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RESEARCH ARTICLE

Vehicle Following Control via V2V SIMO Communications Using MBD Approach

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ABSTRACT Autonomous vehicle systems have been significantly increasing in design complexity, including precise control, reliable communications, and data security. This paper presents a Model-Based Design (MBD) framework on MATLAB/Simulink to integrate the vehicle model, Vehicle-to-Vehicle (V2V) communication model, and autonomous driving scenario model. A vehicle-following control model is demonstrated to maneuver a follower vehicle using locations and velocities of the leader vehicle sent via V2V. The vehicle model consists of Time to Collision (TTC), velocity decision control, path-following control, and vehicle dynamics. The follower vehicle decision is modeled by MathWorks Stateflow considering the important factors including velocities, positions, lanes, obstacles, and buildings that effect V2V communication efficiency. Simulink Design Verifier which is a formal verification tool was then used to verify the TTC, velocity decision, and path following control. The test coverage analysis and test harness were repeated to generate test patterns with 100% coverage results. The experiments were done under the following communications and environmental conditions: single-input-single-output (SISO) without buildings, SISO with buildings, and single-input-multiple-output (SIMO) with buildings. The resulting communication packet delivery ratios were 100%, 95.32%, and 99.91%, respectively. This reveals that the proposed method can effectively model the vehicle following control and autonomous driving scenario including the effects of V2V communications efficiencies.

INDEX TERMS Model-based design (MBD), vehicle following control, V2V communications, SISO, SIMO, formal verification.

I. INTRODUCTION

Autonomous vehicles are developing quickly to improve safety and decrease traffic accidents. An autonomous vehicle analyzes its environment and makes decisions using data from sensors like Light Detection and Ranging (LiDAR), cameras, or radar, as well as information from other vehicles via V2V communications. The design and verification of such autonomous vehicles under various driving scenarios are extremely complicated. Model-Based Design (MBD) is a systematic approach that allows full development flow in a single environment, including modeling, test scenarios, and test coverage analysis.

Autonomous vehicles can be classified into five levels: Level 0 - No Automation, Level 1 - Driver Assistance, Level 2 - Partial Automation, Level 3 - Conditional Automation, Level 4 - High Automation, and Level 5 - Full Automation. The Adaptive Cruise Control (ACC) system has been widely studied. The ACC system gets the data from multi-sensors such as LiDAR, optical sensors (cameras), and radar. This information will be used to calculate Time to Collision (TTC) to control vehicle velocity and maintain distance between vehicles. A personalized ACC system based on driving style recognition and model predictive

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control (MPC) successfully met different driving style requirements and guaranteed various performances from real vehicle experiments [1]. A study of adaptive cruise control's design guaranteed a safe distance between vehicles and prevented collisions [2], [3], [4]. The combined use of MPC and neural networks has been employed to analyze the actions of the driver operating the leading vehicle, with the objective of mitigating the adverse effects on the trailing vehicle [5], [6], [7], [8]. MATLAB/Simulink, Carsim, and PreScan have been contributing to enhancing the performance of the ACC system by modeling vehicles and generating traffic situations. In ACC system, TTC can be obtained from the velocity and distance between vehicles, which are sensed by the follower vehicle. However, such TTC values are not good enough for collision avoidance in the case of a leader vehicle's sudden brakes or lane change and without vehicle communication.

The Co-operative Adaptive Cruise Control (CACC) system was developed from the ACC system by employing vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communications to improve the accuracy of analyzing the distance between vehicles and surrounding objects. The IEEE 802.11p standard is a short-wave communications standard that is extensively employed for vehicle-to-vehicle communication in CACC systems. Many research investigations [9], [10], [11], [12] have focused on vehicle-to-vehicle communications to enhance the safety and performance of autonomous vehicle systems. In addition, MPC with the SA-PSO algorithm, which was proposed for the CACC system, effectively resolved the non-linearity issue, resulting in improved distance between vehicles [13]. The development of the CACC system involved conducting tests on an actual car in order to examine the system's performance and assess its effectiveness through an analysis of the frequency domain. These tests demonstrated that the wireless data given facilitates a decrease in the inter-vehicle distance [14].

The Scene Suite and Simulation of Urban Mobility (SUMO) simulation platforms were used to examine the impact on road safety of different penetration rates of V2V communication and ACC. The results show that the combination of V2V communication and ADAS-ACC can increase road safety at high penetration rates [15], [16], [17]. This demonstrated that the ACC system must be integrated with V2V communications to be able to increase safety. A research project improved the efficiency of high-density truck platooning by utilizing two types of vehicle-to-vehicle communication technologies: IEEE 802.11p and 3GPP. The decreased fuel consumption and higher traffic efficiency were proved [18], [19]. Developments in car-following model design using the VISSIM simulation software illustrated that the software can be used to effectively observe and investigate driving behavior for autonomous vehicles and connected autonomous vehicles (CAV) [20], [21], [22], [23]. The development of an automated vehicle overtaking system that utilizes vehicle-to-vehicle communications and incorporates overtaking safe-distance model parameters was proposed [24]. The system design is based on the integration of fuzzy theory and PreScan/MATLAB software. The obtained outcomes demonstrate that the algorithm described in such a study is both practical and efficient, thereby reducing the risk of overtaking. The achieved results show that the proposed algorithm is practical and efficient, which decreases the risk of overtaking. CarSim simulation and adaptive neuro-fuzzy predictor-based control (ANFPC) were used to examine the impact of CACC on traffic flow [25]. The results demonstrate that fuel consumption can be decreased while still maintaining driving safety and comfort.

The above literature reviews show increasingly complex design requirements for autonomous vehicle systems, including precise control, communications, and data security. Therefore, the vehicle following control via V2V communications is developed in this paper, where the novelty and contributions of our study are as follows:

- An MBD framework is proposed to integrate the vehicle model, V2V communication model, and autonomous driving scenario model.
- Vehicle following control via SISO and SIMO V2V communications in urban environments for autonomous vehicles is illustrated.
- Test scenarios are created in the MATLAB/Automated Driving Toolbox module.
- Formal verification is first introduced to generate test cases and analyze the test coverage of the proposed framework.

The structure of this paper is organized as follows: Section II describes the background including CACC and vehicle communication. Section III provides the vehicle following model. Results and discussion are in Section IV. Finally, the conclusion is in Section V.

II. BACKGROUND

The background includes a CACC system, which is developed from the traditional ACC system and vehicle communications.

A. CACC

The traditional ACC was developed to aid in regulating the speed of vehicles to increase the efficiency of road traffic, reduce the rate of accidents, and reduce the energy usage of vehicles. The traditional ACC system and its components are shown in Fig. 1.

According to Fig. 1, the follower vehicle on the left side will use data from the radar sensors and the camera sensors to calculate the velocity and the distance between the two vehicles. This data will be used as inputs for the collision detection system, where outputs are warning display and Autonomous Emergency Braking (AEB). The vehicle communication technologies were also applied to improve

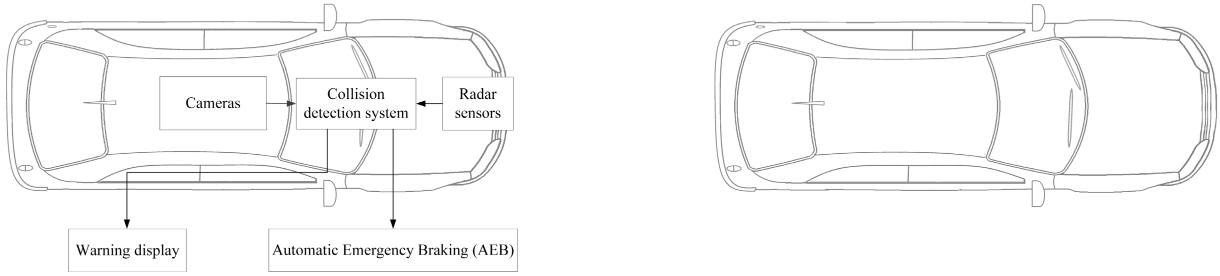


FIGURE 1. Traditional ACC system.

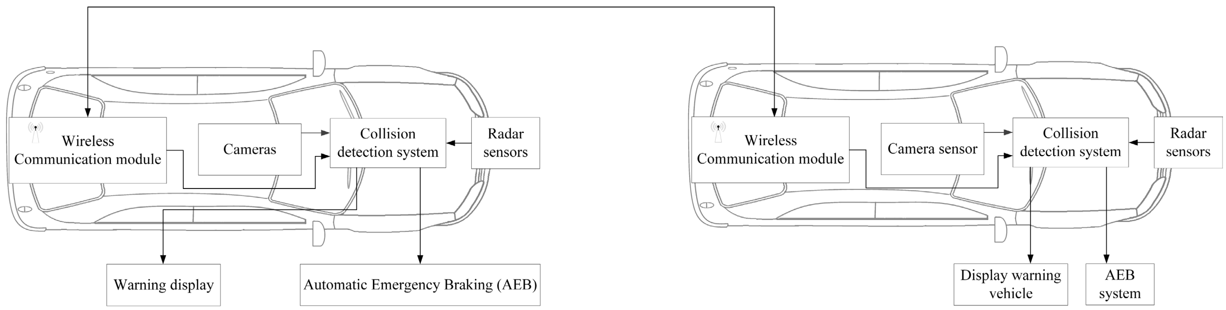


FIGURE 2. CACC System.

the ACC system's reliability, resulting in a more flexible and efficient system. Fig. 2 then shows the CACC, where in this system, the follower vehicle uses information from the leader vehicle to make decisions.

B. VEHICLE COMMUNICATION

1) SINGLE INPUT SINGLE OUTPUT (SISO) COMMUNICATION

The SISO communication is a prevalent format for wireless communication systems because of its simplicity as shown in Fig. 3. The SISO system composes of one transmitter (T_{X_0}) and one receiver (R_{X_0}).

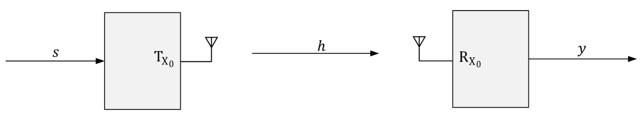


FIGURE 3. SISO communication techniques.

The output signal from the SISO communication system can be determined by (1).

$$y = hs + n \tag{1}$$

Here, y is the output signal, s is the input signal, h is the channel, and n is the noise of the communication system.

2) SINGLE INPUT MULTIPLE OUTPUT (SIMO) COMMUNICATION

It was found that multipath fading makes the radio signal quality of SISO communication technology worse in certain environments, like those with tall buildings, trees, bridges, and other obstacles. This means that related important parameters of the autonomous vehicles cannot be calculated correctly. A more reliable communication method, namely SIMO, has been applied instead. The SIMO communication consists of a transmitter with one antenna and a receiver with more than one antenna. The SIMO communication system shown in Fig. 4 contains a receiver with two antennas. We can determine the output Y by using (2).

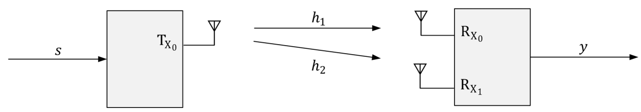


FIGURE 4. SIMO communication technique.

$$Y = Hs + N \tag{2}$$

Here, s is the input signal, H refers to channels, and N is the noise of all communication channels. In this work, the leader vehicle is the transmitter with one antenna, while the follower vehicle is the receiver with two antennas. The redundant antenna increases the receive diversity, wherein the same data is received across separate fading channels in order to mitigate the effects of fading.

3) IEEE 802.11P

IEEE 802.11p is a modification to the IEEE 802.11a specification that allows for wireless communication in vehicular environments. To analyze vehicle communications,

TABLE 1. Parameters of the IEEE 802.11p and the IEEE 802.11a.

Parameters	802.11a	802.11p	Change
Bit rate ($Mbit/s$)	6,9,12,18,24, 36,48,54	3,4.5,6,9,12, 18,24,27	Half
Modulation Mode	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM	No changes
Code rate	$1/2, 2/3, 3/4$	$1/2, 2/3, 3/4$	No changes
Number of sub-carriers	52	52	No changes
Symbol duration (μs)	4	8	Double
Guard time (μs)	0.8	1.6	Double
Preamble duration (μs)	16	32	Double
Sub-carrier spacing (MHz)	0.31250	0.15625	Half

the most important parameters are listed in Table 1, where the comparison between the IEEE 802.11a and IEEE 802.11p is also given [29], [30].

C. SUMMARY OF EXISTING OF CACC SYSTEMS

We note that since it was found that the CACC system reduces road accidents more when compared to the ACC system, the advantages and disadvantages related to this issue were also provided in Table 2.

III. VEHICLE FOLLOWING MODEL

This section presents a MBD approach to modeling vehicle-following, which is one of the major functions of the CACC system. The vehicle-following system controls the driving maneuvers of a leader vehicle and a follower vehicle in autonomous mode. Both vehicles use vehicle-to-vehicle communications to exchange status information such as positions and speeds. The important factors to consider for vehicles are Vehicle-to-Vehicle (V2V) communications, velocity, position, lane, building, and obtracle. Therefore, the proposed vehicle model includes Time-to-Collision (TTC), velocity decision control, path-following control, and vehicle dynamics. Then, an autonomous driving scenario is modeled to form the vehicle-following model in various V2V communications and environmental conditions.

A. VEHICLE MODEL

Fig. 5 presents the vehicle-following model based on MBD, including leader and follower vehicles. The position and velocity data of the leader and follower vehicles can be exchanged via V2V communications based on the IEEE 802.11p standard. The basic message format of the V2V communications consists of a Medium Access Control (MAC) header, an IP header, a User Datagram Protocol (UDP) sequence, a message type, and data, respectively. We employ two V2V communication techniques, SISO and SIMO, to assess communication performance and reliability. Using the MBD method, the TTC calculation, velocity decision control, path following control, and vehicle dynamics for the follower vehicle are designed and implemented in MATLAB/Simulink. They are also described below.

1) AUTONOMOUS EMERGENCY BRAKING CONTROL USING *TTC*

The *TTC* is the ratio of the distance and velocity between vehicles, it is essential for vehicle collision detection systems. To obtain the safe braking distance of the follower vehicle (F), the positions and the velocities of both vehicles are evaluated in real-time via V2V communications, as shown in Fig. 6. To avoid a collision, when the driver of the leader vehicle (L) applies the brakes, the follower vehicle will keep the velocity of $V_f(t)$ related to the velocity of the leader vehicle $V_l(t)$ and the distance between vehicles $d_s(t)$ in the accept condition calculated from *TTC* in (3). The positions $(x_l(t), y_l(t))$, and $(x_f(t), y_f(t))$ are used to calculate $d_s(t)$, the stopping distance d_f, and the distance of the leader vehicle traveled from the previous point d_l. Latitudes and longitudes from the GPS module are transformed to x and y values based on the tangential plane. For example, $V_l(t_1)$ and $V_l(t_2)$ are the initial and final velocities of L after hitting the break, $V_f(t_1)$ and $V_f(t_2)$ are the initial velocities and final velocity of F.

$$TTC(t) = \frac{d_s(t)}{V_f(t) - V_l(t)} \quad (3)$$

2) VELOCITY DECISION CONTROL

Velocity decision control is used to either increase velocity or decrease velocity for safe overtaking. Velocity decision control proposed in our system is explained in two different cases, including overtaking decisions and look ahead decisions, respectively.

Case 1: Overtaking decision

In this work, two lanes and a lane's width have been used to demonstrate overtaking decision conditions. However, in our model, they can be flexibly varied depending on real-world scenarios. Therefore, n of lanes with different lengths can be assigned in the model, as demonstrated in Fig. 7. The follower vehicle has to provide safety criteria for deciding whether to brake, move, pass, or stop. The TTC and positions of both vehicles are the primary variables used as a decision-making criterion.

As illustrated in Fig. 7, both vehicles were assigned to run in the first lane, with the follower vehicle having a higher speed than the leader vehicle. When the follower vehicle detects the vehicle in front, it will automatically reduce its speed and keep the distance between the two vehicles within a safe distance. After the leader vehicle has changed position to the center on the second lane (P_l) as defined in (4), the follower vehicle increases speed and passes it (*Overtaking*).

From (4), P_l is the position of the leader vehicle in the center of the second lane, y_0 and y_1 are the y-axis road position, and we can find the width of the road from $(y_1 - y_0)$. From this solution, the follower vehicle will only overtake

TABLE 2. Summary of the literature review.

Reference	Technique	Pros	Cons
[1]	- ACC - MPC	MPC was used to meet the requirements of ride comfort and safety.	Not include communication techniques
[2-4]	- ACC - Simulation	Basic techniques for vehicle following control.	Not include communication techniques
[5-8]	- ACC - MPC - Neural network - Simulation	MPC and neural network approaches could analyze driver behavior while ensuring vehicle following.	Not include communication techniques
[9-12]	- CACC - Simulation	Communication approaches were used to reduce collisions on the road.	Only use the SISO technique for V2V
[13]	- CACC - SA-PSO - MPC	Improved distance between vehicles.	Only use the SISO technique for V2V
[14]	- CACC - Real testing	Test communication between vehicles on real roads.	Only use the SISO technique for V2V
[15-17]	- CACC - SUMO software test	SUMO software could examine the impact on road safety.	Only use the SISO technique for V2V
[18,19]	- CACC - IEEE 802.11p - 3GPP	Improved efficiency of high-density truck platooning.	Only use the SISO technique for V2V
[20-23]	- CACC - VISSIM	VISSIM simulation software could observe and investigate driving behavior.	Only use the SISO technique for V2V
[24]	- CACC - Fuzzy	Fuzzy theory could reduce the risk of overtaking.	Only use the SISO technique for V2V
[25]	- CACC - CarSim - ANFPC	CarSim simulation software and ANFPC could decrease fuel consumption.	Only use the SISO technique for V2V
This work	- CACC - IEEE 802.11p - Multiple antenna - Formal verification - MBD	MBD with SISO and SIMO can model vehicle communications in urban environments. Formal verification can enhance the test coverage of the framework.	Simulate communication between two vehicles

when the vehicle in front moves to the center of the second lane.

In Fig. 8, when the leader vehicle has successfully changed lanes, the follower vehicle can increase its speed to pass the leader vehicle. In this case, the follower vehicle will constantly monitor the location of the leader vehicle. The solution to making such a decision is shown in (4) with the condition of acceptable g, where g is a safe gap between vehicles. We note that in our experiment the vehicle width is not over 2 meters. From (4), overtaking with the condition, if P_l is higher than or equal to $(3/4)(y_1 - y_0) - (Car_{width}/2)$, this indicates that the leader vehicle is in Lane 2 and the follower vehicle can then overtake.

$$Decision = \begin{cases} Overtaking, & \text{if } P_l \geq \dfrac{3}{4}(y_1 - y_0) \\ Overtaking\ with\ condition, & \text{if } P_l \geq \dfrac{3}{4}(y_1 - y_0) - \dfrac{(Car_{width})}{2}\ and\ acceptable\ g \end{cases} \tag{4}$$

Case 2: Lookahead decision

During overtaking, it is possible that the leader vehicle may suddenly change back to Lane 1, which could have caused the accident. To avoid these accidents, a solution for making passing choices that include continually checking the location of the leader vehicle has been proposed.

$$Decision = \begin{cases} Overtaking, & \text{if } P_l - \dfrac{(Car_{width})}{2} - \dfrac{1}{2}(y_1 - y_0) > 0 \\ Slow\ down, & \text{if } P_l - \dfrac{(Car_{width})}{2} - \dfrac{1}{2}(y_1 - y_0) \leq 0 \end{cases} \tag{5}$$

Fig. 9, shown look ahead choice is one of the situations during overtaking in order to forecast the movement of the leader vehicle by continuously observing its behavior. From (5), the follower vehicle takes into account the position of the center of the road, the middle of the lane, and the width of the vehicle. The results can be made into two decisions: 1) if the leader vehicle has passed the road's center line $P_l - (Car_{width})/2 - ((y_1 - y_0)/2) > 0$, the follower vehicle can overtaking, and 2) if there is a trend for the follower vehicle to change back to Lane 1, $P_l - (Car_{width})/2 - ((y_1 - y_0)/2) \leq 0$, the follower vehicle will slow down and keep distance.

3) PATH FOLLOWING CONTROL

The Path Following Control (PFC) system helps to keep the car under control while it travels down straight and curvy

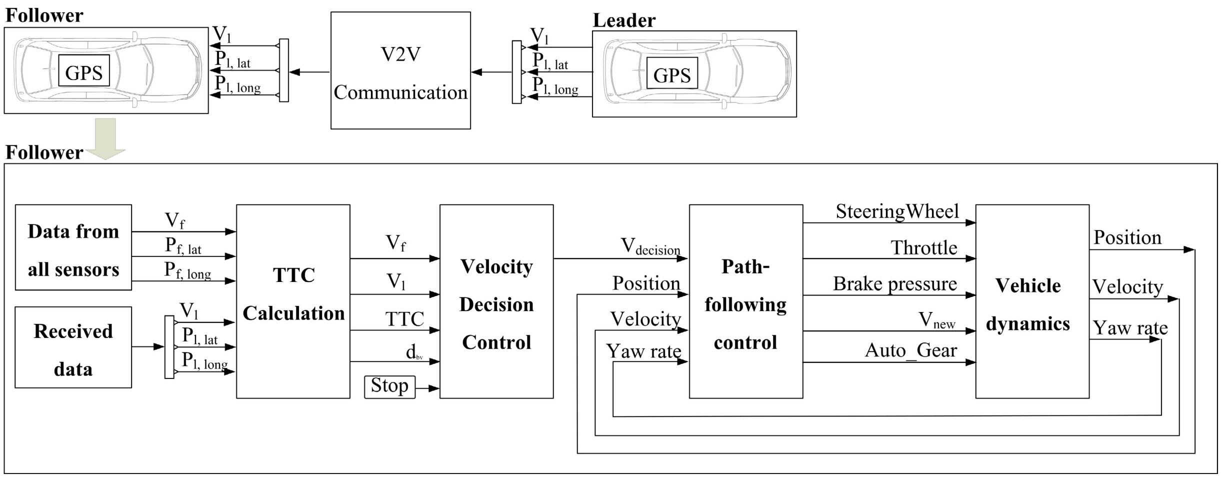


FIGURE 5. Vehicle following model based on MBD.

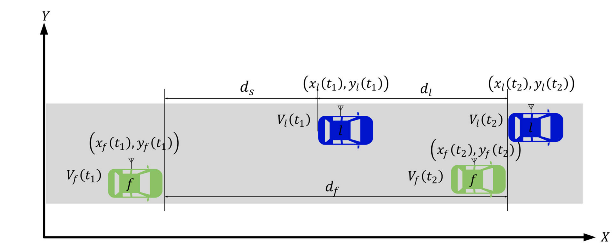


FIGURE 6. Illustration of vehicle movements on a straight road.

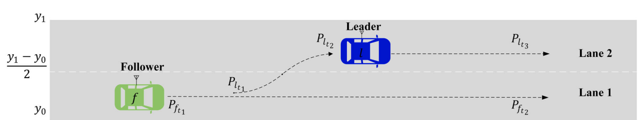


FIGURE 7. Complete lane change of the leader vehicle and follower vehicle overtaking.

highways. PFC has control over the leader vehicle's velocity and distance. This block includes ACC with stop-and-go and lane-keeping assist systems. In Fig. 5, the input of the path follower includes desire velocity, position, velocity, and yaw rate. The output of the path following control includes the steering wheel, throttle, brake pressure, new velocity, and gear status, which are used to control the direction and velocity of the P_f.

4) VEHICLE DYNAMICS

The vehicle dynamics include engine, transmission, chassis, and shift logic. The input parameters for vehicle dynamics include steering wheel angle, percentage of maximum throttle, brake pressure, and initial velocity. In this work, we made a model of a vehicle based on the kinematic bicycle model, which is the basic model for controlling vehicles shown in Fig. 10, where ℓ_r and ℓ_f are the longitudinal distances from the vehicle's center of gravity to the front

FIGURE 8. Overtaking with the condition.

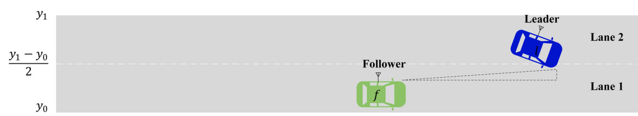


FIGURE 9. A decision to overtake leader vehicle.

and rear of the vehicle, respectively, The motion equation in Fig. 10 can be expressed as (6) and (7), where δ_r, δ_f, and V are the angle of the rear, front wheels, and velocity respectively. The slip angle β can be solved by (8). The angle ψ is the heading angle of the vehicle, which can be solved by (9).

$$\dot{X} = V\cos(\psi + \beta) \tag{6}$$

$$\dot{Y} = V\sin(\psi + \beta) \tag{7}$$

$$\beta = \tan^{-1}\left(\frac{\ell_r}{(\ell_f + \ell_r)}\tan(\delta_f)\right) \tag{8}$$

$$\dot{\psi} = \frac{V}{\ell_r}\sin(\beta) \tag{9}$$

When the vehicle changes direction, the vehicle dynamic model is updated to generate new location, velocity, and yaw rate values, which are all returned to the path follower as inputs.

B. DRIVING SCENARIO MODEL CONSIDERING COMMUNICATION EFFICIENCY

A vehicle capable of autonomous driving can go forward, change lanes, and avoid collisions without human intervention. Autonomous driving systems are combinations of TTC, velocity decision control, path following control, vehicle

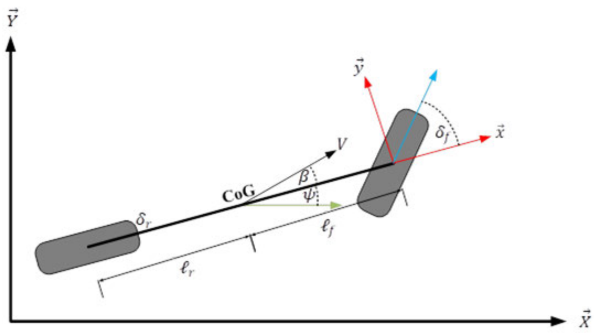


FIGURE 10. Kinematic bicycle model [31].

dynamics, data from all sensors, and received data from the other vehicle via V2V communication. The autonomous driving scenario model is a simulation of driving on the road.

In this section, we will provide an example of a test case involving two cars following one another on a two-lane road with a lane width of four meters. V2V communication occurs when two cars are within a specific distance of one another to exchange information about their velocity and position. To verify vehicle communication efficiency and overtaking decisions, the vehicle in front will be assigned to change lanes from Lane 1 to Lane 2. After that, the leader vehicle immediately changes lanes back to lane one under the following communication and environmental conditions: 1. SISO and no buildings 2. SISO and buildings 3. SIMO and buildings.

Although the safety model and vehicle-to-vehicle communication have vastly improved, if there are buildings nearby, vehicle-to-vehicle communication will be affected and the signal received will be significantly decreased [26]. The experiment simulated two cars traveling down a straight road and exchanging information via V2V communications. When the leader vehicle changes lanes, the follower vehicle maintains a safe distance between vehicles based on TTC. We have three experimental scenarios shown in Figs. 11-13.

Scenario I: The vehicles communicate their intended turning directions using V2V messages. This scenario is characterized by an obstructing building between the two vehicles on a collision course, without any large surfaces available for reflections from the transmitter vehicle to the receiver vehicle as shown in Fig. 11. Thus, the line-of-sight (LOS) conditions are not optimal which will affect the message delivery rates.

Scenario II: The communication and directions of vehicles are the same as in scenario I. This scenario includes building environments, in which the V2V communication packet delivery rates are based on channel measurements collected with the HHI channel sounder [27], [28].

Scenario III: In this scenario, the V2V communication paradigm is changed from SISO to SIMO, but the direction and speed of the vehicle remain similar to those in scenario I and scenario II.

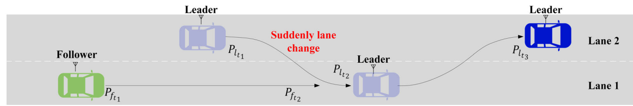


FIGURE 11. Scenario I, the vehicle-following scenario based on SISO and no building.

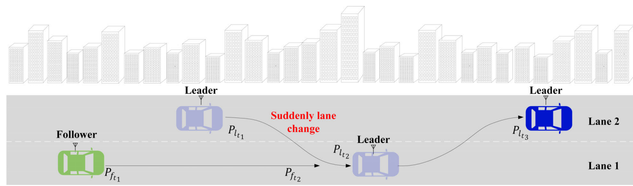


FIGURE 12. Scenario II, the vehicle-following scenario based on SISO and building.

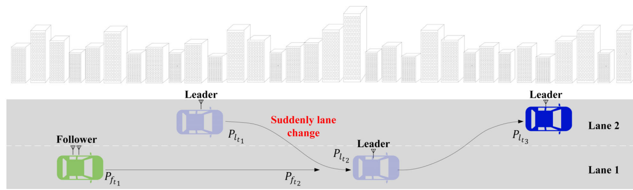


FIGURE 13. Scenario III, the vehicle-following scenario based on SIMO and building.

The parameter setup used in each scenario is shown in Table 3.

C. FOLLOWER DECISION

To follow the testing procedure in a variety of scenarios, we designed the follower vehicle decision as represented in Fig. 14.

Fig. 14. shows the decision-making design of the following vehicle, which enables the following vehicle to maintain a defined distance, speed control, and overtaking capability automated. Seven input values were used in the above state flow: TTC, LeadVelocity, inVelocity, Yposotion, LeadPo, FollowerPo, and stop. Each input provides the autonomous decision-making of the follower vehicle. In the state flow design, there are four states including.

State Default: When the experiment is initiated, the two vehicles will exchange information using V2V communication. The position and velocity values are utilized to calculate all input, if the criteria are not met, the follower vehicle will operate at the initial speed.

State V1 The state during which the trailing vehicle maintains the same speed as the leading vehicle, applying into consideration all Y-axis position values, the TTC values, and the current position of the two vehicles.

State V2 Where there is a sudden cut-off, and the distance between the vehicles is too small the follower vehicle will slow down as much as possible to avoid a collision.

State V3 In the absence of obstructing vehicles in the same lane, the follower vehicle increases its speed to inVelocity.

TABLE 3. The parameters and environmental setup.

Scenario	V2V communication	Velocity (km/hr)		Building environments
		Leader vehicle	Follower vehicle	
Scenario I	SISO	21	58	NO buildings
Scenario II	SISO	21	58	High building environments
Scenario III	MISO	21	58	High building environments

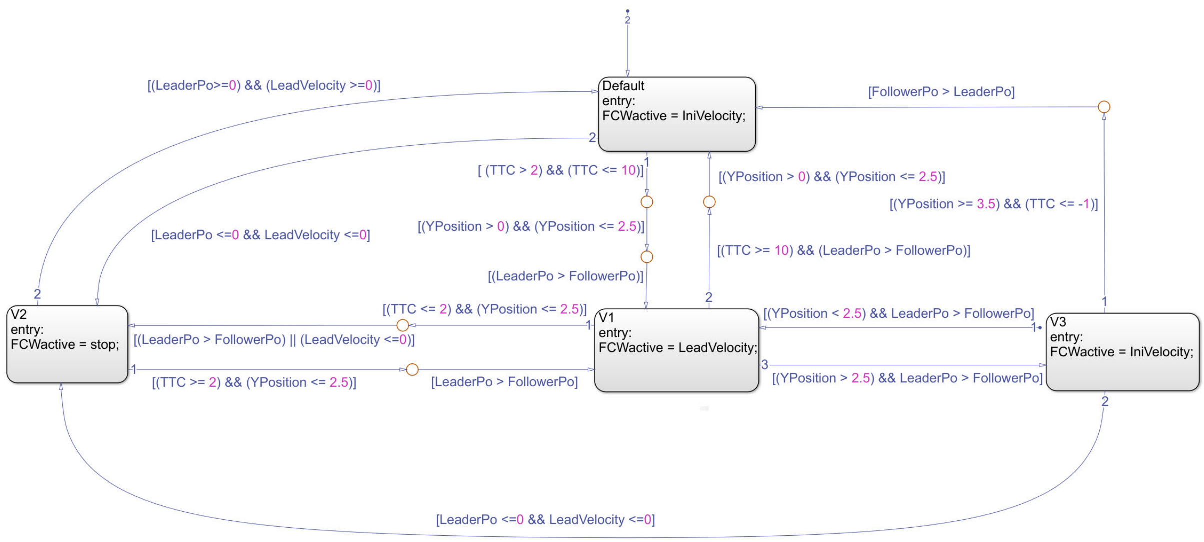


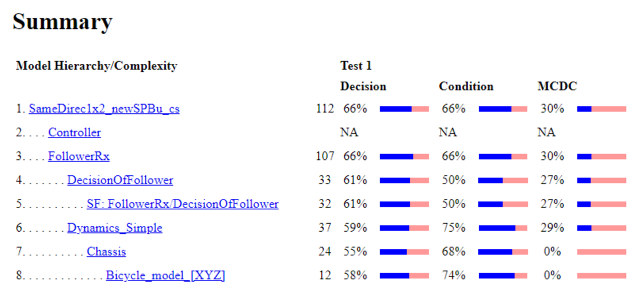
FIGURE 14. Follower vehicle decision.

IV. RESULTS AND DISCUSSION

When constructing a CACC system, it is challenging to evaluate system performance on real-world field experiments. Difficulty in building a real-world field test system, high investment in the construction of the test track, and waste of time setting up equipment for testing are the main obstacles to the development of the CACC system. Consequently, simulation-based verification has the potential to reduce the evaluation cost of the CACC systems. In this work, MATLAB and Simulink were used to implement the simulation system. The impact on communications within the CACC system will be analyzed by utilizing various contexts, as shown in Table 3. Here, the formal verification method was applied to generate test cases and analyze simulation coverage metrics. The communication efficiency between vehicles was investigated in terms of the reduction of the inability to receive signals in certain ranges, resulting in an error in the decision-making of the following vehicle.

A. SYSTEM VERIFICATION

Formal verification is used to verify that a system is operating in accordance with its specifications. Simulink Stateflow was used to follower vehicle decision using TTC, velocity decision, and path following control. Then, test vectors were generated by using Simulink Design Verifier^{TM} according to the scenarios and verification objectives that describe desired


Summary

Model Hierarchy/Complexity		Test 1 Decision	Condition	MCDC
1. SameDirec1x2_newSPBu_cs	112	66%	66%	30%
2. . . . Controller		NA	NA	NA
3. . . . FollowerRx	107	66%	66%	30%
4. . . . . . . DecisionOfFollower	33	61%	50%	27%
5. . . . . SF: FollowerRx/DecisionOfFollower	32	61%	50%	27%
6. . . . . . . Dynamics_Simple	37	59%	75%	29%
7. . . . . Chassis	24	55%	68%	0%
8. . . . . Bicycle_model_[XYZ]	12	58%	74%	0%

FIGURE 15. Coverage analysis result by the MC/DC method.

and undesired system behaviors. To increase the reliability of the simulation, a coverage analysis method consisting of Decision coverage, Condition coverage, Execution coverage, and Modified condition/decision coverage (MC/DC) were used to detect design errors.

1) COVERAGE ANALYSIS RESULT

As mentioned in Section III, Velocity Decision Control is crucial to the design of a vehicle-following system, which uses inputs from multiple vehicle components to make decisions. The TTC value is used to the criteria for assigning the new speed to the follower vehicles. After collecting the new speed, it will be sent to the Path Follower and Vehicle

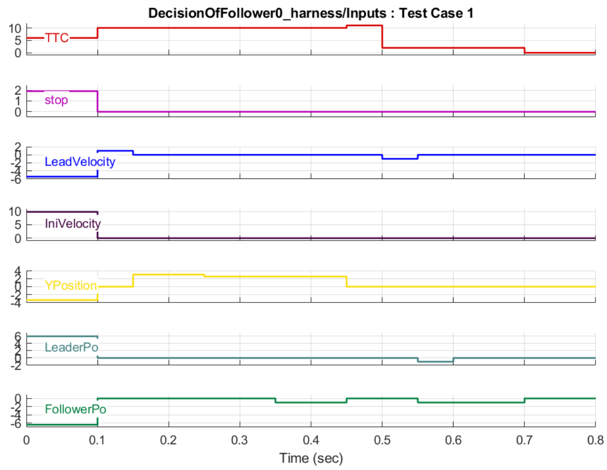


FIGURE 16. Test case 1 for test coverage in DecisionOfFollower model.

Summary

Model Hierarchy/Complexity		Test 1 Decision	Condition	MCDC
1. DecisionOfFollower	34	100%	100%	100%
2. . . . DecisionOfFollower	33	100%	100%	100%
3. . . . . . . SF: DecisionOfFollower	32	100%	100%	100%

FIGURE 17. Coverage analysis result after used generated test case by MATLAB.

dynamic to match the new speed. After applying the MC/DC method to test the function of the following vehicle system, the result is shown in Fig. 15.

The coverage results show that the designed system can evaluate the test integrity of the system at 66 % of the decision, 66 % of the condition, and 30 % of the MC/DC. The Velocity Decision Control section is displayed in the DecisionOfFollower parameters, where the final result of the test has been found to be 61 % of Decision, 50 % of Condition, and 27 % of MC/DC. The results of the coverage analysis show that the system design validation is not sufficiently thorough as it should be. For improved test coverage, we uses the test harness approach to testing in sections of DesisionOfFollow. After that, we will create a test case to test coverage again, the result of the test case is shown in Fig. 16.

Fig. 16 displays the first of eight generated test cases. The Test Case will be sent back to DecisionOfFollower model as an additional input for coverage analysis. The results of the test are shown in Figs. 17- 18.

Fig. 17, shows the coverage results after using a test case to analyze the DecisionOfFollower model, the result shows the coverage effect increased from 61 %, 50 %, and 27 % to 100 %.

Fig. 18, shows the highlights of the analysis results of the DecisionOfFollower model under the MC/DC test.

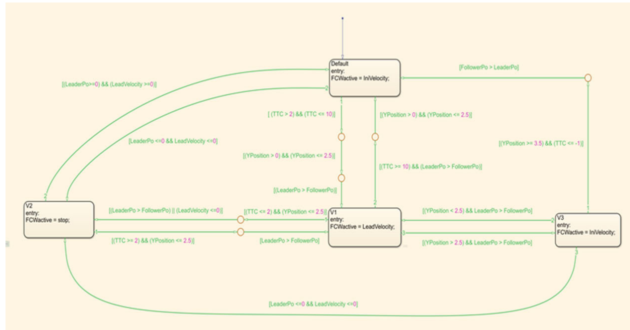


FIGURE 18. Highlight analysis results on the DecisionOfFollower model under MC/DC test.

B. EFFECTS OF ENVIRONMENTS ON COMMUNICATION EFFICIENCY

This section illustrates the effects of wave reflection on vehicle-to-vehicle communication efficiency. The results from an experiment of all scenarios from Table 3 are shown in Figs. 19- 21.

1) SISO WITHOUT BUILDINGS

Scenario I uses a single-input, single-output antenna for each vehicle in an environment without wave reflection from buildings. The speed and position information of the leader vehicle is transmitted to the follower vehicle when it comes within communication range. Such information will be analyzed to obtain the distance between vehicles, collision time, and control speed. Fig. 19 shows the simulation results of the vehicle following model in Scenario I, which uses SISO communications in an environment without buildings. The results were separated into four graphs: vehicle's positions, distance between vehicles, TTC, and vehicle's speeds.

In Fig. 19(a), the blue and red lines represent the speed of the leader and follower vehicles running at a constant speed of 21 km/h and 58 km/h, respectively. From this graph, we can divide it into four periods:

1) Period 0-15 seconds is the period when the follower vehicle approaches the leader vehicle at a speed of 58 km/h.

2) During the period 15 - 42 seconds, the follower vehicle slows down to 21 km/h, the same speed as the leader vehicle, to keep the distance between vehicles at a safe distance for emergency stops. The graph shows that the rear vehicle follows the front vehicle at a constant distance.

3) From 42 - 48 seconds, the leader vehicle changes from Lane 1 to Lane 2. Then, after the vehicle behind checks the current position of the leader vehicle, it will speed up to 58 km/h for overtaking the vehicle in front.

4) Period 48 - 65 seconds is the moment when the vehicle behind successfully overtakes the vehicle in front. From the positions of the two vehicles as shown in Fig. 19(a), the distance between the leader and the follower vehicles is calculated as shown in the yellow line in Fig. 19(b). The distance between the vehicles obtained is used to determine

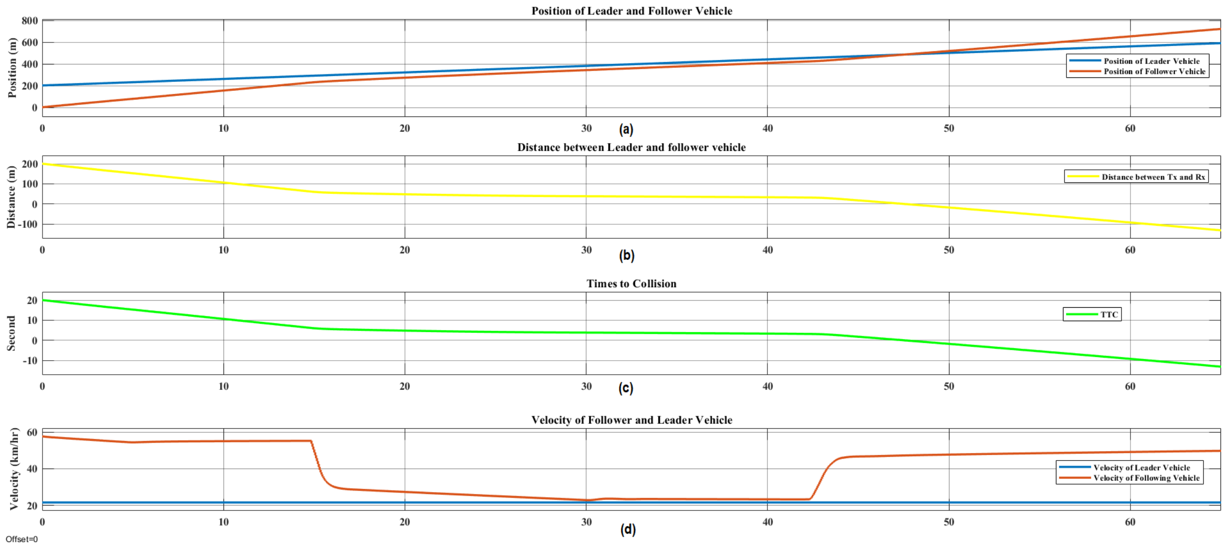


FIGURE 19. **Position, distance, TTC, and velocity of each vehicle under the SISO communication without a high building environments.**

the TTC according to the design process in Section III, as shown in the green line in Fig. 19(c). The TTC is used to control the speed of the follower vehicle and the distance between the vehicles. Fig. 19(d) shows that the follower vehicles can control their speed correctly to prevent collisions. This is because the follower vehicle receives information from the leader correctly in a no-buildings environment.

When both vehicles are within range of each other, the velocity and position of the vehicle in front are sent to the vehicle behind it. Such information will be used to automatically adjust the spacing between vehicles, the time before a crash, and the speed. Fig. 19 represents the simulation results of the vehicle following the model in Scenario I, which uses SISO communications in an environment without buildings. The results were separated into four graphs: each vehicle's position, the distance between vehicles, TTC, and each vehicle's speed. The blue and red lines in the first graph represent the speed of the leader and the follower vehicles running at a constant speed of 21 km/hr and 58 km/hr, respectively.

2) SISO UNDER URBAN ENVIRONMENT

This section relies on simulating the motion of the two vehicles and the SISO antennas as in the experiment in section IV-B1 but changes the environment with high buildings that can generate the wave reflection. The simulated results of vehicles traveling in such an urban environment are shown in Fig. 20 which also shows four graphs. Each graph indicates that there is a range in which vehicles behind cannot receive data from vehicles in front due to reduced communication efficiency in urban environments. In Fig. 20(b), the yellow line indicates that there are periods when the follower vehicle is unable to calculate the distance between the vehicles, resulting in the calculation of the TTC value shown in the green line in Fig. 20(c) being also faulty. As an inaccurate TTC result, the speed control of the vehicle behind is inadequate, as shown by the red line in Fig. 20(d), which indicates a risk of collision between two vehicles.

3) SIMO UNDER URBAN ENVIRONMENT

In this experiment, the same urban situation was used as in Section SISO under an urban environment, but the antenna was changed to SIMO antennas to increase the communication capability of the device. Fig. 21 shows the simulation results obtained from the SIMO V2V communication under an urban environment, resulting in good signal reception from the leader vehicles. Therefore, the distance calculation shown as the yellow line in Fig. 21(b) and the TTC value shown as the green line in Fig. 21(c) were correct. As a result, the follower vehicles can accurately control the speed and distance between the leader vehicles, as shown in the red line in Fig. 21(d).

Obviously, a comparison of the effects of environments on communication efficiency under Scenarios I, II, and III can be done by considering the ability to control the speed and the distance between the vehicles as shown in Fig. 19. SISO communication works well in the no-buildings environment as in Fig. 19(a) and poorly in a simulated high-building environment in a rural area as shown in Fig. 20(b). To mitigate the effects of invalid communication, the SIMO communication technique was applied to V2V communication, as shown in Fig. 21. The vehicle following can be safely done by the SIMO communication, which is robust in rural areas with tall buildings.

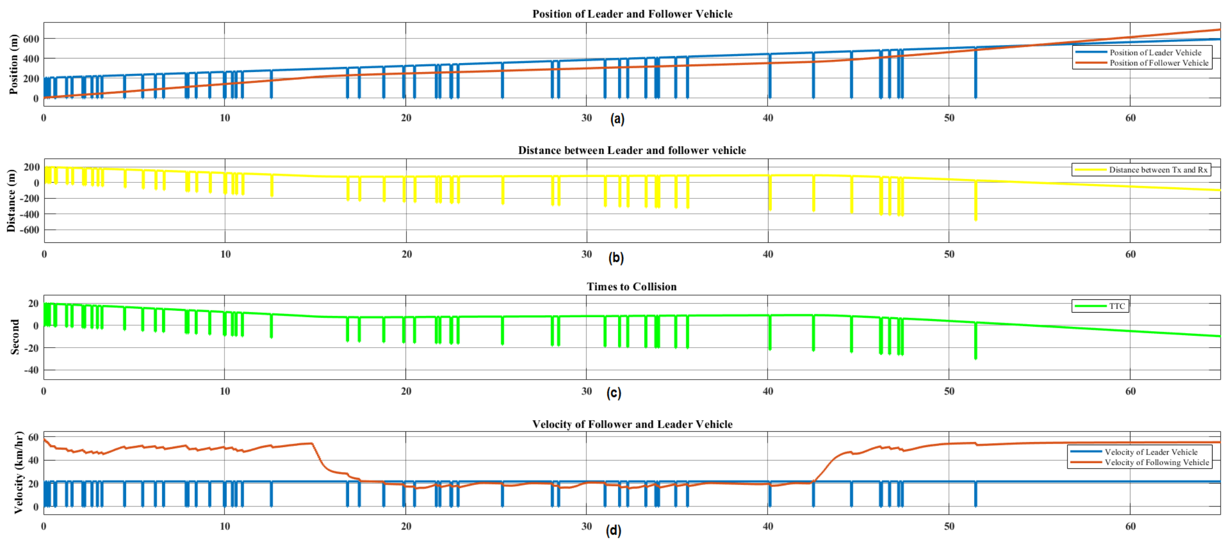


FIGURE 20. Position, distance, TTC, and velocity of each vehicle under the SISO communication with a high building environments.

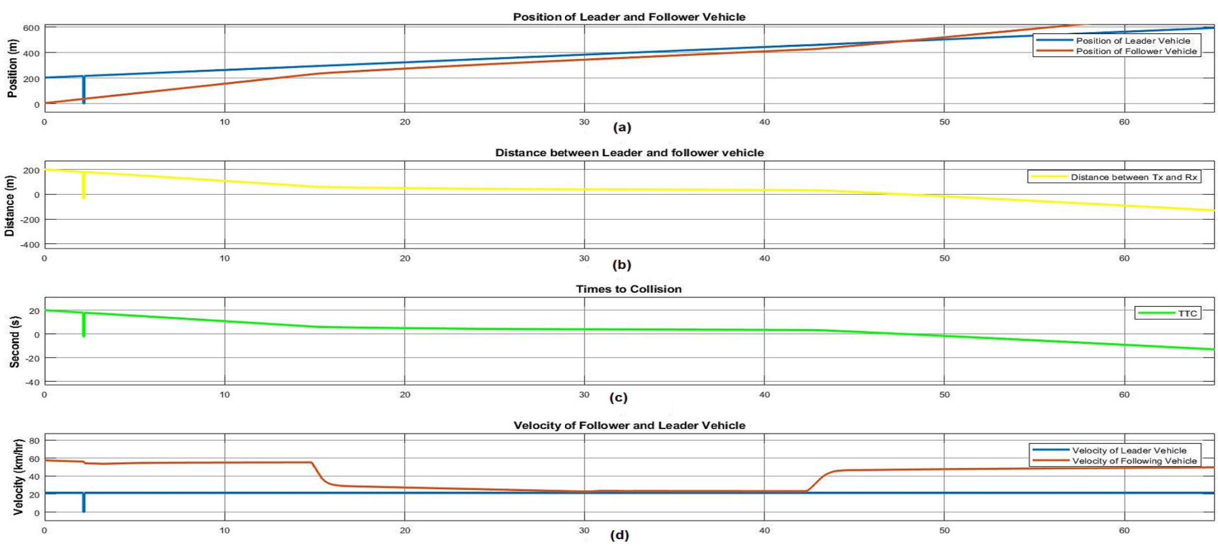


FIGURE 21. Position, distance, TTC, and velocity of each vehicle under the SIMO communication with high building environments.

TABLE 4. Packet delivery ratio.

Scenario	V2V communication	PDR
Scenario I	SISO	100%
Scenario II	SISO	95.32%
Scenario III	MISO	99.91%

4) PACKET DELIVERY RATIO

Table 4 shows the PDR values, which indicate the ratio of data packets received to data packets sent. The PDR values in scenarios I, II, and III were 100%, 95.32%, and 99.91%, respectively. Although the PDR in Scenario II is as high as 95.32%, considering the time interval of 0-15 seconds in Fig. 20, the distances between vehicles are greater than in the other periods, which causes the PDR in this period to be lower than others. As a result, the vehicles behind cannot maintain a smooth speed.

V. CONCLUSION

This paper has presented a vehicle following control model of an autonomous vehicle using the Model-Based Design (MBD) approach. The follower vehicle decision has been modeled by MathWorks Stateflow considering the important factors including velocities, positions, lanes, obstacles, and buildings that affect V2V communication efficiency. The communication and environmental conditions, including 1. SISO and no building, 2. SISO and buildings, and 3. SIMO and buildings were modeled and verified by the formal verification method. The experimental results found that the design of the CACC system by MBD method reduces design time, test time, and verification time. In addition, it was found that the communication between vehicles using SISO techniques will be accurate when used in situations free from obstacles or buildings, but the efficiency of communication is reduced when there are obstacles or buildings. It was found that the problem could be solved by using the SIMO technique, which resulted in the follower vehicle being able to control the speed and distance between vehicles accurately.

In this paper, we studied two-vehicle scenario models using MATLAB. As the SUMO simulation platform can be extremely portable for inter- and multi-modal, space-continuous, and time-discrete traffic flow and communication networks, the integration of MATLAB and SUMO will be investigated in more complicated models in our future work.

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