad (6)$$

$$y_k=Ce_k \qquad (7)$$

where

$$\mathbf{e}_k = \begin{pmatrix} err \\ \dot{err}_k \\ \ddot{err}_k \end{pmatrix} = \begin{pmatrix} -(\text{R-SIVD}) \\ \dot{\text{R}} \\ \ddot{x}_k \end{pmatrix} \qquad (8)$$

where, err_k is spacing error, $\dot{err}_k$ is range-rate (relative velocity between the two vehicles), and $\ddot{err}_k$ is the absolute acceleration of the ACC vehicle. Each element of the error vector ($\mathbf{e}_k$) is the quantity which is measured by the ACC system and the control objective is to steer these

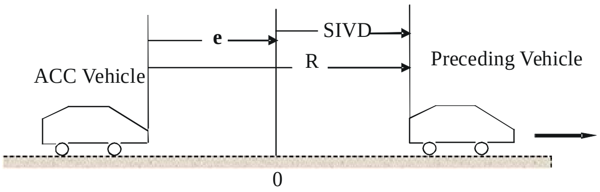

FIG. 7. COORDINATE FRAME FOR TRANSITIONAL MANOEUVRE.

quantities to zero [2]. u_k is the control input, and y_k is the system output at time step k. The system matrices **A** and **B** can be obtained from the comparison of Equation (5) and Equation (6).

$$\mathbf{A}=\begin{pmatrix}1 & T & 0\\ 0 & 1 & T\\ 0 & 0 & 1-\dfrac{T}{\tau}\end{pmatrix},\qquad \mathbf{B}=\begin{pmatrix}0\\ 0\\ \dfrac{T}{\tau}\end{pmatrix} \tag{9}$$

And the system matrix C is defined as [2]:

$$\mathbf{C}=\begin{pmatrix}1 & 0 & 0\\ 0 & -1 & 0\end{pmatrix} \tag{10}$$

The control input constraint included in the MPC control formulation is:

$$u_{\min}\le u_k\le u_{\max} \tag{11}$$

The dimension of **AU** is N_C and N_C is 3 samples, therefore, the constraints are fully imposed on all the components in **AU** and can be translated to the six linear inequalities as:

$$\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ -1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix}\begin{bmatrix}\Delta u(k_i)\\ \Delta u(k_i+1)\\ \Delta u(k_i+2)\end{bmatrix}\le\begin{bmatrix}u_{\max}-u(k_i-1)\\ u_{\max}-u(k_i-1)\\ u_{\max}-u(k_i-1)\\ u_{\min}+u(k_i-1)\\ u_{\min}+u(k_i-1)\\ u_{\min}+u(k_i-1)\end{bmatrix} \tag{12}$$

And the state and collision avoidance constraints incorporated in the MPC control formulation are:

$$y_k=\begin{pmatrix}err_k\\ -\dot{err}_k\end{pmatrix}\le\begin{pmatrix}\mathrm{SIVD}\\ v_{preceding}\end{pmatrix} \tag{13}$$

$$\mathrm{SIVD}=hv_{preceding} \tag{14}$$

where, h is the headway time. The parameters which have been used in MPC controller formulation are shown in Table 2.

4.2 ACC Vehicle Response against a Halt Preceding Vehicle

In this encounter scenario, the ACC vehicle, in the speed control mode, with an initial velocity of 30 m/s detects a preceding vehicle which is at rest at a distance of 110m. In this scenario the ACC vehicle model has to decelerate from 30 m/s to the rest position. The spacing error between the two vehicles is -110m and the initial range-rate between the two vehicles is 30 m/s as shown in Equation (15). According to Bageshwar, *et al.* [2], this scenario is possible to avoid the collision as for the given range-rate of 30 m/s, the required minimum range is 106m to decelerate to the velocity of the target vehicle. The required SIVD in this scenario is at the origin of the coordinate frame (Section 4.1) of the TM which remains constant throughout the length of the simulation as the preceding vehicle's velocity is equal to zero.

Based on this encounter scenario the initial error vector can be defined as:

$$\mathbf{e}(0)=\begin{pmatrix}err\\ \dot{err}_k\\ \ddot{err}_k\end{pmatrix}=\begin{pmatrix}-(\text{R-SIVD})\\ \dot{\mathrm{R}}\\ \ddot{x}_k\end{pmatrix}=\begin{pmatrix}-(110-0)\\ 30\\ 0\end{pmatrix}=\begin{pmatrix}-110\mathrm{m}\\ 30\mathrm{m}/s\\ 0\end{pmatrix} \tag{15}$$

where, -110m is the initial spacing error, 30 m/s is the initial range-rate, and the 3rd element of the vector is the absolute acceleration of the ACC vehicle. It should be noted that the spacing error is equal to –(R–SIVD), here R is the initial range (relative distance) which is 110m and SIVD is the specified inter-vehicle distance which is 0m in this case.

TABLE 2. CONTROLLER PARAMETERS

Discrete Time Sample	T	0.1s
Time Lag	τ	0.5s
Tuning Operator	R	1
Set Point	r	0
Headway Time	h	1s
Prediction Horizon	N_P	230 Samples
Control Horizon	N_C	3 Samples
Upper Acceleration Limit	u_{max}	0.25g
Lower Acceleration Limit	u_{min}	-0.5g

The simulation results in Fig. 8 show the ACC vehicle response for two different situations. In the first situation, the ACC vehicle is analysed without using any constraint. In the second condition only the control input constraint is included in MPC formulation while the states and collision avoidance constraints are not included in the control algorithm. It can be seen in Fig. 8(c) that without any constraints the ACC vehicle's acceleration is going below -0.5g m/s^2, the ACC vehicle successfully executed the TM and can establish a the SIVD with the zero range-rate with the preceding vehicle. However, an ACC vehicle should obey the constraints in any of its mode of operation and in any driving situation. With the control input constraint included only, the ACC vehicle cannot establish a safe SIVD and smashes with the preceding vehicle as shown in Fig. 8(a). The control input commands for both situations are shown in Fig. 8(d). It can also be observed from Fig. 8(b) that the ACC vehicle is travelling with a negative velocity. This is due to the reason that the states constraints and collision avoidance are not included in the controller formulation. Therefore, it is necessary to include states constraints and collision avoidance in the formulation of the MPC control algorithm.

Fig. 9 shows the same simulation scenario as shown in Fig. 8 but this time the states and collision avoidance constraints are also included in MPC algorithm. The MPC control law computes initially the deceleration commands for the ACC vehicle, Fig. 9(d). After reaching the deceleration limits the deceleration commands remains active till *t*=5.93s followed by the acceleration commands to bring the velocity of the ACC vehicle down in order to establish the SIVD with the zero range-rate. The velocity of the preceding vehicle is zero during the entire simulation time so the SIVD. It can be seen in Fig. 9(a) that the ACC vehicle established the required SIVD and manoeuvres to the origin of the coordinate frame (Section 4.1) with the zero range-rate. Therefore, it is necessary to include control input, states and collision avoidance constraints in the controller formulation in order to execute the TM successfully and avoid the accident with the preceding vehicle.

These results have also been validated against the Bageshwar, *et al.* [2] model. The simulation produced in Fig. 9 matches well with their results. It should be noted that in their results the simulation was stopped when the ACC vehicle came to a complete halt while its absolute acceleration still shows a negative sign. This does not show the complete response of the ACC vehicle. On the contrary, Fig. 9 shows the ACC vehicle response for a longer time to emphasize that all the control objectives have been achieved.

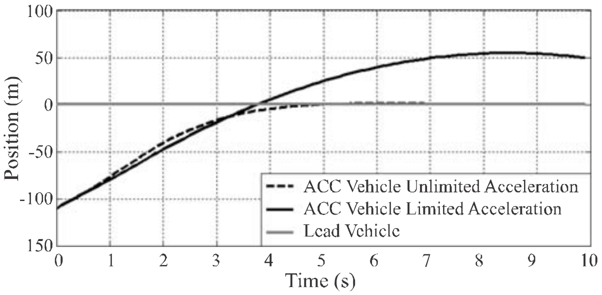

FIG. 8(A). POSITION OF VEHICLE

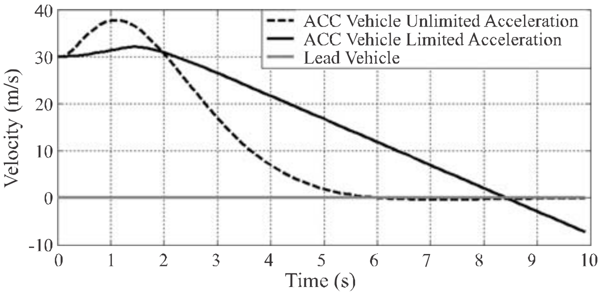

FIG. 8(B). VELOCITY OF VEHICLE

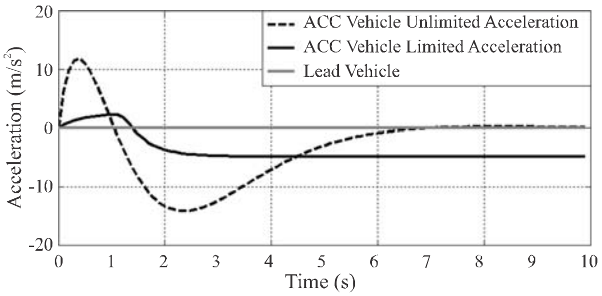

FIG. 8(C). ABSOLUTE ACCELERATION OF VEHICLE

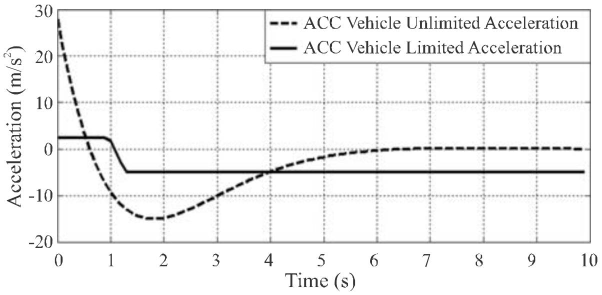

FIG. 8(D). COMMANDED ACCELERATION

5. CONCLUSIONS

Two control algorithms; PID and MPC, for the ULC of an ACC vehicle have been synthesized and analysed in this paper. Basic ordinary PID controller is used for the distance control of an ACC vehicle. These controllers are easy to set up and allow high performance on the micro-controller due to low demands of calculating power. Problems arise, if several variables have to be controlled within the constrained boundaries, e.g. states and control constraints as we have seen in the above simulation results. It has been observed that the functionality of the PID controller is limited and approaches for stability determination of more than one variable are complicated.

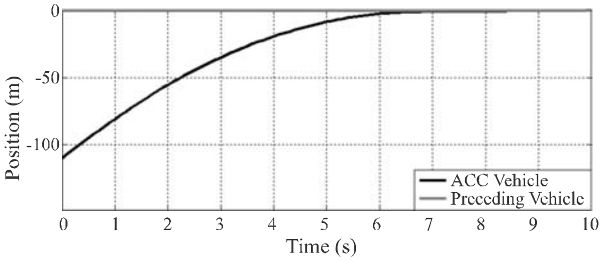

FIG. 9(A). POSITION OF VEHICLE

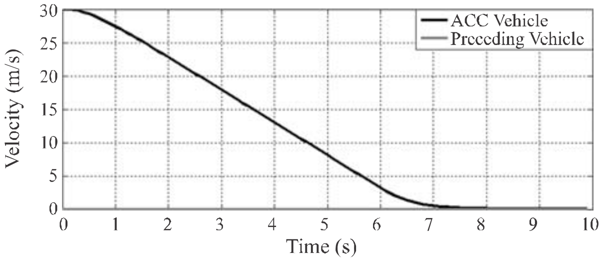

FIG. 9(B). VELOCITY OF THE VEHICLE

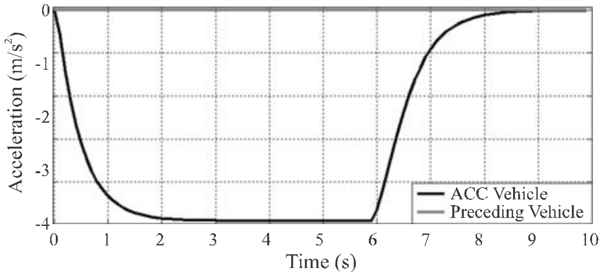

FIG. 9(C). ABSOLUTE ACCELERATION OF ACC VEHICLE

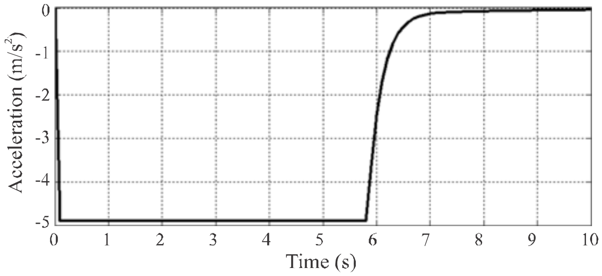

FIG. 9(D). COMMANDED ACCELERATION

The main advantages of using MPC method over PID control strategy are incorporating the operational constraints (control input, states and collision avoidance) in the control algorithm during the analysis process and an online optimization can be achieved. The control input constraints are fully applied on all the components of $\mathbf{AU}_k$ and have been translated as six linear inequalities.

The simulation results obtained from PID method for the first situation are satisfactory. In has been observed that using PID control methods, the ACC vehicle is establishing the desired SIVD based on the headway-spacing policy, performing the control tasks discussed in Section 1 and executing smoothly the required TMs.

The analysis carried out in the second situation shows that PID method can establish the required SIVD with the zero range-rate when no acceleration limit is applied on the control input (u), and the ACC vehicle exceeds the acceleration limits (-0.5g). When the acceleration limit is applied to the control input (u), the ACC vehicle is unable to achieve the required control objectives described in Section 1. The ACC vehicle is initially accelerating whereas it should decelerate straight away for the given initial range between the two vehicles. Also, the ACC vehicle is executing negative velocity, which does not satisfy the constraint in Equation (2), and finally, it cannot avoid the collision with the halt preceding vehicle.

The MPC strategy is not a new control method of control design and is being used for different applications. It mainly solves standard optimal control problems where the optimization is carried out in a finite horizon. The difference between the MPC and the other control methods is that MPC solves the optimal control problem on-line for the current states of the system rather than solving it off-line using a feedback policy as in the case of other control methods. The main difference between the MPC and PID control strategies is that the MPC control strategy uses the desired reference trajectory which is computed using the prediction model then, the MPC controller modifies the plant characteristics in order to follow the desired reference trajectory. Whereas, the control action taken by the PID control strategy is based on the past errors which can be viewed as if the driver is driving the vehicle using the rear-view mirror.

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