Analysis of an ACC System for Sliding Mode and MPC under Transitional Manoeuvers

ZEESHAN ALI MEMON*, DUR MUHAMMAD PATHAN*, AND TANWEER HUSSAIN**

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ABSTRACT

Two different control algorithms, sliding mode and MPC (Model Predictive Control) are employed to analyse the performance of a linear vehicle model equipped with an ACC (Adaptive Cruise Control) system. Both controllers are analysed under critical TM (Transitional Maneuvers) to investigate their suitability for the ACC system. The simulation results, for the same scenario, from both controllers' approach have been compared. The results show that the MPC is more robust than the SMC (Sliding Model Controller). The results show that the SMC algorithm is not suitable for the proposed vehicle model. The shortcomings of the SMC have been highlighted and the comparisons are made with the previous studies. The proposed approach can be useful for the selection of the appropriate controller for the given application.

Key Words: **Adaptive Cruise Control, Sliding Mode Control, Model Predictive Control, Transitional Manoeuvers, Vehicle Control.**

1. INTRODUCTION

A control system can be defined as a system which consists of interconnected components, designed to achieve a desired objective. The main purpose of a feedback system is to control the behaviour of a system in order to benefit the user, provided that the nature of the controlled system is well understood and modelled. The challenging task for a controller is to perform well in spite of uncertainties present in a system [1].

The system to be controlled in this study is a two-vehicle model, Fig. 1, which comprises of a target (preceding) and an ACC vehicle. The target vehicle is based on the non-linear vehicle model [2] which includes engine, torque converter, transmission, and drivetrain models and the ACC vehicle model is based on the first-order vehicle model. The longitudinal controller system of an ACC vehicle is usually composed of two separate controllers, the ULC (Upper Level Controller) and LLC (Lower Level Controller) [3], Fig. 2. The objectives for the ACC vehicle are to establish and maintain a SIVD (Specified Inter Vehicle Distance) with zero range-rate behind the preceding vehicle under steady-state and TM. A TM can be defined as a manoeuvre performed by the ACC vehicle to establish the SIVD using measurements of range, range-rate, and the ACC vehicle velocity and acceleration. There are two requirements for a successful TM: (1) the ACC vehicle

*Assistant Professor, and **Lecturer,
Department of Mechanical Engineering, Mehran University of Engineering & Technology, Jamshoro.

must establish a zero range-rate when at the SIVD; and, (2) the ACC vehicle must avoid a collision with the preceding vehicle [4].

In previous studies, a variety of control strategies have been proposed for an ACC vehicle, most common of them are, sliding mode strategy [5-10], CTG (Constant Time Gap) [4,11], and MPC [4,12-15]. Bageshwar, et. al. [4] have presented a comparison of CTG and MPC control algorithms for a first-order ACC vehicle model during the TMs. They found shortcomings associated with the CTG method and recommended the MPC control method for the ACC analysis during the critical TMs. The comparison of MPC method with the other control methods for the ACC vehicle analysis has not been covered in previous studies. Therefore, in this paper the comparison of MPC and sliding mode controller has been performed for a more detailed investigation.

A simple ACC vehicle model used in the previous studies is based on a first-order lag (delay) [11,13]. This delay is assumed in control input signal computed by ULC. In this paper, it is referred as first-order vehicle model. This delay corresponds to the function of LLC. This first-order model is used between ULC and LLC (Fig. 2) can be defined as [11,13].

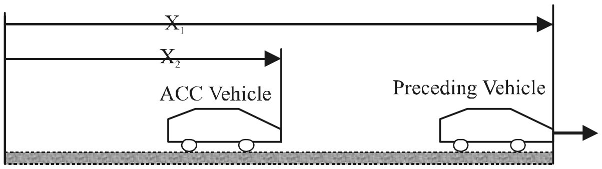

FIG. 1. A TWO-VEHICLE SYSTEM

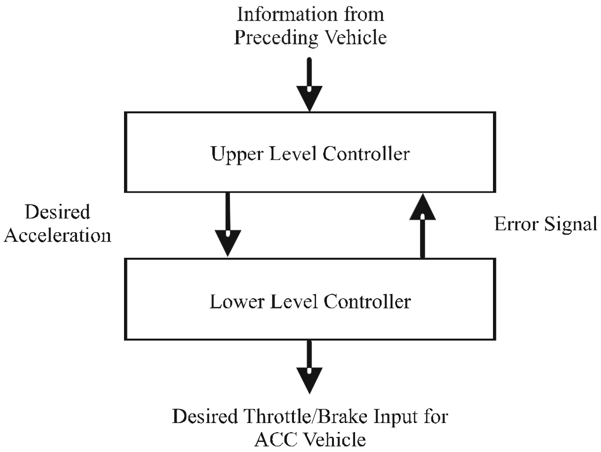

FIG. 2. ACC VEHICLE LONGITUDINAL CONTROL SYSTEM [11]

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

where, x, $\dot{x}$ and $\ddot{x}$ are the absolute position, velocity, and the acceleration of the ACC vehicle. u represents the control input signal calculated by the ULC. τ is delay assumed in the function of LLC. The first-order model is used for the following two important reasons:

(i) The ULC can be proposed and analysed using first-order model because the vehicle dynamics and nonlinearities from engine, transmission, are aerodynamic drag are not considered in the first-order model.

(ii) The results obtained from the first-order model may be used for the validation of the nonlinear ACC vehicle analysis.

One of the important objectives of this study is to develop and analyse the ULC using two well-known control strategies under steady-state and transitional operations. The two control strategies used for the upper-level controller synthesis are:

(1) Sliding Mode Control

(2) MPC (Model Predictive Control)

The key objectives for the control methods are:

(1) Follow easily required acceleration signal.

(2) Attain and retain a SIVD in a reasonable way.

(3) Optimize the operation of the system while respecting constraints.

2. ACC SYSTEM

In addition to the speed control mode, an ACC system equipped vehicle can control the speed to retain a SIVD from a preceding vehicle [6, 16-17]. This additional feature is termed as vehicle following mode. Therefore, both throttle and brake inputs are needed to manage the distance and the relative speed between both vehicles.

2.1 Vehicle Controllers

Spacing control law is created for ULC of the ACC vehicle. The ULC uses kinematic relation between two vehicles and the ACC vehicle velocity and acceleration to calculate the desired acceleration for the LLC [4]. The LLC then utilizes these acceleration signal to produce the required accelerator/stopping signals for the ACC car so it can follow the control signals calculated by the ULC [6]. The error signal produced due to variation in the longitudinal motion of both vehicles is sent back to the ULC where the desired acceleration for the next time step is computed.

3. SMC METHOD

Sliding mode is an advanced type of variable structure system. SMC is an efficient tool to control complex high-order dynamic plants operating under uncertainty conditions. SMC can be conveniently used for both non-linear systems and systems with parameter uncertainties due to its discontinuous controller term. That discontinuous control is used to negate the effects of nonlinearities and/or parameter uncertainties [18]. The sliding mode approach is used in this study for the longitudinal dynamic control of an ACC vehicle in order to minimise the effects generated due to the nonlinearities in a vehicle dynamic model.

It may happen that the control as a function of the system state switches at high (theoretically infinite) frequency; this motion is called sliding mode [19]. The sliding mode approach is a method which transforms a higher-order system into first-order system. In that way, a simple control algorithm can be applied, which is very straightforward and robust [18].

VSC (Variable Structure Control) systems, as the name suggests, are a class of systems where the control law is changed during the control process according to some defined rules which depends on the state of the system [20]. The purpose of the switching control law is to drive trajectory of the nonlinear plant state onto a pre-specified (user-chosen) surface in the state space and to maintain the *plant's state* trajectory on this surface for subsequent time. The surface is called a switching surface. This surface is also called a sliding surface (sliding manifold). Once intercepted, the switched control maintains the plant's state trajectory on the surface for all time steps and the plant's state trajectory slides along this surface [18-20].

3.1 SMC Technique for a Two-Vehicle System

The above discussion gives a brief understanding of the SMC technique. The SMC technique is now applied to a 2-vehicle system comprising of a target and an ACC vehicle. Ferrara, et. al. [7] longitudinal dynamic model for a follower vehicle has been developed using a SMC which is based on headway spacing policy.

A variable $d=x_1-x_2$ is introduced which is the relative distance between the preceding and ACC vehicle measured by ACC vehicle. The aim is to steer d be equal to:

$$L(\dot{x}_2) = h\dot{x}_2 \tag{2}$$

where, h is the 'headway time'. Measuring from the ACC car, the error is expressed as:

$$e = L(\dot{x}_2) - d = h\dot{x}_2 - x_1 + x_2 \tag{3}$$

The control objective can be redefined so as to manoeuvre e to zero, and it can be used as sliding variable using sliding mode technique [18,20]

$$S = e = h\dot{x}_2 - x_1 + x_2 \tag{4}$$

According to Edwards, et. al. [20] and Utkin [18], the controller command (u) needs to meet the following reaching condition.

$$\dot{S}S \le -\eta|S| \tag{5}$$

where η is sliding mode constant. Equation (5) describes that an appropriate selection of the control signal needs to promise.

$$\dot{S} = -\eta \operatorname{sgn}(S) \tag{6}$$

where η is selected suitably high to meet Equation (5) condition, which automatically confirms that the sliding surface $S=0$ is attained in the specific time [20]. Differentiating Equation (4), one has:

$$\dot{S} = hu - \dot{x}_1 + \dot{x}_2 \tag{7}$$

By putting Equation (6) in Equation (7), it is likely to calculate the acceleration which the ith car should achieve to meet Equation (5) condition, i.e.

$$u = \frac{1}{h}(-\eta \operatorname{sgn}(S) - \dot{x}_2 + \dot{x}_1) \tag{8}$$

The control input (u) is applied to Equation (1) to determine the response of the first-order ACC vehicle model. After several attempts, η is selected as 2, which gives satisfactory results.

3.2 Preceding Vehicle with Throttle Input of 50 Degrees and Same Initial Conditions for Both Vehicles

In this scenario, same initial speeds and same initial accelerations except the vehicle positions for both vehicles are considered, the throttle input for the preceding vehicle is set to 50 degrees for the entire simulation time of 30s. Both vehicles are starting from rest and the initial positions of the preceding vehicle and the ACC vehicle are 10 and 0m respectively.

In the case of sliding mode method, both the control input (u) and the acceleration of the first-order ACC vehicle (which is actually a first-order lag in the control input (u) command) model have been plotted in Fig. 3(a). The control input (u) is computed using the sliding surface, Equation (4). Using a suitable value of $\eta(\eta=2)$, the control input (u) satisfies the condition in Equation (5) and makes the system state to move towards the sliding surface and reach it in finite time Fig. 3(e). A high frequency switching takes place as the system trajectories repeatedly cross the sliding surface and this high frequency motion is called chattering. The parameter η decides the rate of convergence of system states towards the sliding surface and the magnitude of chattering in the sliding mode.

The effect of the chattering is not significant during the u computation. It has been noticed that when u is applied to the first-order ACC vehicle model, the lag (τ=0.5s) in control input (u) results in a higher magnitude of chattering. This is due to the discontinuous reaching condition Equation (6). The effect of this chattering can be seen in Fig. 3(a). Using the smaller values of lag (τ) reduce the magnitude of chattering. The lag is considered due to lag in actuators, the bandwidth of the lower-level controller that tracks the desired acceleration and filtering of the radar sensor. The chattering can be avoided by taking into account the dynamics of the actuators in the model and by improving the bandwidth of the LLC or by using a linear reachability condition.

Fig. 3(b) shows the velocities of both vehicles, Fig. 3(c) shows the positions of both vehicles, Fig. 3(d) shows the range between the two vehicles, and Fig. 3(e) shows the phase portrait for the ACC vehicle. These results seem promising during steady-state operation. The velocity of the ACC vehicle matches well with the preceding vehicle velocity Fig. 3(b), the ACC vehicle is obeying the headway spacing law and tracking the desired SIVD Fig. 3(d), and the most importantly, the ACC vehicle is switching to the sliding surface (phase portrait) and follows it for the rest of the simulation time Fig. 3(e).

4. MPC TECHNIQUE FOR THE TWO VEHICLE SYSTEM

The section discusses the MPC strategy for 2-vehicle system based on a target and an ACC vehicle and their location are denoted by x_1 and x_2 respectively, see Fig. 1.

MPC is a control algorithm in which a prediction of a system's behaviour is made to produce a sequence of optimal control input. MPC forms a prediction model to obtain the future response of the system by using a known set of future control input, and by making use of the known system response to controlling inputs [21-22].

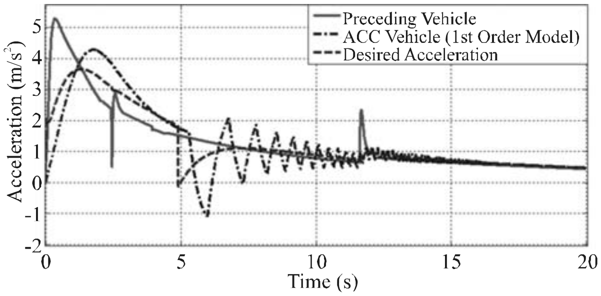

FIG. 3(a). ACCELERATIONS OF VEHICLES

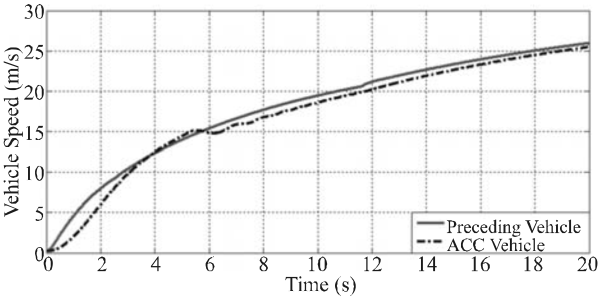

FIG. 3(b). VELOCITIES OF VEHICLES

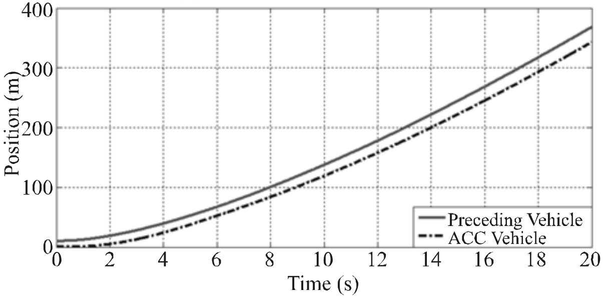

FIG. 3(c). POSITIONS OF VEHICLES

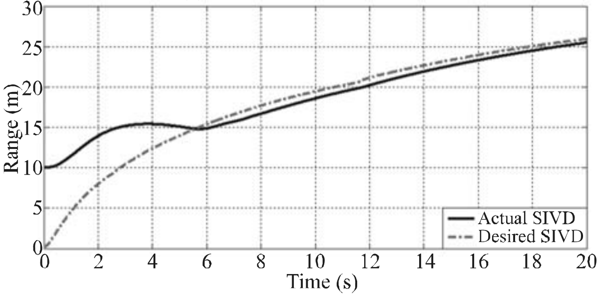

FIG. 3(d). RANGE BETWEEN BOTH VEHICLES

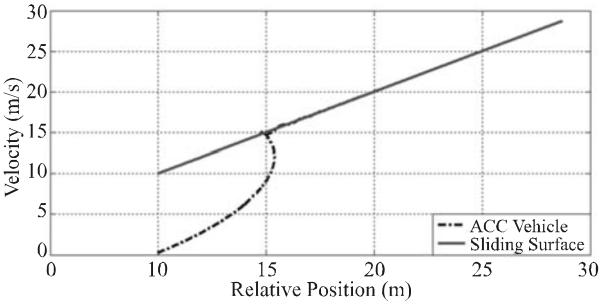

FIG. 3(e). PHASE PORTRAIT

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

$$\begin{pmatrix} x_2(t+T) \\ \dot{x}_2(t+T) \\ \ddot{x}_2(t+T) \end{pmatrix} = \begin{pmatrix} 1 & T & 0 \\ 0 & 1 & T \\ 0 & 0 & 1-\dfrac{T}{\tau} \end{pmatrix} \begin{pmatrix} x_2(t) \\ \dot{x}_2(t) \\ \ddot{x}_2(t) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \dfrac{T}{\tau} \end{pmatrix} u(t) \tag{9}$$

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

4.1 Coordinate Frame for TMs

It is equally important to establish and comprehend the mathematical link between the ACC vehicle and the target car. It should be noted that desired SIVD between the 2 cars changes linearly with the target car's speed so as the headway time (h) between the 2 cars remains same.

A coordinate frame [4], Fig. 4, moves with the same speed as preceding vehicle. The frame is necessary to find out the relative motion of ACC vehicle with respect to preceding vehicle. An origin is marked on this frame on the required SIVD and the aim of the controller is to manoeuvre ACC car to that point so the zero relative velocity with the target car can be established. R is relative distance (range) between the 2 cars.

The discrete-time state-space model of the error vector between the 2 cars is:

$$\mathbf{e}_{k+1} = \mathbf{A}\mathbf{e}_k + \mathbf{B}u_k \tag{10}$$

$$y_k = \mathbf{C}\mathbf{e}_k \tag{11}$$

where,

$$\mathbf{e}_k = \begin{pmatrix} err \\ \dot{err}_k \\ \ddot{err}_k \end{pmatrix} = \begin{pmatrix} -(\text{R-SIVD}) \\ \dot{\text{R}} \\ \ddot{x}_k \end{pmatrix} \tag{12}$$

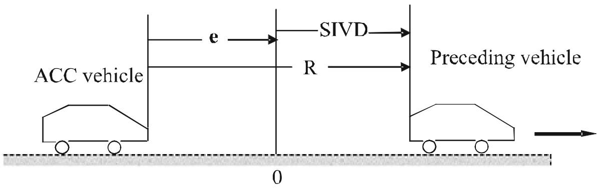

FIG. 4. COORDINATE FRAME FOR TRANSITIONAL MANOEUVRE

where, err_k is spacing error, $\dot{err}_k$ is range-rate , $\ddot{err}_k$ and is the fixed acceleration of the ACC car. Every term of the $\mathbf{e}_k$ is determined by the ACC system and the aim is to manoeuvre this error vector to zero [4]. u_k is the control input, and y_k is the output. By comparing Equations (9-10), the matrices A and B are acquired as.

$$\mathbf{A} = \begin{pmatrix} 1 & T & 0 \\ 0 & 1 & T \\ 0 & 0 & 1-\dfrac{T}{\tau} \end{pmatrix}, \qquad \mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ \dfrac{T}{\tau} \end{pmatrix} \tag{13}$$

matrix C can be expressed as [4]:

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \end{pmatrix} \tag{14}$$

The constraints formulated are acceleration constraints of the ACC car, Equation (15), state constraint, the collision avoidance restriction, Equation (16), and terminal restriction which mean that the ACC car should set up a safe distance SIVD and zero relative velocity.

$$u_{\min} < u_k < u_{\max} \tag{15}$$

$$y_k = \begin{pmatrix} err_k \\ -\dot{err}_k \end{pmatrix} \le \begin{pmatrix} \text{SIVD} \\ v_{preceding} \end{pmatrix} \tag{16}$$

$$SIVD = hv_{preceding} \tag{17}$$

where, h is the headway time. The parameters for the MPC technique are given in Table 1.

TABLE 1. CONTROLLER PARAMETERS

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

4.2 Preceding Vehicle with Throttle Input of 50 Degrees and Different Initial Conditions for Both Vehicles

In this situation, the distance between preceding vehicle and ACC vehicle is 60m. The ACC vehicle at a speed of 30m/s in the speed control mode perceives a preceding vehicle which is accelerating from 10m/s. The throttle input for the preceding vehicle is 50 degrees and the simulation runs for 20s. The initial error vector (**e**) for this situation is:

$$\mathbf{e}(0) = \begin{pmatrix} err \\ \dot{err}_k \\ \ddot{err}_k \end{pmatrix} = \begin{pmatrix} -(\text{R-SIVD}) \\ \dot{\text{R}} \\ \ddot{x}_k \end{pmatrix} = \begin{pmatrix} -(60-10) \\ 20 \\ 0 \end{pmatrix} = \begin{pmatrix} -50\text{m} \\ 20\text{m}/s \\ 0 \end{pmatrix} \tag{18}$$

The ACC vehicle response has been analysed for two different situations: (1) the ACC vehicle without any constraint considered, and (2) the ACC vehicle with all constraints incorporated in the formulation of the MPC control algorithm. The result shows for both situations (Fig. 5) that the ACC vehicle performs the required TM successfully by initially manoeuvring to set up the desired SIVD and then maintaining it for the rest of the simulation with the zero range-rate. The comparison shows in Fig. 5(a) that the ACC vehicle, situation (2), manoeuvres quickly to reach the preceding vehicle's velocity than the ACC vehicle velocity profile without acceleration limits. Fig. 5(b) shows the positions of both vehicles. The ACC vehicle distance, relative to preceding vehicle, can be seen in Fig. 5(d). ACC vehicle accelerations for both situations are shown in Fig. 5(c). The ACC vehicle, without the control input constraint, only concerns with establishing a SIVD with zero-range-rate and is unable to meet the other requirements of the TM. Fig. 5(b) shows the positions of both vehicles. With the initial range of 60m the simulation starts and then the ACC vehicle initially reduces the range, Fig. 5(d), once the desired SIVD is achieved the ACC vehicle then continues to follow the preceding vehicle. It should be noted that after establishing the SIVD the preceding vehicle's velocity is continuously increasing so the desired SIVD and it can be seen in Fig. 5(d) which shows the range between the two vehicles. Once the SIVD is established then the range between the two vehicles becomes equal to the SIVD.

One can conclude after analysing the ACC vehicle response under two different encounter scenarios that the MPC control algorithm can successfully manoeuvre the ACC vehicle, with the given initially conditions, to the desired SIVD and with the zero range-rate. Another advantage of using the MPC control algorithm is that the MPC can incorporate the constraint in its formulation which improves the system stability and robustness.

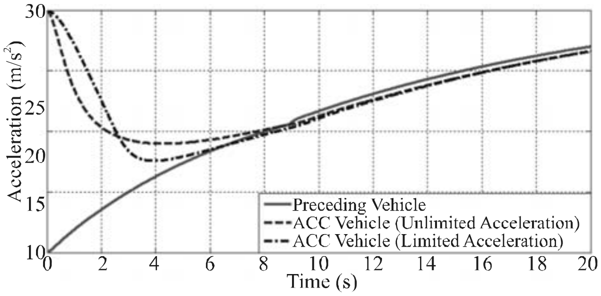

FIG. 5(a). VELOCITIES OF VEHICLES

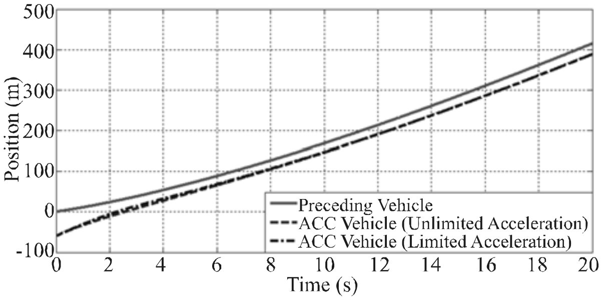

FIG. 5(b). POSITION OF VEHICLES

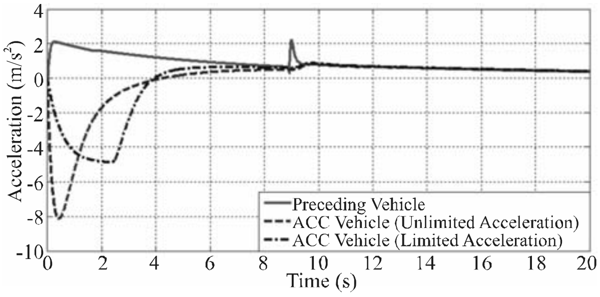

FIG. 5(c). ABSOLUTE ACCELERATION OF VEHICLES

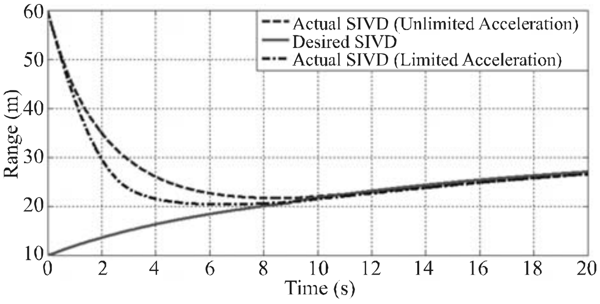

FIG. 5(d). RANGE

The validation of these results has been performed by comparing with results by Bageshwar, et al. [4]. The comparison shows a good agreement between the two results because the first-order ACC vehicle is achieving the required control objectives. It should be noted that the Bageshwar, et al. [4] results does not show any detail about the preceding vehicle, e.g. what is throttle input for the preceding vehicle, engine details, gear ratio, etc. Also the behaviour of the preceding vehicle is not showing the actual vehicle behaviour. On the contrary, in this study the preceding vehicle is based on the complex vehicle model, which means a realistic reference target for the ACC to achieve.

5. CONCLUSIONS

This paper presents the design and analysis of the upper-level controller of a vehicle equipped with ACC system using two different control approaches; sliding mode and MPC. The analyses show that MPC method is more effective than sliding mode method because MPC can incorporate the operational constraints within its formulation and it can perform an online optimization.

In has been observed due to the chattering effect the sliding mode control method is not suitable for the two-vehicle system considered in this study. As this study is focusing on the critical TMs, therefore, the chattering effects will be higher under these critical manoeuvres.

The difference between MPC and sliding mode control is that the 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. Moreover, the difference between sliding mode and MPC mode control strategies is that MPC employs prediction model to compute the desired reference trajectory and then adjust the plant characteristics to track the desired reference trajectory. Whereas, sliding mode method uses the past errors to determine the required control action. This can be viewed as if the driver is driving the vehicle using the rear-view mirror.

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REFERENCES

[1] Dorf, R.C., and Bishop, R.H., "Modern Control Systems", New Jersey, Prentice Hall, 2001.

[2] Ali, Z., "Transitional Controller Design for Adaptive Cruise Control Systems", Ph.D. Thesis, University of Nottingham, UK, 2011.

[3] Rajamani, R., and Zhu, C., "Semi-Autonomous Adaptive Cruise Control Systems", IEEE Transactions on Vehicular Technology, Volume 51, No. 5, pp. 1186-1192, 2002.

[4] Bageshwar, V.L., Garrard, W.L. and Rajamani, R., "Model Predictive Control of Transitional Maneuvers for Adaptive Cruise Control Vehicles", IEEE Transactions on Vehicular Technology, Volume 53, No. 5, pp. 1573-1585, 2004.

[5] Sun, M., Lewis, F.L. and Ge, S.S., "Platoon-Stable Adaptive Controller Design", 43rd IEEE Conference on Decision and Control, Atlantis, Paradise Island, Bahamas, 2004.

[6] Girard, A.R., Spry, S., and Hedrick, J.K., "Intelligent Cruise-Control Applications", IEEE Robotics and Automation Magazine, Volume 12, No. 1, pp. 22-28, 2005.

[7] Ferrara, A., and Vecchio, C., "Collision Avoidance Strategies and Coordinated Control of Passenger Vehicles", Nonlinear Dynamics, Volume 49, No. 4, pp. 475-492, 2007.

[8] Connolly, T.R., and Hedrick, J.K., "Longitudinal Transition Maneuvers in an Automated Highway System", Journal of Dynamic Systems, Measurement, and Control, Volume 121, No. 3, pp. 471-478, 1999.

[9] Gerdes, J.C., and Hedrick, J.K., "Vehicle Speed and Spacing Control Via Coordinated Throttle and Brake Actuation", Control Engineering Practice, Volume 5, No. 11, pp. 1607-1614, 1997.

[10] Rajamani, R., Choi, S.B., Law, B.K., Hedrick, J.K., Prohaska, R., and Kretz, P., "Design and Experimental Implementation of Longitudinal Control for a Platoon of Automated Vehicles", Transactions of the ASME, Volume 122, No. 3, pp. 470-476, 2000.

[11] Rajamani, R., "Vehicle Dynamics and Control", New York, Springer, 2006.

[12] Corona, D., and Schutter, B.D., "Adaptive Cruise Control for a SMART Car: A Comparison Benchmark for MPC-PWA Control Methods", IEEE Transactions on Control Systems Technology, Volume 16, No. 2, pp. 365-372, 2008.

[13] Li, S., Li, K., Rajamani, R., and Wang, J., "Model Predictive Multi-Objective Vehicular Adaptive Cruise Control", IEEE Transactions on Control Systems Technology, Volume 18, No. 6, pp. 1-11, 2010.

[14] Zlocki, A., and Themann, P., "Improved Energy Efficiency by Model Based Predictive ACC in Hybrid Vehicles Based on Map Data", 10th International Symposium on Advanced Vehicle Control, Loughborough University, UK, 2010.

[15] Li, S., Li, K., and Wang, J., "Development and Verification of Vehicular Multi-Objective Coordinated Adaptive Cruise Control Systems", 10th International Symposium on Advanced Vehicle Control, Loughborough University, UK, 2010.

[16] Haney, P.R., and Richardson, M.J., "Adaptive Cruise Control, System Optimisation and Development for Motor Vehicles", The Journal of Navigation, Volume 53, No. 1, pp. 42-47, 2000.

[17] Liang, C.Y., and Peng, H., "Optimal Adaptive Cruise Control with Guaranteed String Stability", Vehicle System Dynamics, Volume 31, pp. 313-330, 1999.

[18] Utkin, V., Guldner, J., and Shi, J.X., "Sliding Mode Control in Electromechanical Systems", London, Taylor & Francis, 1999.

[19] Bhatti, A.I., Spurgeon, S.K., Dorey, R., and Edwards, C., "Sliding Mode Configuration for Automotive Engine Control", International Jounal of Adaptive Control and Signal Processing, Volume 13, pp. 49-69, 1999.

[20] Edwards, C., and Spurgeon, S.K., "Sliding Mode Control: Theory and Applications", London, Taylor & Francis, 1998.

[21] Camacho, E.F., and Bordons, C., "Model Predictive Control", London, Springer, 2004.

[22] Maciejowski, J.A., "Predictive Control with Constraints", Prentice Hall, 2002.