Fuzzy Sliding Mode Control System Design for Car-Following Behavior in Real Traffic Flow

A.Ghaffari[1], A. Khodayari[2], B. Gharehpapagh[3], S.Salehinia[4]

1,3 Mechanical Engineering Department, South Tehran Branch, Islamic Azad University, Tehran, Iran. 2, 4 Mechanical Engineering Department, Pardis Branch, Islamic Azad University, Tehran, Iran.

arkhodayari@dena.kntu.ac.ir

Abstract

In this paper a control system has been designed to improve traffic conditions in car following maneuver. There are different methods to design a control system. In this paper design approach is based on the Fuzzy sliding mode control (FSMC) system. The aim of designing FSMC system is to achieve safe and desire longitudinal distance and less lateral displacement. In order to control and obtain desired longitudinal and lateral movements, suitable values of composite torque and steering angle is generated. At first to design of FSMC system, a nonlinear dynamics model of vehicle with three degrees of freedom is presented and validated with real traffic data. Then, the performance of the FSMC system has been evaluated by real car following data. At the end, the simulation results of FSMC are compared with the first and second order sliding mode control. Simulation result shows that performance of FSMC is better than sliding mode control. Also by comparing between FSMC and real driver, it is shown that FSMC is much safer than a real human driver in keeping the longitudinal distance and also the FSMC produces less lateral displacement in the lateral movement too.

***Keywords**: Fuzzy sliding mode control, nonlinear vehicle dynamics model, car following maneuver.*

1. Introduction

Intelligent transportation system has become one of the important subjects in urban traffic problem recently. The subjects of energy consumption, vehicle safety, convenience of drivers and passengers and increasing in travel time have been taken a lot of attention from researchers according to improve intelligent transportation system concept. Due to these subjects, various control systems have been applied in vehicles such as Adaptive Cruse Control (ACC), Intelligent Speeding Adaptation (ISA), Desire Reference Path Generation (DRPG), etc.

In the designing process of a control system for driving behavior, one of the main steps is the automotive traffic flow definition. There are various theories attempt to describe the automotive traffic flow process such as car following, lane changing and overtaking. Car following is based on the follow and leader vehicles (FV and LV) concept, in which rules of how a driver follows his/her immediate leading vehicle based on both experimental observations and theoretical (i.e., psychological) considerations [1].

Furthermore, car following is one of the common traffic behavior in many traffic fields such as railway, highway and etc. Car following is a crucial tactical-level model for a microscopic simulation system. It describes the longitudinal action of a driver when it follows another car and tries to maintain a safe distance to the LV, as shown in Fig. 1.

One of the major achievements is the control laws for collision avoidance while the front car brakes suddenly in emergency in the course of their following operation [2]. However, due to the complexity of the car following problem, the current control of car following operation mainly dependents on the drivers subjective judgment and their corresponding behavior. Thus, human errors make significant impact on the safety of this behavior.

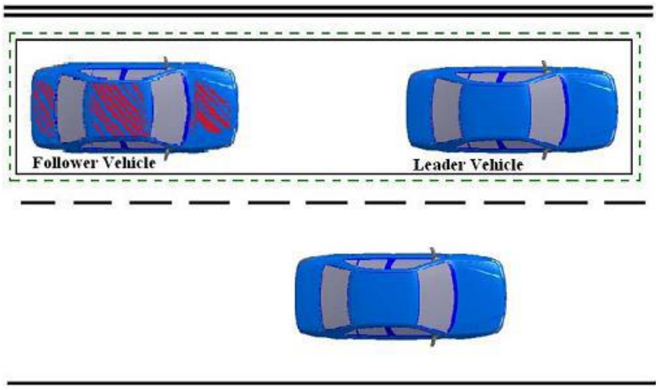

Fig1. Driver-vehicle unites (LV and FV) in car following behavior

Nowadays various control systems have been designed based on longitudinal and lateral movement control for car following maneuver. For example Menhour et al. have proposed a control system for longitudinal and lateral vehicle movements. Proposed control system has ensured an automatic path tracking via vehicle steering angle and driving/braking wheel torque [3]. This control system is based on flatness of vehicle dynamics model. Also they proposed another control system in [4] that is based on model-free design for decoupled longitudinal and lateral control. Chaibet et al. have proposed a control system for vehicle based on second order sliding mode control that has been evaluated for integrated longitudinal and lateral control [5].

Decoupling longitudinal and lateral fuzzy control vehicle systems have been proposed under the assumption of small varying velocity and steering angle in [6]. The single-input fuzzy logic controller has been used for longitudinal control. Besides improving the lateral control of the vehicle, the pole-placement technique with proposed fuzzy gain scheduling and observer design also has been developed.

A new velocity control method has been developed by using fuzzy logic that has been considered steering angle in addition to velocity error and integral of the velocity error [7]. The fuzzy system has been used in designing process of the controller because of the highly nonlinear nature of vehicle model. Also the fuzzy system has been designed based on two cascades connected Mamdani-type Fuzzy Inference System (FIS) for the vehicle velocity control. Cabello et al. have proposed a longitudinal control system based on fuzzy logic control structure for a wide range of velocity, implementing ACC and Stop & Go control. Also a bicycle model of the vehicle has been considered as dynamics model [8]. In addition, a vehicle steering control as a lateral control has been designed based on first order sliding fuzzy interval type-2 control [9]. The related results in [9] show high performances of this method over the first order sliding mode control in terms of error tracking.

Although sliding mode control is one of the methods for robustness, its major drawback is chattering phenomena problem. FIS is one of the solutions for this problem. Fuzzy logic has some advantages such as capacity in dealing with uncertain system and nonlinear system. In general, fuzzy control which consists of several innovative decision rules is suitable for ill modeled systems with being available of qualitative knowledge of an experienced operator. Therefore, in contrast to the current control algorithm, there is a fuzzy control system which consists of several innovative decision rules. This algorithm has been proved to be effective, especially when the exact model of the controlled system is not available [10]. Furthermore, combination of fuzzy logic and sliding mode control (FSMC) has been proposed in this paper.

In this study a FSMC is designed in order to control lateral and longitudinal movement by means of providing safe and desire longitudinal distance and less lateral displacement. Moreover, first a nonlinear dynamics model is considered for vehicle and then FSMC system is designed considering the model. The goal of FSMC design is to generate desire composite torque and steering angle in order to reach suitable longitudinal and lateral movement for vehicle in traffic flow. Then by means of simulation, generated composite torque and steering angle from FSMC have been compared with the values by first and second order sliding mode control (1th and 2th SMC).

The remaining parts of this paper are organized as follows: Section II describes the vehicle dynamics model which will be employed in designing of the control system and also in this part the presented vehicle model is validated using real traffic dataset. Section III presents the designing of FSMC system and in section IV the control system will be evaluated. At last, the conclusion is given in section V.

2. Vehicle Dynamics Model

In this section, first a vehicle dynamics model is described in order to simulate the car following maneuver. This model is a nonlinear model with three degrees of freedom. Then, real car following dataset is introduced and then employed to validate the vehicle dynamics model. At the end, the results of model validation are presented.

A. Equation of vehicle motion

As it is mentioned, vehicle model is a nonlinear model so for simplifying the model, there are four assumptions which are summarized as follows [11]:

1- Neglecting from the roll, the pitch and the vertical dynamics

2- Small values for vehicle slide angle.

3- Only translations in the longitudinal and lateral directions and the yaw rotation are allowed.

4- All angles are sufficiently small in order to allow linear approximation.

The simplified dynamics model of the vehicle in canonical form has been given by the following equations:

$$\dot{v}_{x_s} = f_0 + g_0 T_c \quad (1)$$

$$\dot{v}_{y_s} = f_1 + g_1 \delta_f \quad (2)$$

$$\ddot{\psi}_s = f_2 + g_2 \delta_f \quad (3)$$

$$\begin{cases} f_0 = \frac{-T_{rr}}{I_{eff}} - \frac{c_x v_{x_s}^2}{m} + v_{y_s}\dot{\psi}_s \\ g_0 = \frac{1}{I_{eff}} \\ f_1 = \frac{-2c_f}{m}\frac{v_{y_s}+l_f\dot{\psi}_s}{v_{x_s}} - \frac{2c_r}{m}\frac{v_{y_s}-l_r\dot{\psi}_s}{v_{x_s}} - \frac{c_y v_{y_s}^2}{m} + v_{x_s}\dot{\psi}_s \\ g_1 = \frac{2c_f}{m} \\ f_2 = \frac{-l_f}{I_z} 2c_f \frac{v_{y_s}+l_f\dot{\psi}_s}{v_{x_s}} + \frac{l_r}{I_z} 2c_r \left(\frac{v_{y_s}-l_r\dot{\psi}_s}{v_{x_s}}\right) \\ g_2 = \frac{l_r}{I_z} 2c_f \end{cases} \quad (4)$$

In the design process of the control system, longitudinal distance and lateral displacement between FV and LV and also their variations are needed. Furthermore, first absolute position and the yaw angle of FV have been obtained as follows: [5]:

$$\begin{cases} \psi_s(t) = \int_0^t \dot{\psi}_s d\tau + \psi_s(0) \\ x_s = \int_0^t (v_{x_s} cos\psi_s - v_{y_s} sin\psi_s) d\tau \\ y_s = \int_o^t (v_{x_s} sin\psi_s + v_{y_s} cos\psi_s) d\tau \end{cases} \quad (5)$$

Where (0) is the initial value for yaw angle. As shown in the Fig. 2, the longitudinal distance (dxr) and lateral displacement (dyr) can be obtained as follows:

$$\begin{bmatrix} d_{xr} \\ d_{yr} \end{bmatrix} = R(\psi_l)\left(\begin{bmatrix} x_s + l_f cos\psi_s \\ y_s + l_f sin\psi_s \end{bmatrix} - \begin{bmatrix} x_l - l_r cos\psi_l \\ y_l - l_r sin\psi_l \end{bmatrix}\right) \quad (6)$$

Where (ψl) is rotation matrix concerning the angle of ψl. The r, s and l symbols are referring to the relative values, FV values and LV values respectively.

The derivatives of (6) are given as follows:

$$\begin{cases} \dot{d}_{xr} = -v_{x_l} + d_{yr}\dot{\psi}_l + v_{x_s} cos\psi_r + (v_{y_s} + \dot{\psi}_s l_f) sin\psi_r \\ \dot{d}_{yr} = -v_{y_l} + (l_r - d_{xr})\dot{\psi}_l - v_{x_s} sin\psi_r + (v_{y_s} + \dot{\psi}_s l_f) cos\psi_r \end{cases} \quad (7)$$

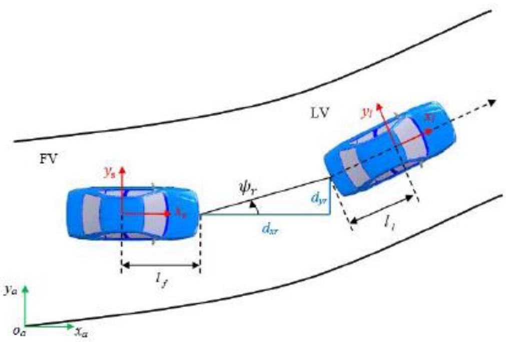

Fig2. Relative positioning of FV and LV.

The second derivation of longitudinal distance and lateral displacement are:

$$\ddot{d}_{xr} = a_0 + b_0 T_c + c_0 \delta_f$$
$$\ddot{d}_{yr} = a_1 + b_1 T_c + c_1 \delta_f \quad (8,9)$$

Where

$$a_0 = -\dot{v}_{xl} + d_{yr}\ddot{\psi}_l + \dot{d}_{yr}\dot{\psi}_l + f_0 cos\psi_r - v_{xs} sin\psi_r \dot{\psi}_r + (v_{ys} + l_f \dot{\psi}_s) cos\psi_r \dot{\psi}_r + (f_1 + f_2 l_f) sin\psi_r \quad (10)$$

$$b_0 = g_0 cos\psi_r \quad (11)$$

$$c_0 = (g_1 + g_2 l_f) sin\psi_r \quad (12)$$

$$a_1 = -\dot{d}_{xr}\dot{\psi}_l + d_{xr}\ddot{\psi}_l - (\dot{v}_{yl} - \ddot{\psi}_l l_r) - f_0 sin\psi_r - (v_{ys} + l_f \dot{\psi}_s) sin\psi_r \dot{\psi}_r + (f_1 + f_2 l_f - v_{xs}\dot{\psi}_r) cos\psi_r \quad (13)$$

$$b_1 = -g_0 sin\psi_r \quad (14)$$

$$c_1 = (g_1 + g_2 l_f) cos\psi_r \quad (15)$$

$$\psi_r = \psi_l - \psi_s \quad (16)$$

B. Real Traffic Dataset

In order to evaluate the performance of the presented dynamics model, a dataset of car following system is required. Therefore, the real car following data known as NGSIM dataset is used. This dataset is from US Federal Highway Administration's and collected in United States which includes information about the vehicles pursuit behavior [12]. In 2005, a dataset is built based on the path traveled by vehicles which are driving on the California State 101 highway in the morning peak times. The data is registered by eight cameras located on 10 buildings next to the highway. As shown in Fig.3, vehicle's path is registered every fifteen minutes, in a 640 meter distance of the highway. This dataset is known as "US-101" and includes 18 characteristics for each DUV such as vertical and horizontal position, velocity, acceleration, time, number of road, type of vehicle, front vehicle, etc [13]. The extracted data from this dataset is not filtered and, therefore, have noise in measurement. For this reason, the data must be filtered. So a moving average filter has been applied to all data [14].

C. Validation of dynamics model

Performance of the proposed dynamics model must be investigated in real traffic conditions. For this purpose, second derivation of longitudinal relative distance, lateral relative 8

Displacement and FV yaw angle from the real traffic data have been compared with the ones of the model. Fig. 4 shows the comparison result.

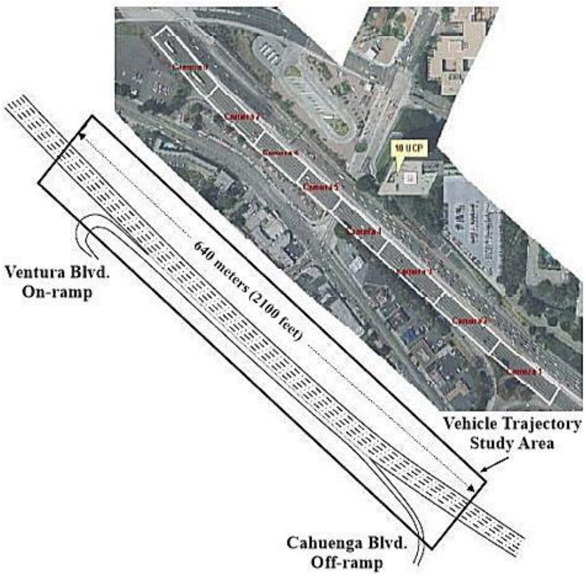

Fig3. Section of 101 inter-state highway in Amerville, Sanfransisco, California [14]

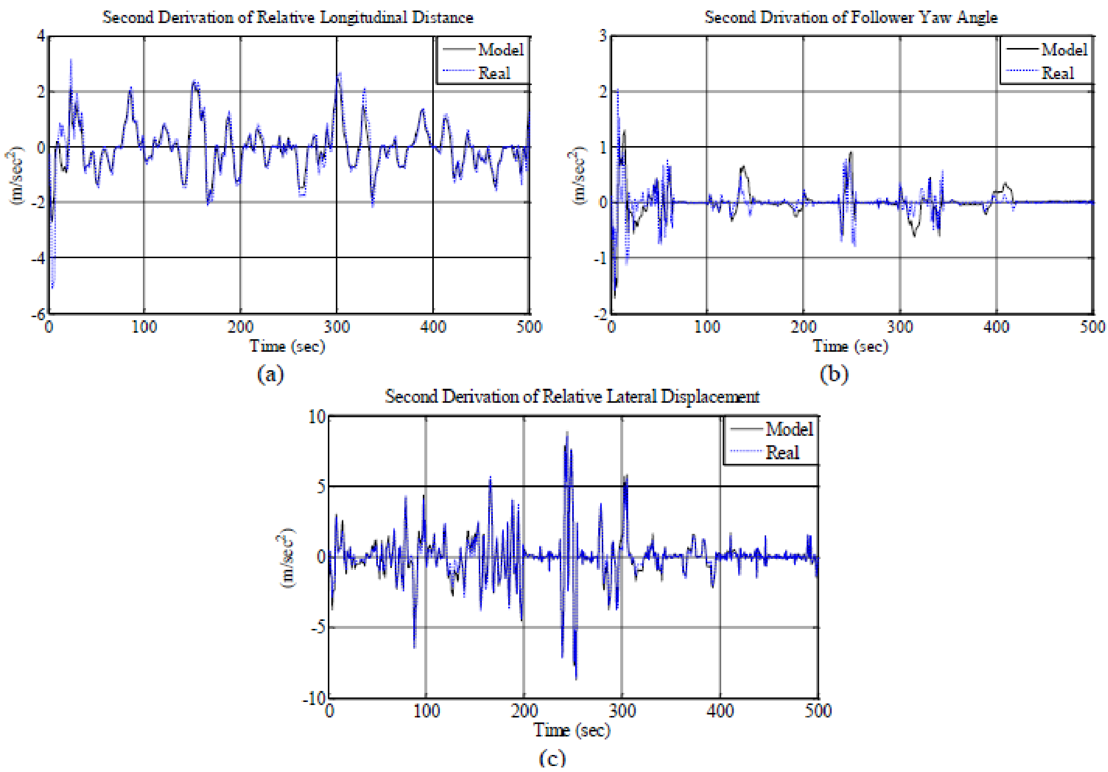

Fig4. Comparison between the dynamics model and real FV's data in second derivation of (a) relative longitudinal distance, (b) follower yaw angel, (c) relative lateral displacement

Table I. Results of Error for Vehicle Dynamic Model: Second Derivation of Longitudinal Distance

Criteria	Test 1	Test 2	Test 3	Mean
MAPE	0.1735	0.1634	0.3577	0.2315
RMSE	0.0242	0.1132	0.0148	0.0507
SDE	0.2846	0.1398	0.6028	0.3424

Table II. Results of Error for Vehicle Dynamic Model: Second Derivation of Lateral Displacement

Criteria	Test 1	Test 2	Test 3	Mean
MAPE	0.2846	0.2177	0.1375	0.2133
RMSE	0.0012	0.0005	0.0041	0.0019
SDE	0.6381	0.0230	0.6317	0.4309

As it can be seen in Fig. 4, performance of the dynamics model is very similar to the behavior of real driver in traffic. Also various criteria were used to calculate model outputs errors. The criterion mean absolute percentage error (MAPE), according to (10), shows the mean absolute error that can be considered as a criterion to model risk to use it in real-world conditions. Root mean squares error (RMSE), according to (11), is a criterion to compare error dimension in various models. Standard deviation error (SDE), according to (12), indicates the persistent error even after calibration of the model. In these equations, xi shows the real value of the variable being modeled (observed data), $\hat{x}$ denotes the real value of variable modeled by the model and N is the number of test observations [15].

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\frac{|x_i - \hat{x}_i|}{x_i} \qquad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \hat{x}_i)^2} \qquad (11)$$

$$SDE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{|x_i - \hat{x}_i|}{x_i} - \frac{MAPE}{100}\right)^2} \qquad (12)$$

Errors of vehicle dynamic model outputs for the second derivation of longitudinal distance and the second derivation of lateral displacement considering these criteria are summarized in Table I and Table II. The last column of tables shows the mean value of each error criteria.

As it can be seen from Table I and Table II, the dynamics model has low error values. The results show that the proposed model has a high compatibility with real car following behavior data. In the next chapter, the vehicle dynamics model will be employed in the designing of the FSMC system.

3. Fuzzy Sliding Mode Control System Design

In this section the design of the control system is described. The general design objective of control system is to maintain a safe longitudinal distance and produce less lateral displacement by generating suitable values for system inputs (composite torque and steering angle). Control system design is based on combining fuzzy inference system and sliding mode control (FSMC). Presented dynamics model in previous chapter is used in design of FSMC system. As it is shown in Fig. 5, the total system inputs are divided into two sections: equivalent control inputs and fuzzy control inputs [10]:

$$u = ueq + ur \qquad (13)$$

That ueq and ur are equivalent control inputs and fuzzy control inputs respectively. First, equivalent control inputs are obtained by using sliding mode method.

Furthermore, sliding surfaces based on sliding mode is defined. Because of integrated control aim, longitudinal and lateral surfaces are needed. Definition of longitudinal and lateral surfaces are done in order to FV maintain a safe longitudinal distance with the LV and also to minimize the lateral motion of the FV in the car following situation. So as shown in Fig. 6, the longitudinal sliding surface that prevents FV from collision, has been defined in (14) and lateral sliding surface is obtained according to (15) [16]:

$$S_{long} = d_{xr} + (d_0 + hv_{xs}) \qquad (14)$$

$$S_{lat} = (\dot{d}_{yr} + \lambda\dot{\psi}_r) + c_1(d_{yr} + \lambda\psi_r) + c_2\int(d_{yr} + \lambda\psi_r)d\tau \qquad (15)$$

Which h refers to headway time and $d0$ refers to distance of stopping. It must be noted that these values are considered to be constant. Also λ is a weighting coefficient.

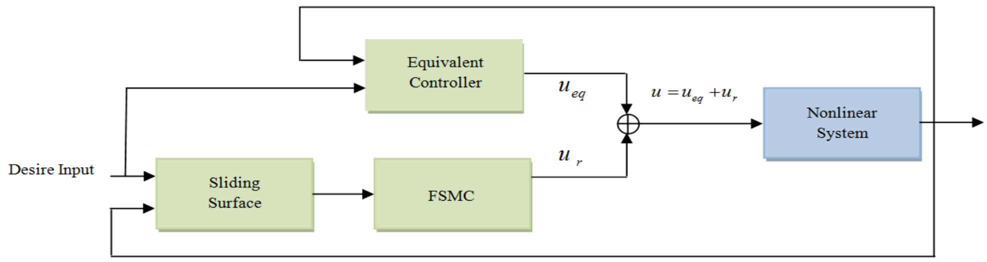

Fig5. Block diagram of designed control system

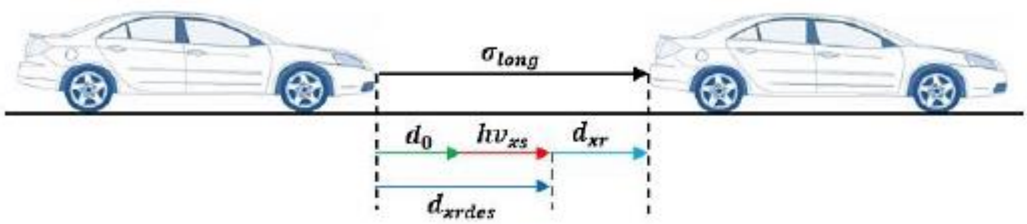

Fig6. vehicle's inter distance model [16]

So the total sliding surfaces are:

$$S = [S_{long}, S_{lat}]^T \tag{16}$$

After determination of sliding surfaces, equivalent control inputs must be defined. These values are obtained by means of the sliding surface. So, for obtaining equivalent control inputs, $\dot{S}$ must be zero:

$$\dot{S} = [\dot{S}_{long}, \dot{S}_{lat}]^T = 0 \tag{17}$$

So

$$\dot{S} = \begin{bmatrix} \dot{d}_{xr} + h\dot{v}_{x_s} \\ (\ddot{d}_{yr}\lambda\ddot{\psi}_r) + a_1(\dot{d}_{yr} + \lambda\dot{\psi}_r) + a_2(d_{yr} + \lambda\psi_r) \end{bmatrix} \tag{18}$$

Equation (18) also can be written like:

$$\dot{S} = G + B \begin{bmatrix} T_c \\ \delta_f \end{bmatrix} \tag{19}$$

Where

$$G = \begin{bmatrix} \dot{d}_{xr} + hf_0 \\ a_1 + \lambda\ddot{\psi}_r - f_2 + c_1(\dot{d}_{yr} + \lambda\dot{\psi}_r) + c_2(d_{yr} + \lambda\psi_r) \end{bmatrix} \tag{20}$$

And

$$B = \begin{bmatrix} hg_0 & 0 \\ b_1 & c_1 - \lambda g_2 \end{bmatrix} \tag{21}$$

Therefore, the equivalent control inputs that are equivalent composite torque and steering angle are obtained as follows:

$$u_{eq} = \begin{bmatrix} T_{c_{eq}} \\ \delta_{f_{eq}} \end{bmatrix} = -B^{-1}G \tag{22}$$

Now, to designing a FSMC system, in addition of equivalent control inputs, fuzzy control inputs are also needed. Next step, the FIS is designed. In this FIS, as it is shown in Fig. 7, there are two inputs and an output.

The inputs are values of S and $\dot{S}$ (sliding surfaces and their first order derivation) and the output is a desire value for vehicle's input. As stated before, desire values for vehicle's input is consisted as controlled composite torque or steering angle for each longitudinal and lateral movements. Therefore, the values of S and $\dot{S}$ must be normalized.

The term of fuzzy control is obtained as follows:

$$u_r = k_{fs}u_{fs} \tag{23}$$

Where k_{fs} is the normalized factor and ufs is the fuzzy control input that is given as follows:

$$u_{fs} = [u_{fs_{lang}} \; u_{fs_{lat}}]^T \tag{24}$$

In the above equation $ufslang$ and $ufslat$ are longitudinal and lateral fuzzy control inputs respectively that can be obtained by using the FIS as follow:

$$u_{fs_{lang}} = FSMC(S_{long}, \dot{S}_{long})$$
$$u_{fs_{lat}} = FSMC(S_{lat}, \dot{S}_{lat}) \tag{25,26}$$

Then, according to the fuzzy rules assigning that is shown in Table III, ufs can be obtained. The obtained fuzzy surface that is shown in Fig. 8 illustrates the relationship between two inputs of FSMC and its output. It is noted that kfs coefficients can be calculated according to the stability condition: $S\dot{S}$<0.

Linguistic in variables are defined as NB (negative big), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium) and PB (positive big) as shown in Table III, so there are 49 fuzzy rules.

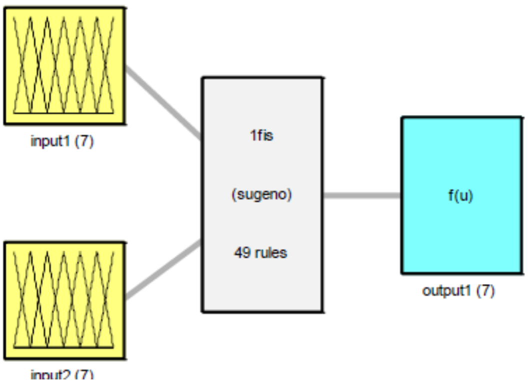

Fig7. schematic of the designed FIS

Table 3. Fuzzy rules for designed FIS

$u_{fs}(i)$		s_i						
		PB	*PM*	*PS*	*ZE*	*NS*	*NM*	*NB*
$\dot{s}_i$	*PB*	NB	NB	NB	ZE	ZE	ZE	PS
	PM	NB	NB	NB	ZE	ZE	ZE	PS
	PS	NB	NB	NM	ZE	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	NS	NM	NS	ZE	ZE	PM	PB	PB
	NM	NS	ZE	ZE	ZE	PB	PB	PB
	NB	NS	ZE	ZE	ZE	PB	PB	PB

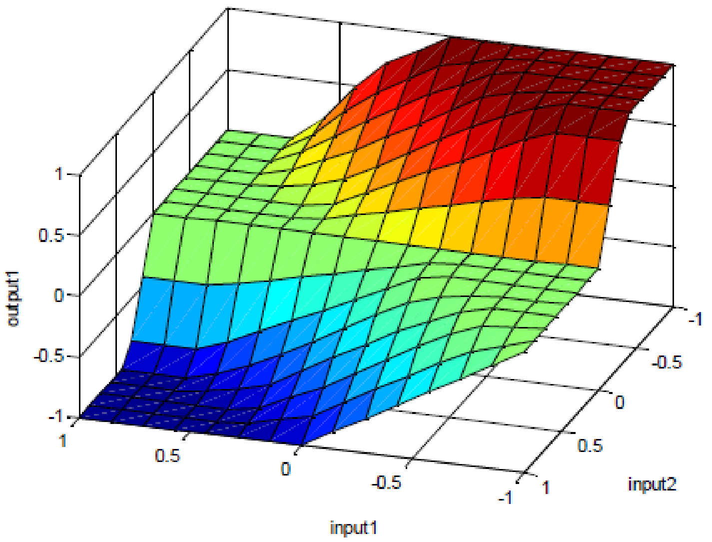

Fig8. Fuzzy surface from the designed FIS

4. Discussion and Results

In this section, the performance of the designed FSMC system will be investigated through simulation. Performance of the FSMC system is presented by comparing this system by real driver and first and second order sliding mode control system. In order to assess performance of proposed FSMC system, real traffic dataset is used. So FSMC system is simulated with real car following data and then the results are discussed.

In order to evaluate the performance of designed control system, a FV vehicle data has been randomly selected from dataset. The required information for the FV and its LV is extracted.

The sampling time for the simulation and car following control was set to 0.1 second. As Previously mentioned, the main objective of the controller is to maintain the longitudinal distance between FV and LV in a safe region and produce minimum lateral motion. These aims can be reached by generating proper composite torque and steering angle. Hence in this paper, Pipes rule [17, 18] has been used for safe distance determination between two vehicles:

$$S = L(1+\frac{V_{FV}}{4.47}) \tag{27}$$

Where L and V_{FV} refer to length and velocity of FV respectively.

For the simulation of the randomly chosen test vehicle, the necessary data for this vehicle and its preceding vehicle (LV) was extracted from the dataset. Variable values such as: longitudinal and lateral acceleration, longitudinal and lateral velocity and also longitudinal and lateral position of the vehicles are extracted from the real car following dataset.

First, for investigating of control system performance, the comparison is done among the outputs of the 1th and 2th SMC and also FSMC systems and real driver for composite torque and steering angle values. Fig. 9 shows the results of comparison As it can be seen from the Fig. 9, the 1th SMC range of the steering angle is out of the real values range and values of the composite torque aren't smooth in the whole path that; a disturbance occurs in proximity of t=40 Sec and t=340 Sec. Also, as it is shown in Fig. 9 (c) and (d), the 2th SMC behavior isn’t similar to the real driver at all. Besides, because of extreme change rates of these values, the 2th SMC can't provide comfort for passengers and driver.

The other hand, values range of controlled steering angle and composite torque from FSMC are close to the values range of the real data. In addition, change rates of these values are much less than the change rates of the real data. Fewer variations in the same period of time assure steadier motion and the comfort of the passengers. These factors result in lower consumption of energy and steadier travel of the vehicle which also guarantee the comfort of passengers. Furthermore FSMC is the more suitable than 1th and 2th SMC.

Furthermore, one of the outputs of the FSMC system is velocity, Fig. 10 shows the velocity comparison between real driver and designed control system performance.

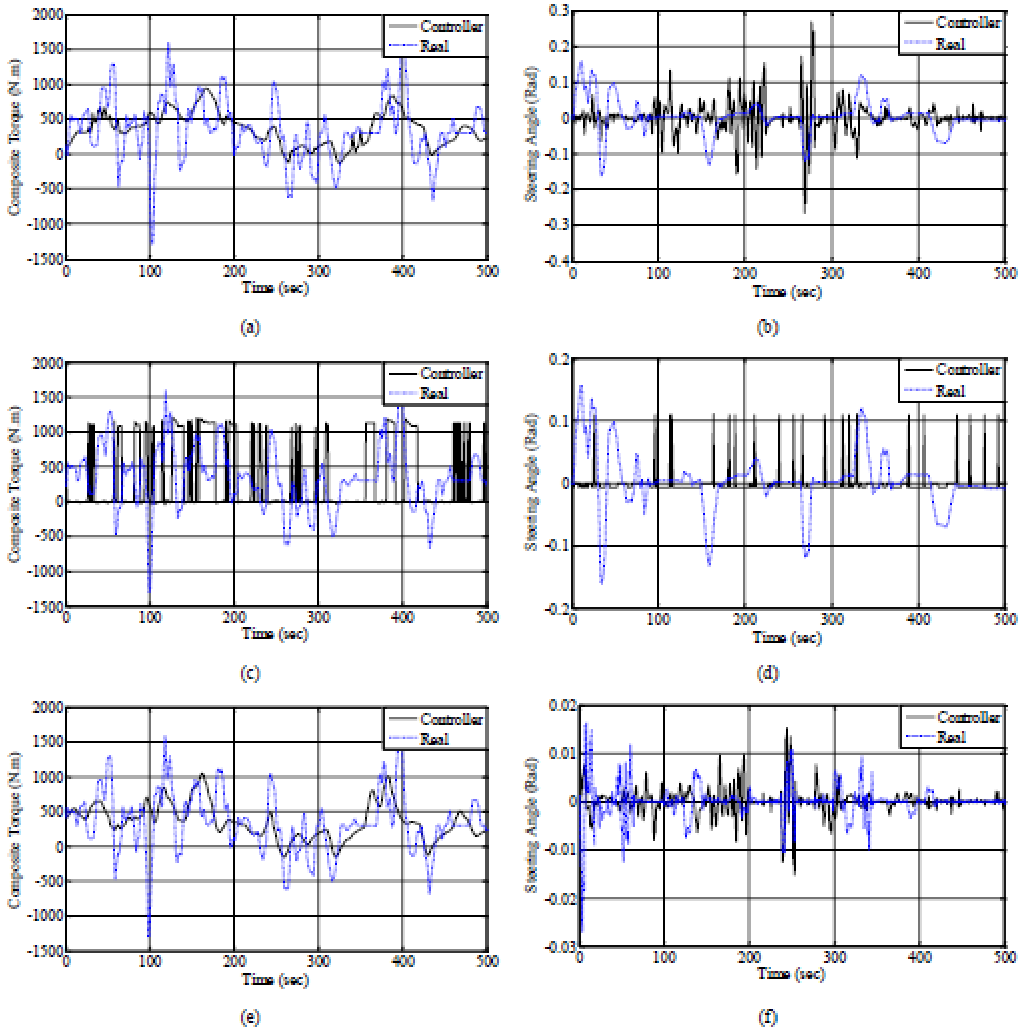

Fig9. Comparison between control system and real driver: (a) composite torque and (b) steering angle for 1th SMC; (c) composite torque and (d) steering angle for 2th SMC; (e) composite torque and (f) steering angle for FSMC.

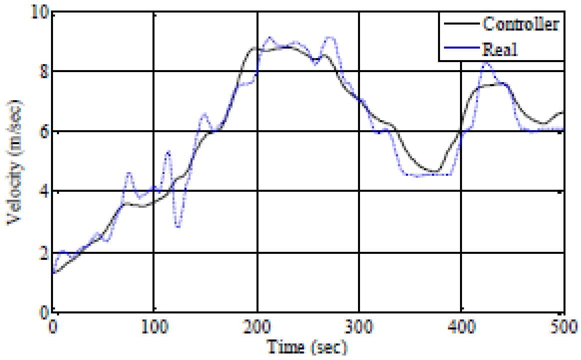

Fig10. Comparison between the velocity of the FSMC and FV's real behavior

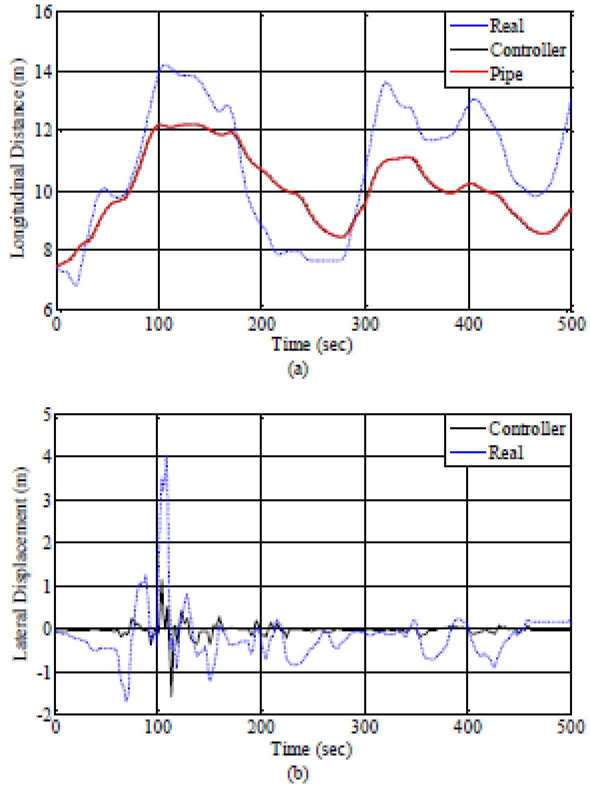

Fig11. Comparison between the results of FSMC and FV's real behavior: (a) longitudinal distance, (b) lateral displacement

The result of comparison from Fig. 10 shows that the velocity variation of FSMC is smoother than real driver. Smoother velocity variation leads to steadier motion that provides comfort for passengers and also lower consumption of energy.

Finally, performance evaluation of the control system regarding the longitudinal and lateral motions is done through simulation. The control system must be able to maintain a safe longitudinal distance with LV and also to produce less lateral displacement. Fig. 11 shows the simulation comparisons between real driver and FSMC.

As it can be seen from Fig. 11 (a), when the real driver kept a very long unnecessary distance with its LV, the FSMC system has been following the Pipes safe distance accurately and kept a sufficient distance and avoided the unnecessary gap. It also confirms that the FSMC system decreases the length of the platoon of vehicles in the traffic flow. Besides, when the real driver kept a short distance with its LV, the FSMC system also has been following safe distance too.

According to the Fig. 11 (b), controlled lateral deviation between FV and LV is much less than the real driver values. So the goal of the lateral motion control is reached and the FV shows less fluctuation in the lateral movements of car following maneuvers and thus provides comfort for passengers.

In addition, error criteria (10-12) are used to calculate controller and driver errors at maintaining safe distance. The results of these errors are shown in the Table IV and Table V.

As it can be seen from Table IV and Table V, unlike the driver, controller has low error values of maintaining a safe distance with its LV. Results show that the designed controller has a strong capability of maintaining a safe distance.

5. Conclusion

In this paper, control of longitudinal and lateral motion of vehicles in car following maneuver is achieved through designing a FSMC system. The objective design of control system is to produce desirable values for vehicle inputs that are composite torque and steering angle. The controller tries to control the composite torque in a way to keep the relative longitudinal distance at a safe region. Also by controlling the steering angle of the FV, the relative lateral displacement is minimized. The important aspect of this type of control system is the combination of sliding mode features such as robustness and fuzzy reasoning advantage. Moreover, for designing of FSMC, a nonlinear vehicle dynamics model of vehicle with three degrees of freedom is employed. To investigate the performance of the designed control system, the result of the designed FSMC system is compared with the behavior of real drivers, 1th and 2th SMC. The simulation results show that the performance of the FSMC is much better than the 1th and 2th SMC and also it doesn't have the chattering problem of SMC. In addition, FSMC system maintains a safe distance with its LV and has a behavior much safer than that of the real driver. Fewer variations of composite torque, velocity and steering angle in the same period of time assure the comfort of vehicle and provide a pleasant trip for passengers. Also, the FSMC performance leads to lower consumption of energy and steadier travel of the vehicle. In addition, by keeping the FV in a proper distance with its LV, the FSMC system decreases the length of the platoon of vehicles in the traffic flow.

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Table3. Results of Error in keeping the safe distance for real driver

Criteria	Test 1	Test 2	Test 3	Mean
MAPE	18.1582	7.1851	3.4946	9.6126
RMSE	2.6489	0.2277	0.2681	1.0482
SDE	313.4366	125.2256	49.7281	162.7968

Table V. Results of Error in keeping the safe distance for controller

Criteria	Test 1	Test 2	Test 3	Mean
MAPE	0.2846	0.2177	0.1375	0.2133
RMSE	0.0012	0.0005	0.0041	0.0019
SDE	0.6381	0.0230	0.6317	0.4309

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Nomenclature

v_x, v_y	Longitudinal and lateral vehicle velocity
T_c	Equivalent drive and brake torque
T_{rr}	Rolling resistance
C_x, C_y	Longitudinal / lateral aerodynamic drag coefficients
M	Vehicle mass
I_{eff}, I_z	Effective longitudinal inertia / inertia moment about the yaw axis through the vehicle center of gravity
l_f, l_r	Distance of the front and rear tires from center of gravity of vehicle
c_f, c_r	Cornering stiffness of the front and rear tires
δ_f	Steering angle