Modeling And Simulation of Vehicle Dynamics and Information Propagation in a Connected Autonomous Vehicle Environment

Team 12

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Project GitHub link:
https://github.gatech.edu/ychen3254/CSE6730Project1

Abstract

Vehicle-to-vehicle (V2V) communications under the connected vehicle context have the potential to enhance the safety, mobility and environmental sustainability of the current transportation system. Understanding the information propagation characteristics in space and time is a key enabler for V2V-based traffic systems. Exchanged information enabled by wireless communication technologies that will benefit the traffic includes both beacon information such as vehicle velocity and position and special-purpose information such as collision, road construction. Due to the propagation of such information, the vehicle dynamics are expected to be influenced. This study proposes a microscopic two-layer model to characterize the information flow propagation wave (IFPW). The traffic flow propagation is formulated in the lower layer as a system of ordinary differential equations based on the Cooperative Intelligent Drive Model (C-IDM). The upper layer adopts agent-based modelling leveraging wireless communication coverage concepts to describe information dissemination between V2V-equipped vehicles. The capacity and stability improvement benefits of the proposed C-IDM model are compared with the traditional Intelligent Drive Model (IDM) in literature. The IFPW speed is illustrated for heterogeneous traffic conditions under different communication constraints. The proposed model can capture the spatiotemporal relationships between the traffic and V2V communication layers, and aid in the design of novel information propagation strategies to manage traffic conditions under V2V-based traffic systems.

1. Project Description

With the fast advancements in automation and connectivity, the future of ground transportation and people's daily commute might become quite different. Connected autonomous vehicles (CAVs) are likely to gradually replace the human-driven vehicles (HDVs) commonly seen on the road today. Connected vehicles (CVs) are enabled by vehicles equipped with wireless communications technologies, mainly being DSRC based on IEEE 802.11p standards and C-V2X based on 3GPP cellular LTE (long term evolution) standards [1] [2]. Although those two technologies have been the mainstream CV technologies for years, it is noted that because DSRC and C-V2X are technically incompatible as well as the failure of DSRC to take hold in the industry in the past decade, the Federal Communication Commission (FCC) decided to adopt only C-V2X technology for vehicle-to-vehicle (V2V) communication starting from Nov 18, 2020 in order to maximize the spectrum efficiency. Compared with on board sensors limited by the radar range, V2V communication could provide smoother, safer, and more reliable driving experience by overcoming the distance limitation with wireless communication capabilities. When designed and deployed correctly, a network of CAVs will increase traffic throughput, alleviate traffic congestion, and improve traffic safety. Besides, autonomous vehicles (AVs) can leverage the connectivity benefits for better decision-making compared with human drivers.

Although the potential benefits are expected, at the same time, those emerging technologies are expected to change vehicle behaviors and traffic flow patterns. Vehicle dynamics would adapt CAV characteristics thus differentiating from traditional vehicle dynamics. When CAVs are following other vehicles, the acceleration would be impacts by kinematic information, specifically velocity and position, of the preceding vehicles within communication range. Due to vehicle dynamics, the number of vehicles within the communication range would dynamically change thus forming a dynamic communication topology. On the other side, based on different communication topology, vehicles dynamics can be further changed depending on the amount of periodic information they received. Besides, if there is any special-purpose information newly generated and need to be propagated to other vehicles, the information propagation speed would be influenced by the underlying vehicle distribution. **Error! Reference source not found.** is artist's conceptual illustration of connected vehicles sharing and transmitting relevant information.

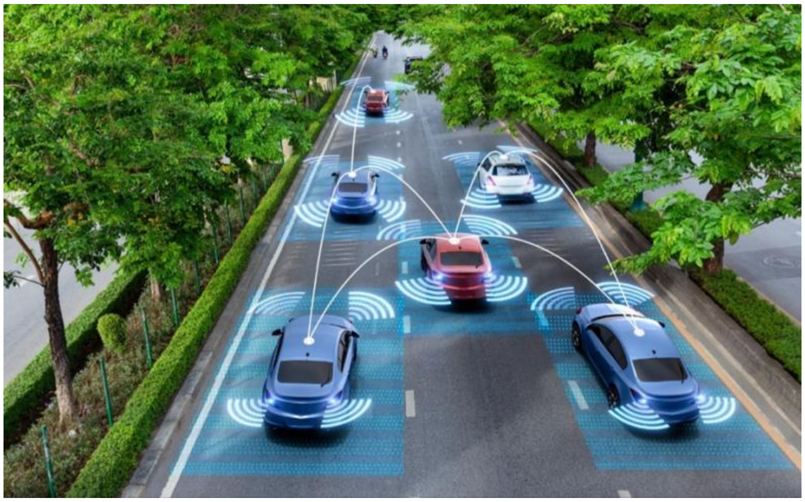

Figure 1. Illustration of connected vehicles [3]

The goal of this project is to investigate the interactions between traffic and information propagation, as well as the impacts of properties for each layer on the other layer. It models and simulates the interaction between wireless communication and traffic flow. Specifically, this study answers the following questions:

1. How periodic information exchange improve the traffic performance?
2. What's the impacts of different communication scheme on vehicle dynamics and traffic flow?
    a. How does information flow characteristics (communication range, communication scheme) influence traffic flow (speed, acceleration, distance between cars)?
3. What's the propagation characteristic of special-purpose information in a CAV environment?
    a. What is the interactive information coverage performance (propagation efficiency) along a specific road under different traffic situations?
    b. How does beacon information exchange influence information propagation?

This study adopts a two-layer structure for modelling the CAV system. The lower layer adopts Cooperative Intelligent Driver Model (C-IDM) to capture the vehicle-level dynamics due to enhanced connectivity enabled by wireless communication. Specifically, it describes the acceleration decision-making process of a CAV following a stream of vehicles and reaction corresponding to the predecessor vehicles' states. Additionally, a V2V wireless communication layer is added to simulate the information exchange and propagation. At this upper layer, a dynamic communication topology, which is time-dependent and determined by communication range, communication mechanism, and distance between vehicles, is incorporated to describe the cooperation manner of CAVs. An agent-based simulation is used to describe the vehicle behaviors including kinematics states and information status. Both beacon information and special-purpose information are explored. Different communication schemes and their impacts are examined.

This study can help to understand how information communication schemes should be designed to improve traffic performance. It also facilitates an in-depth understanding of the interactions between information flow and traffic flow.

2. Literature Review

2.1. Information Propagation in Connected Autonomous Vehicles (CAV)

Autonomous and connected vehicles are expected to revolutionize the transportation system in the near future. Autonomous vehicles are computer-controlled, while connected vehicles are able to share information with surrounding vehicles. V2V communications allow vehicles perceive some threats much sooner than traditional sensors, cameras, or radar can [4]. The National Highway Traffic Safety Administration (NHTSA) estimated that 13-18% of crashes can be prevented, and thousands of lives can be saved with V2V technology [5]. In a vehicle to vehicle (V2V) communication network, periodic information such as speed, heading, and braking status are exchanged among multiple vehicles to improve traffic safety and efficiency. Besides, event-driven information such as road conditions and traffic congestions can also be disseminated among vehicles to enhance their situational awareness, which helps to warn drivers about impending danger, on top of the most advanced crash avoidance technologies present on vehicles today.

The provision of real-time traffic information has been proved to facilitate the efficient utilization of available road capacity. With the development of connected vehicle technology, information can be exchanged among vehicles to assist driving and improve transportation performance, further influencing the traffic flow. Information in V2V environment can be categorized into two types. Beacon information describe vehicle's kinematic states including velocity and position that need to be exchanged periodically for real-time vehicle decision-making, thus influencing immediate vehicle dynamics. Special-purpose information such collision, road construction and potential road hazard is generated by any vehicle in the traffic stream and send the information out to inform other vehicles within the communication range. Information is disseminated on top of the traffic network, thus the information flow propagation pattern is impacted by the underlying traffic flow characteristics. At the same time, the traffic dynamics can also be influenced by the information they received. While the information propagation characteristics in space and time has been extensively explored in literature [6] [7] [8] [9], the influence of information flow propagation on traffic flow is not well understood.

This project will utilize analytical models to study the coupled information flow and traffic flow: how do the information flow characteristics influence traffic flow? What is the information coverage performance along a specific road? The outcome of this study can help to understand how information communication schemes should be designed to improve traffic performance. It also facilitates an in-depth understanding of the interactions between information flow and traffic flow.

2.2. System Behavior Modeling

This section will provide a brief overview of the two essential components of the planned CAV simulation study, which are the vehicle dynamics modelling and the communication system simulation.

In previous work, researchers have analyzed the process of information propagation using stochastic model [8], susceptible-infected epidemic model [9] and cellular automaton model [10]. Both macroscopic and microscopic models have been used. As this study focuses on vehicle-level dynamics, microscopic modelling methods are adopted.

2.2.1 Vehicle Dynamics Simulation for CAVs

There are many different mathematical models to characterize the behavior of car following. Out of the numerous models proposed in this field, the intelligent driver model (IDM) is a well-known, deterministic time-continuous model for describing the dynamics of the positions and velocities of every vehicle [11]. The IDM is governed by a system of 2^{nd} order ordinary differential equations and has the following advantages (just to name a few): (i) the model depends on relative velocity, so it is constructed to be collision-free, (ii) model parameters all have reasonable physical interpretations and can be empirically measured, (iii) these parameters and the stability of the model can be calibrated to empirical data, (iv) it allows for a fast numerical simulation [12].

2.2.2 V2V Communication System Modeling

In literature, both macroscopic and microscopic models have been proposed to describe the communication phenomenon in a V2V networks. Realistic communication constraints including communication range, communication power and communication schemes have been considered in the modelling and simulation process. However, the effects of dynamic communication range have not been fully explored. Besides, while unicast and broadcast communication schemes have been widely explored in the V2V modeling, multicast, which avoids the shortcomings of broadcast explosion and bandwidth requirements while maintaining energy efficiency has not been explored [13]. Analytical models considering communication range and communication schemes are used to model the information exchange process in a connected vehicle environment.

The spatiotemporal relationships between the traffic flow dynamics and V2V communication constraints as well as information characteristics are not well explored in literature. In this study, an interactive two layer framework will be used to model the information propagation in a CAV environment. The traffic layer is modeled by the C-IDM, and the information layer adopts microscopic analytical models to describe the information exchange process of both periodic information and event-driven information. The influence of traffic flow characteristics and communication characteristics on the information propagation process will be examined.

3. Conceptual Model

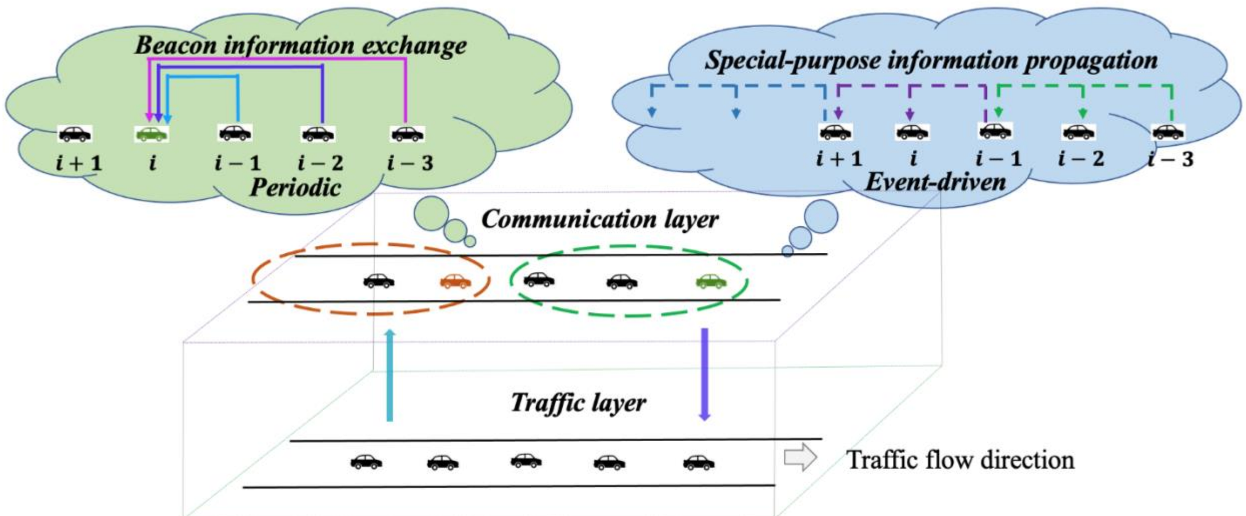

Figure 2. The bi-layer architecture of the CAV system dynamics model

Information that will benefit the traffic includes both beacon information and special-purpose information. Beacon information such as vehicle velocity and position is exchanged periodically between surrounding vehicles to enable cooperative driving. Those information will be used in the real-time vehicle acceleration calculation thus it is time-sensitive. The exchange of beacon information is considered as single-hop communication for vehicles within the communication range of each other. Special-purpose information refers to event-driven messages such as collision, road construction in the imminent downstream traffic direction. Those information are not only interested to the nearby vehicles, but also would help enhance the situational awareness of vehicles in a local area to smooth traffic oscillation and improve driving comfort. The propagation of special-purpose information flow through multi-hop communications.

In a traditional IDM, only two vehicles are considered: a predecessor vehicle and a following vehicle. In this study, we adopt the IDM for the following reasons: (1) The IDM is a multi-regime model, which can provide greater realism than other controllers when capturing dynamics of different congestion level; (2) It provides collision-free behaviors and smooth traffic flow; (3) Many existing studies have used IDM to model connected automated vehicles' longitudinal dynamics. Specifically, this study adopts C-IDM incorporating a cooperative driving strategy to simulate platooning CAVs' dynamics with various communication scheme [14].

However, information can be simultaneously transmitted to multiple CAVs, which motivated the development of the C-IDM. This vehicle dynamics model has two layers, as illustrated in Figure 2, with the vehicular layer simulating traffic flow propagation (similar to a traditional IDM model), while the communication layer models information dissemination among connected vehicles while accounting for communication constraints [14].

The traditional IDM is represented by the following equations:

$$\dot{v}_n(t) = a\left(1 - \left(\frac{v_n(t)}{v_0}\right)^4 - \left(\frac{s^*\big(v_n(t), \Delta v_n(t)\big)}{s_n(t)}\right)^2\right)$$

and

$$s^*\big(v_n(t), \Delta v_n(t)\big) = s_0 + T v_n(t) + \frac{v_n(t)\Delta v_n(t)}{2\sqrt{ab}}.$$

Where v_n represents speed of vehicle n, a is the maximum acceleration, b is the desired deceleration. v_0 denotes the free flow velocity, s^* denotes the desired safe clearance gap, s_0 indicates the minimum clearance gap, and T is the desired time gap to follow the immediate leader vehicle.

However, even though the IDM is well-known and well-studied in recent years, it is by no means a perfect model. Albeaik et al. [11] studied the traditional IDM and found two mathematical and modeling drawbacks:

1. The velocities of specific vehicles might become negative at specific times, which might not be desirable from a modelling point of view.
2. The velocities of specific vehicles might diverge to $-\infty$ in finite time, so that the solution of the system of ODE's ceases to exist.

Most of the time, these, these issues can be avoided when proper initial condition and parameter values are imposed. Table 1. specifies the key parameter values used in the simulation.

Since CAVs can exchange information with multiple vehicles, we can modify the equations above to account for this ability to change vehicle motion based on speed changes of multiple vehicles. The C-IDM equations are:

$$\dot{v}_n(t) = a\left(1 - \left(\frac{v_n(t)}{v_0}\right)^4 - \left(\frac{s^*\left(v_n(t), \Delta\tilde{v}_{n-j+1}(t)\right)}{\sum_{j=1}^{N} \alpha_{nj} w_{nj} \tilde{s}_{n-j+1}(t)}\right)^2\right)$$

and

$$s^*\left(v_n(t), \Delta\tilde{v}_{n-j+1}(t)\right) = s_0 + T v_n(t) + \frac{v_n(t) \cdot \sum_{j=1}^{N} \beta_{nj} w_{nj} \Delta\tilde{v}_{n-j+1}(t)}{2\sqrt{ab}}.$$

Where α and β are weighting coefficients, and w denotes the connectivity among different vehicles. Additionally,

$$\Delta v_n = v_n - v_{n-1}$$
$$\mathrm{s}_n = x_{n-1} - x_n - l$$
$$\sum_{j=1}^{N_n} \alpha_j = 1$$
$$\sum_{j=1}^{N_n} \beta_j = 1$$

For the communication layer, information exchange and propagation depend on communication range, communication frequency and communication scheme. Vehicles within communication range can exchange information. As indicated in Figure 2, the green vehicle can send its information to vehicles within its communication range, denoted by the green dashed line. As vehicles are interested in information downstream and vehicles in front, we only consider the information propagation direction which is opposite to the traffic direction, which is also the common practice in literature. There are two kinds of information considered in this study. As shown in Figure 2, vehicle i is within the communication range of vehicle $i-1$, $i-2$ and $i-3$. Thus can receive velocity and position information of those three vehicles. At each time instant, the velocity and position information of vehicle $i-1$, $i-2$ and $i-3$ are taken as inputs for vehicle i to decide the acceleration of the acceleration for the next time instant. Depending on the communication scheme that vehicle i adopts, it can choose whether to choose all or partial vehicles within its communication range. Usually, communication frequency is 10 Hz, which is also what this study adopted.

Special-purpose information are of interest to vehicles in a local area, thus it needs to be propagated along the upstream traffic flow direction through multi-hop communication. As indicated in Figure 2, a piece of special-purpose information that is trigger by a specific event will be relayed out to other vehicles. For example, information from vehicle $i-3$, can be sent to vehicles within its communication range, including vehicle $i-2$ and vehicle $i-1$. After the information is received by vehicle $i-1$, which is the furthest vehicle location at this hop, vehicle $i-1$ can relay the same information to vehicle i and vehicle $i+1$. As this process continues, the special-purpose information propagates.

4. Simulation Model and Simulation Program

To implement the agent-based traffic modeling task that incorporates the C-IDM and information propagation capability, a traffic simulation architecture is needed. Instead of developing the software architecture from the ground up, the team used an existing traffic simulation framework that is written in Python [15]. This framework is licensed under the MIT License, which allows the rights to use and modify the software. The framework is then heavily modified to suit the unique needs and requirements of this study.

Our simulation has a visualization framework that displays the vehicles' 1D motion on the road. During each timestep, the simulation integrates a system of ordinary differential equations governed by the vehicle dynamics model. The visualization of vehicle motion is realized using pygame [16], which displays a pop-up window of the vehicles in motion on a straight road. However, to generate insightful results in this project, the simulation time and road length needs to be sufficiently long, which make the windowed display somewhat trivial for those cases. Instead, additional functions are written to plot the key vehicle dynamics parameters (such as distance, velocity, and acceleration) and visualize propagation of information in the vehicle platoon. Since the vehicles do not finish the simulation at the same time, data logging stops when the leading vehicle reaches the end of the road.

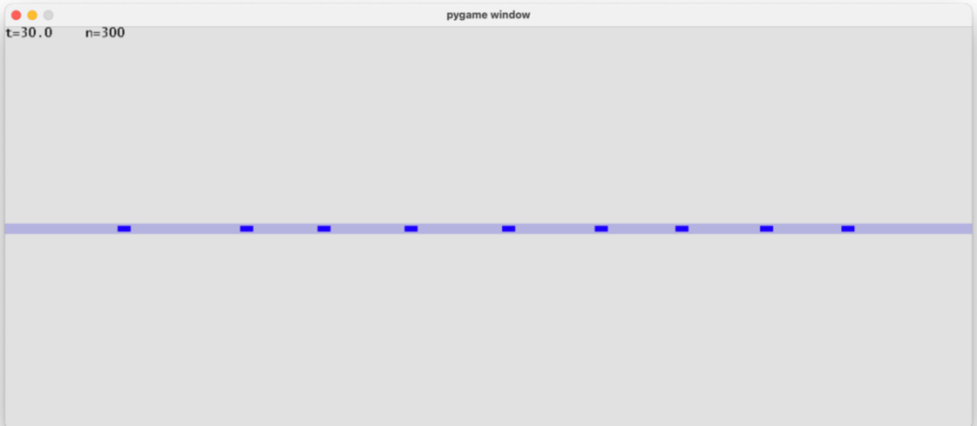

Figure 3. Pygame visualization for the vehicle platoon
with randomized initial car-following distance

5. Verification

As this study proposes a new emerging transportation system, there are no data available to verify and validate the model. However, through making sure the implemented model matched the conceptual model, the verification requirements can be met. When implementing the simulation, the addition of each new feature is carefully checked to ensure that the program is behaving as intended. First, the traditional IDM in the original software architecture is verified. Since the mathematical formulation of IDM prevents vehicle collisions to occur, the distance between every two cars is checked at every instance during the simulation to make sure that vehicle gap is greater than the vehicle length.

Then the vehicle dynamics model is modified to the C-IDM. The implementation of C-IDM includes the check for vehicles in front that are within the communication range, and determination of which vehicles to receive the relevant traffic information. Additionally, during software development, the modeling parameters are checked at runtime in debug mode to make sure that all user-specified parameters (if applicable) have overwritten the default values.

6. Experimental results and validation

In this section, we conducted various simulations to test the vehicle dynamics of the proposed CAV model and the information propagation performance as a result of interaction between the traffic flow and information exchange.

Vehicle dynamics performance

To validate the advantages of the proposed CAV dynamics model and its impacts on the traffic flow and information propagation, various simulation runs are conducted and the results correspond to the hypothesis. The C-IDM requires a set of parameters to model the behavior of connected autonomous vehicles. These parameters and their associated values are listed in Table 1 below:

Table 1. C-IDM simulation parameters

Description	**Symbol**	**Value**
Desired free-flow speed	v_0	$33.33\ m/s\ (120\ km/h)$
Jam distance	s_0	$2\ m$
Safety time headway	T	$1.1\ s$
Maximum acceleration	a	$1\ m/s^2$
Maximum comfortable deceleration	b	$2\ m/s^2$
Vehicle length	l	$5\ m$
Communication radius	R	$150\ m$

Here, the safety time headway refers to the minimum possible time to the vehicle in front. The values used in is study are within the range of values used in many literature [14] [17], and agree well with real world traffic data.

Case parameters are listed in Table 2. For these cases, the number of vehicles is set to 50.

Table 2. Input parameters for vehicle dynamics cases

Input parameters	**Leader velocity profile**	**Communication range (m)**	**Multicast scheme (1:n)**	**Notes**
Case 1	Constant	200	1	IDM (baseline)
Case 2	15 → 28 m/s	200	1	IDM
Case 3	Constant	200	3	CIDM
Case 4	15 → 28 m/s	200	3	CIDM
Case 5	15 → 28 m/s	200	10	CIDM
Case 6	15 → 28 m/s	1500	50	CIDM
Case 7	Constant	200	5	CIDM
Case 8	Constant	1500	50	CIDM

Table 3. Output metrics for vehicle dynamics cases-stability performance

Output (results)	**System stability (Y/N)**	**Steady gap (m)**	**Time to stable state (s)**	**String stability (Y/N)**
Case 1	Y	24	138	N
Case 2	Y	52	164	N
Case 3	Y	17	136	Y
Case 4	Y	37	185	Y
Case 5	Y	26	325	Y
Case 6	Y	27	375	Y
Case 7	Y	14	125	Y
Case 8	Y	12	125	Y

Case 1: Baseline results with the traditional IDM

Now we can generate baseline results to show the traditional IDM in action. The lead car's (car 0) motion is governed by a user-supplied input, then the following vehicles' acceleration is calculated using the traditional intelligent driver model. For the baseline case, the lead car's motion is constant. However, the gap between vehicles is smaller than the steady state vehicle gap. As a result, when each of the following cars is generated, it will first decelerate to increase the distance to the front car, then accelerate again to catch up and reach steady state. Figure 4 through Figure 6 are the vehicle dynamics plots for the first case:

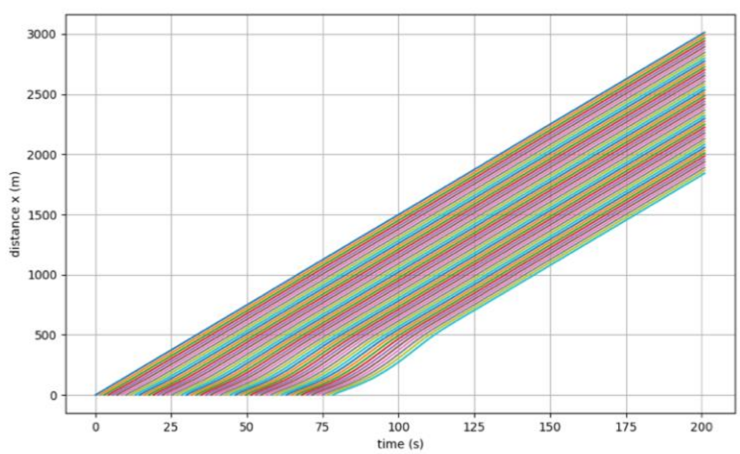

Figure 4. Vehicle position vs. time, case 1

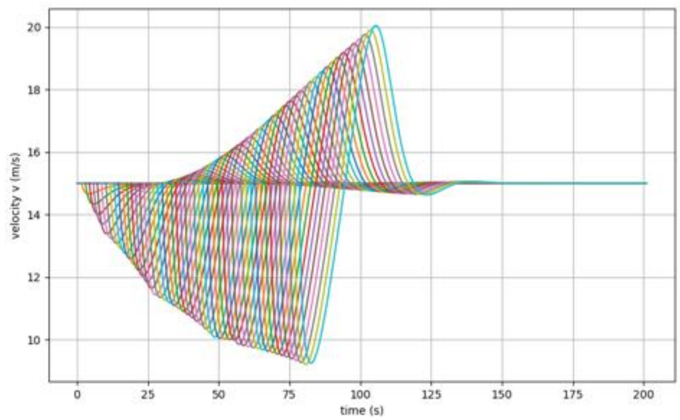

Figure 5. Vehicle velocity vs. time, case 1

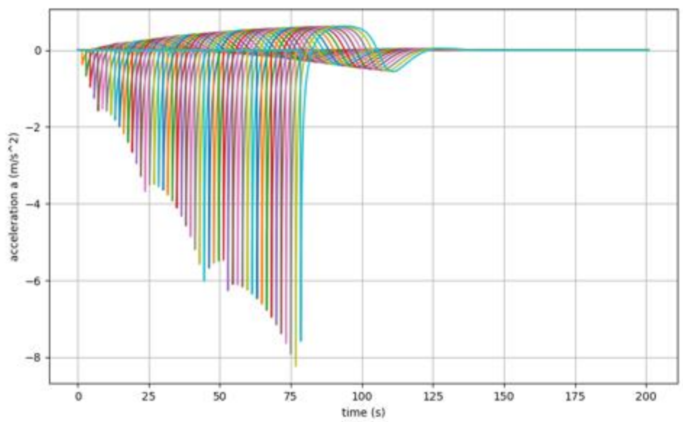

Figure 6. Vehicle acceleration vs. time, case 1

It can be seen that as new cars are introduced, the initial vehicle deceleration increases, which means the vehicle deceleration is propagating and causing system instability.

Case 2: IDM with lead car acceleration

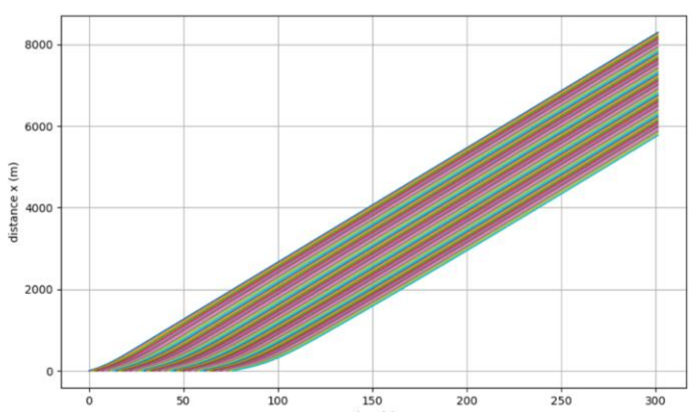

Figure 7. Vehicle position vs. time, case 2

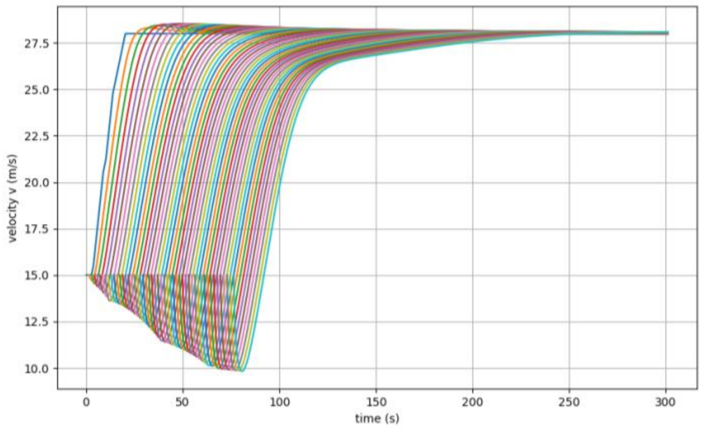

Figure 8. Vehicle velocity vs. time, case 2

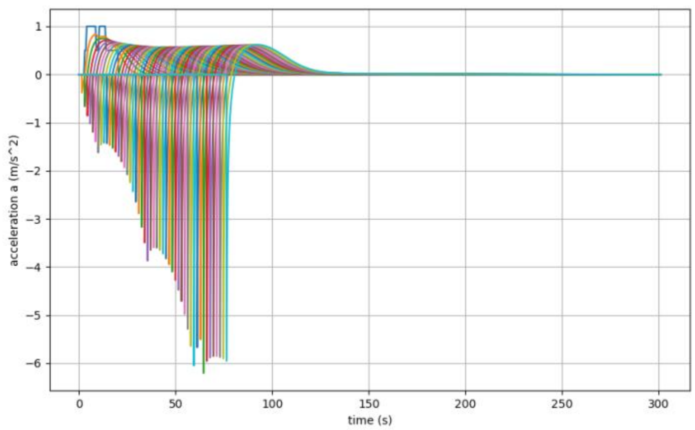

Figure 9. Vehicle acceleration vs. time, case 2

In case 2, the overshoot is kept quite low. However, the initial deceleration is still diverging.

Case 3: CIDM with constant speed leader, receive_info_num_cars = 3

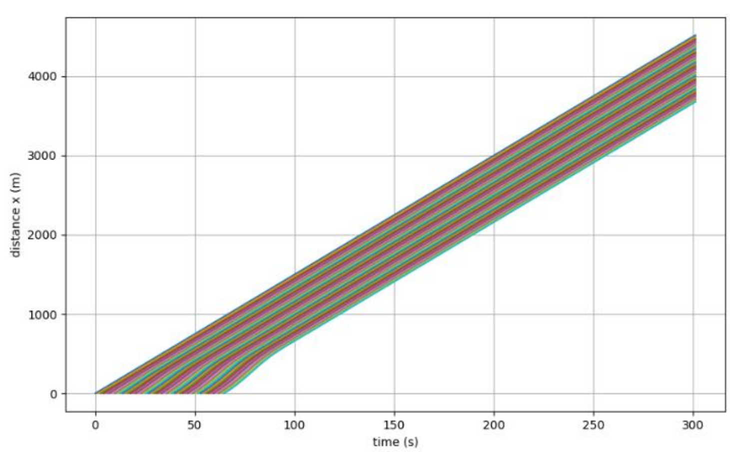

Figure 10. Vehicle position vs. time, case 3

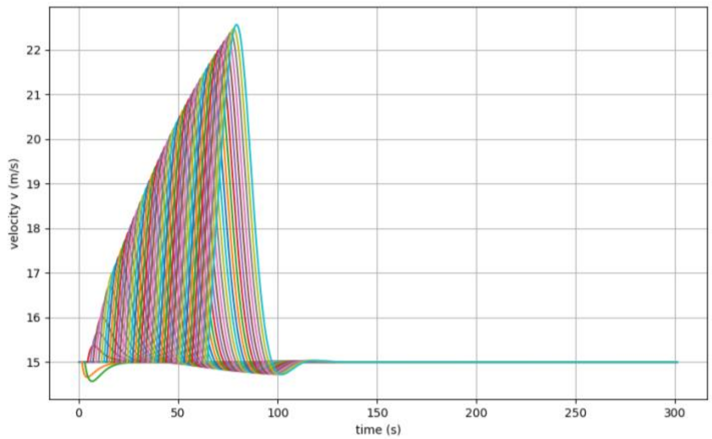

Figure 11. Vehicle velocity vs. time, case 3

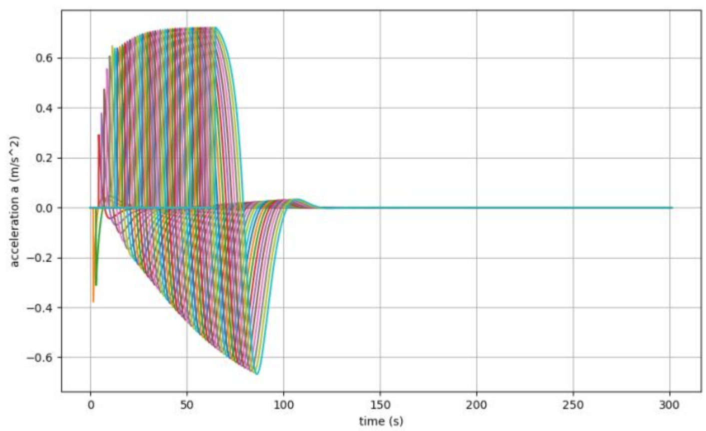

Figure 12. Vehicle acceleration vs. time, case 3

In case 3, the C-IDM is implemented. For the velocity plot, vehicles no longer need to decelerate initially (after car 2). Each of the following cars is accelerating to reduce the gap to the car in front. Unlike the previous two cases with traditional IDM, the acceleration for the vehicle platoon is kept well within reasonable limit.

Case 4: CIDM with accelerating leader, receive_info_num_cars = 3

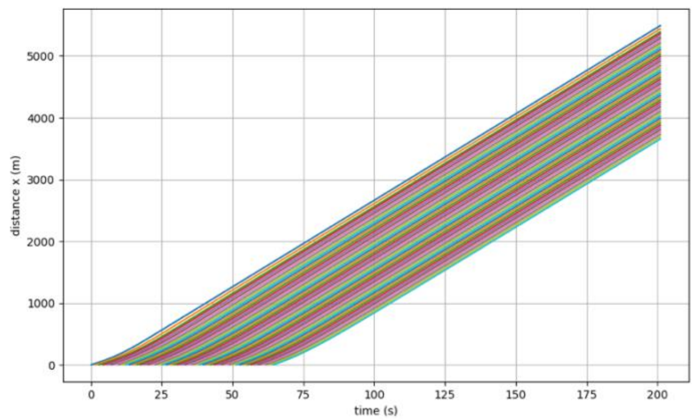

Figure 13. Vehicle position vs. time, case 4

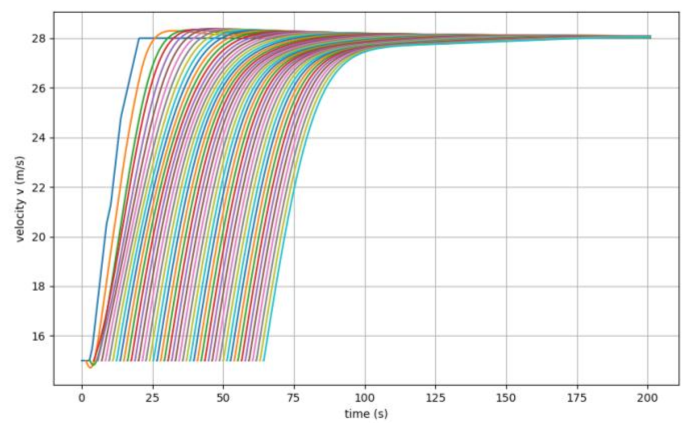

Figure 14. Vehicle velocity vs. time, case 4

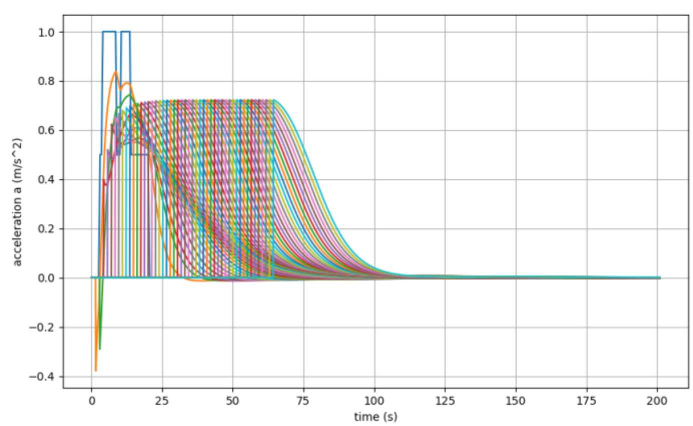

Figure 15. Vehicle acceleration vs. time, case 4

In this case, when the lead vehicle accelerates, the velocity overshoot for the following cars are well controlled. According to the acceleration plot, the system is able to reach stability.

Case 5: CIDM with accelerating leader, receive_info_num_cars = 10

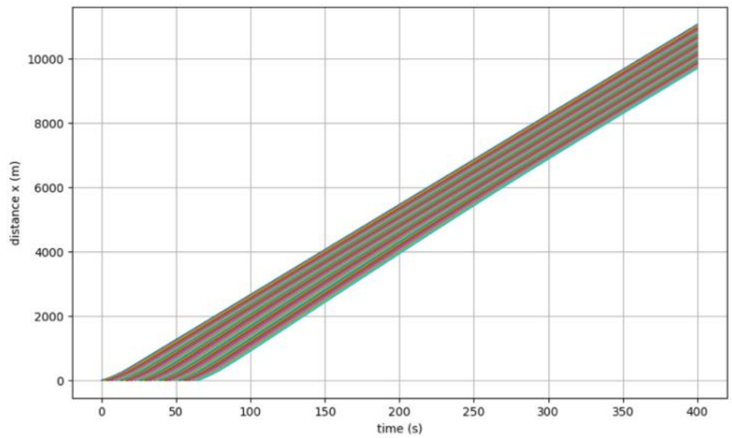

Figure 16. Vehicle position vs. time, case 5

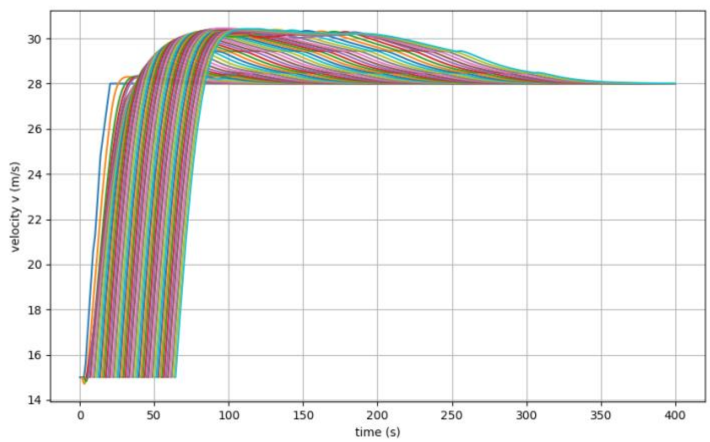

Figure 17. Vehicle velocity vs. time, case 5

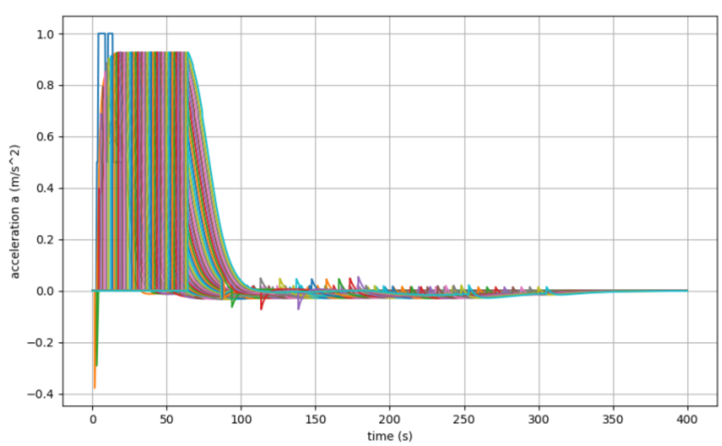

Figure 18. Vehicle acceleration vs. time, case 5

When receive_info_num_cars is increased to 10, there is slightly more overshoot in the vehicle velocity plot. Additionally, there is some fluctuation in the acceleration plot, and this is likely due to numerical noise (since the magnitude of the fluctuations are so small).

Case 6: CIDM with accelerating leader, communication_range = 1500, receive_info_num_cars = 50

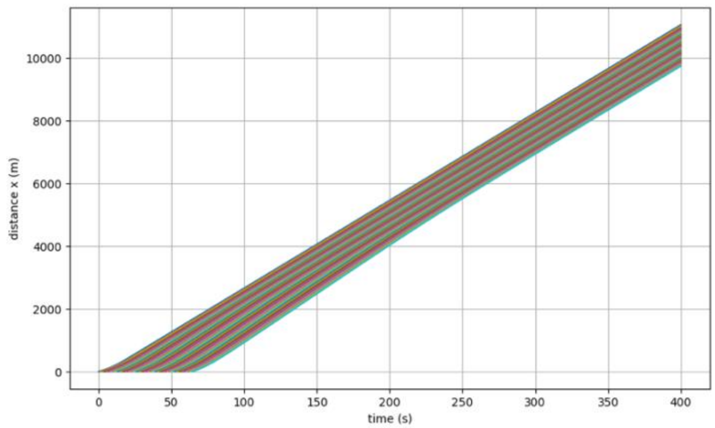

Figure 1919. Vehicle position vs. time, case 6

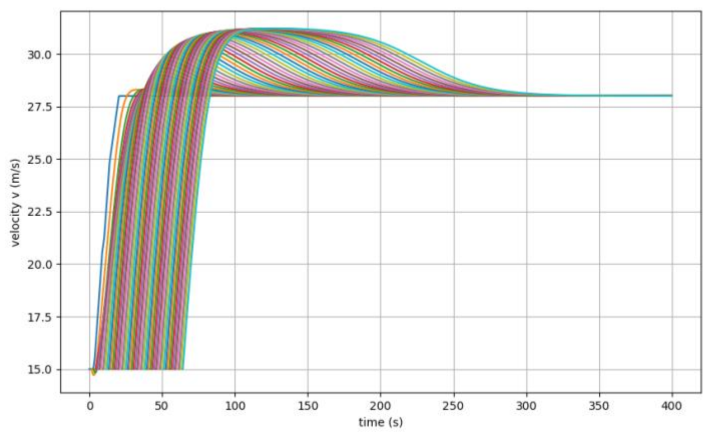

Figure 20. Vehicle velocity vs. time, case 6

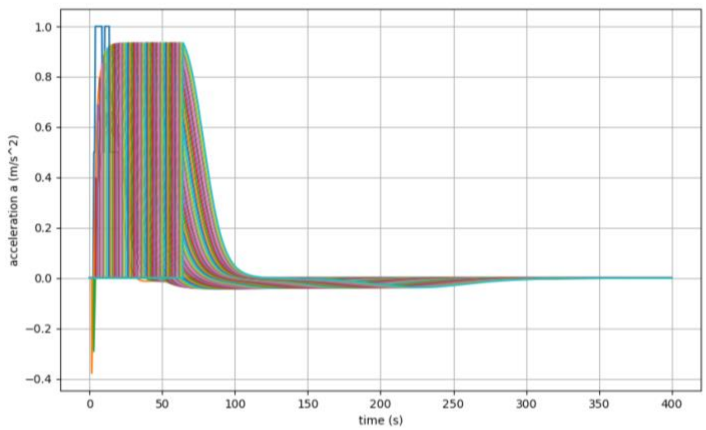

Figure 21. Vehicle acceleration vs. time, case 6

In case 6, the fluctuation is no longer present. The behavior of velocity overshoot is similar.

Case 7: CIDM with constant speed leader, receive_info_num_cars = 5

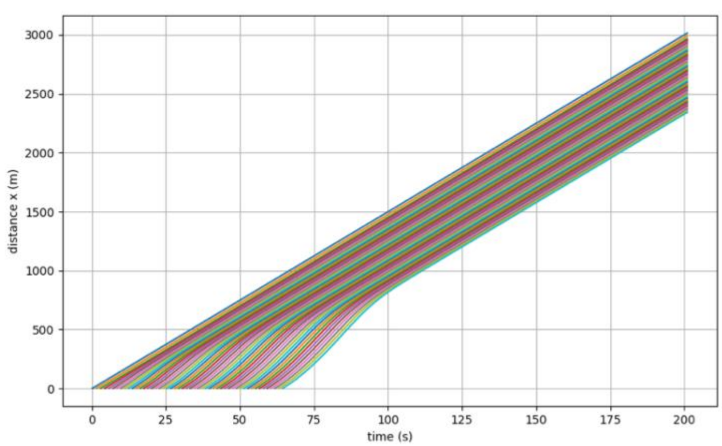

Figure 22. Vehicle position vs. time, case 7

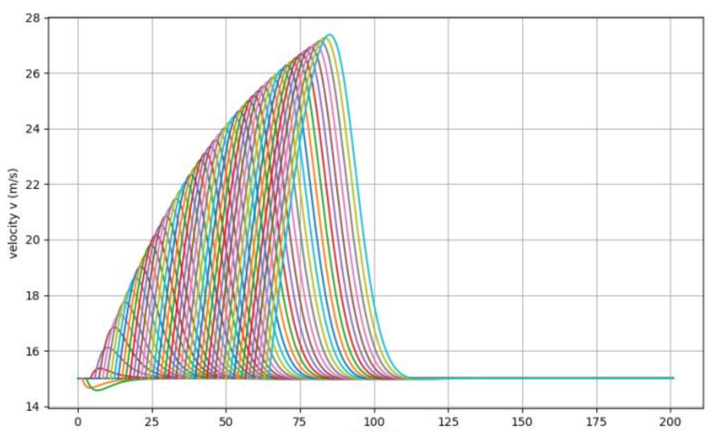

Figure 23. Vehicle velocity vs. time, case 7

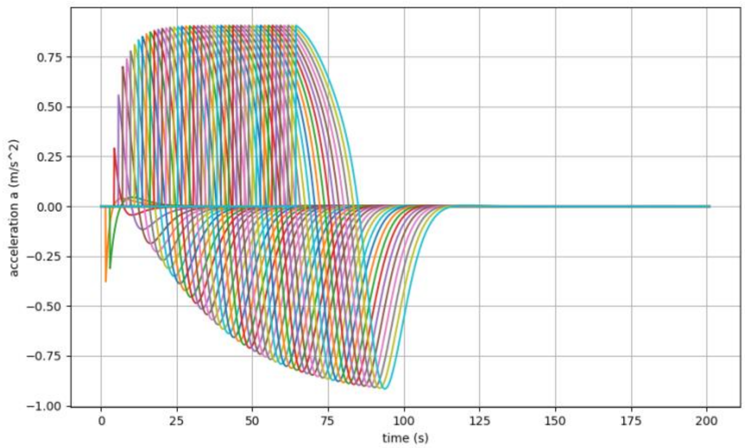

Figure 24. Vehicle acceleration vs. time, case 7

In case 7, the receive_info_num_cars is increased from 3 to 5 when compared to case 3. The magnitude of the initial velocity increase is increased, however, the velocity overshoot (when slowing down to constant velocity) is no longer present.

Case 8: CIDM with constant speed leader, communication_range = 1500, receive_info_num_cars = 50

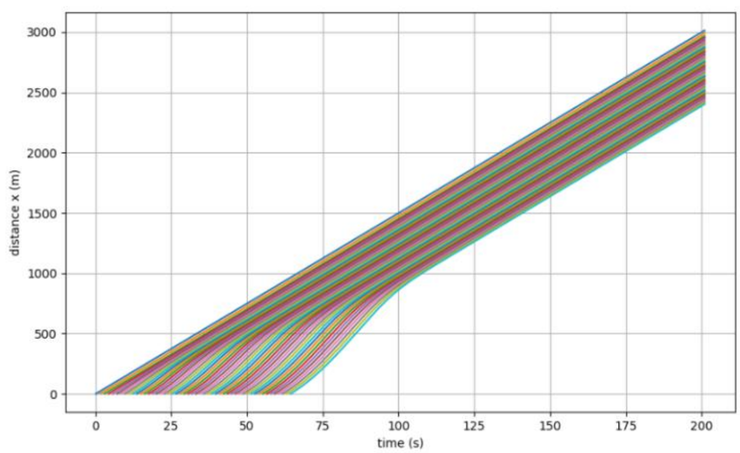

Figure 25. Vehicle position vs. time, case 8

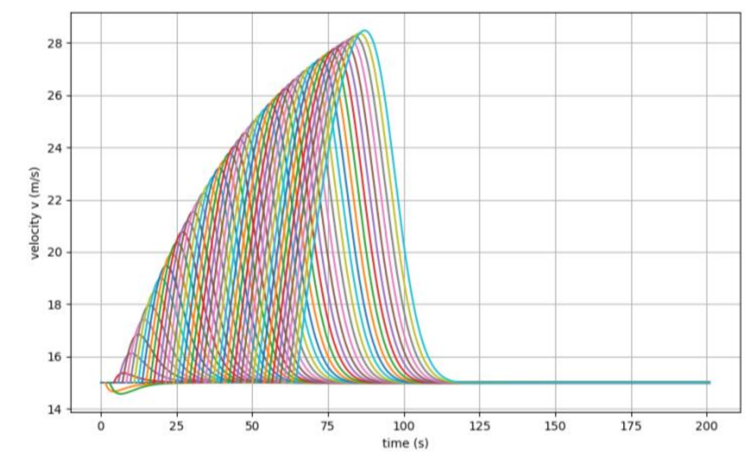

Figure 26. Vehicle velocity vs. time, case 8

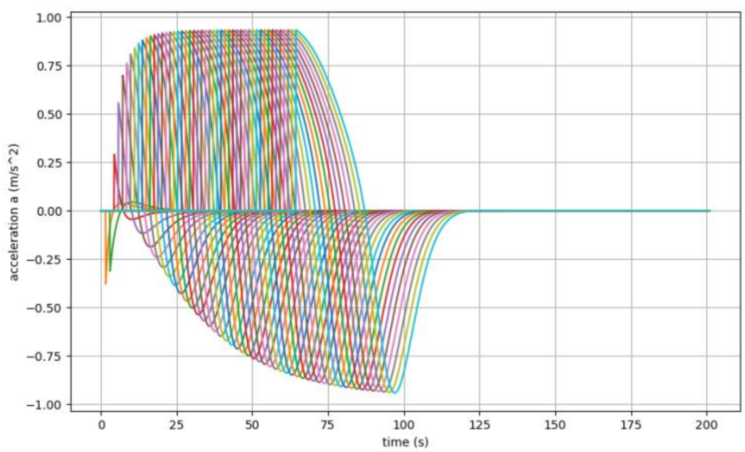

Figure 27. Vehicle acceleration vs. time, case 8

Lastly, a more extreme scenario is shown in case 8. The behavior of the vehicle platoon is almost identical to that of case 7. This means that too much increase in vehicle communication will no longer provide a benefit to the vehicle platoon; the system is entering a state of diminishing return. When designing the communication scheme for real life applications, it is important to consider this behavior.

Special-purpose information propagation performance

To investigate the information propagation characteristics based on the proposed CAV dynamics model and its sensitivity to traffic situation, communication range and communication scheme, various simulation runs are conducted and the results correspond to the hypothesis. The diagrams for different propagation cases are attached in **Appendix I.**

Table 4. Input parameters for information propagation cases

Input parameters	# of vehicles	Communication range (m)	Multicast scheme (1:n)	Initial vehicle gap (m)	Notes
Case 9	200	200	1	20	IDM
Case 10	200	500	1	20	IDM
Case 11	200	500	3	20	CIDM
Case 12	200	200	3	20	CIDM
Case 13	200	600	9	20	CIDM
Case 14	200	600	9	random	CIDM
Case 15	200	200	3	random	CIDM
Case 16	200	200	1	random	CIDM

The results are summarized in Table 5.

Table 5. Results for information propagation cases

Case	Time to cover all vehicles (s)	Propagation speed (m/s)
Case 9	2.4	1666
Case 10	1.0	4444
Case 11	0.9	4111
Case 12	2.1	1762
Case 13	0.7	5142
Case 14	0.9	4888
Case 15	2.5	1760
Case 16	2.4	1833

We can come into the following conclusions:

- Comparing case 9 and 10, we find that increasing communication range increased the information coverage speed for traditional IDM model.
- Comparing case 11 and 12, we find that increasing communication range increased the information coverage speed for C-IDM model.
- Comparing case 13 and 14, we find that different initial conditions for vehicle position barely influence information coverage speed.

- Comparing case 15 and 16, we find that different communication scheme barely influence information coverage speed.
- Comparing case 10 and 11, we find that communication scheme barely influences information coverage speed .
- Comparing case 9 and 12, we find that compared with traditional IDM, information coverage maintains a higher rate in C-IDM traffic .
- Comparing case 11 and 13, we find that communication scheme barely influences information coverage speed for C-IDM.
- Information propagation speed depends on communication range.
- Initial vehicle position distribution barely influences information propagation speed.
- Communication scheme barely influences information propagation speed.

7. Conclusions

In this study, an agent-based modeling framework is used to simulate 1D traffic flow for a vehicle platoon. The vehicle motion is based on the cooperative intelligent driver model (C-IDM), and a bi-layer architecture is used to simulate the interaction between vehicle dynamics and information propagation. With the first set of test cases, different parameters are used to demonstrate the benefits of the C-IDM model. In the second set of cases, impact on information propagation is also examined.

The results show that adding vehicle communication using the C-IDM model will improve the vehicle platoon’s performance, but having too many vehicles in communication with each other will lead to diminishing return. Additionally, the team found that information propagation speed is dependent on communication range, irrespective of models used. Furthermore, while communication scheme and initial vehicle distribution influence the vehicle dynamics, as it is relatively small compared with communication range, the impacts on the information coverage speed and propagation speed are limited.

In terms of future work, the team believes that while connectivity improve traffic performance and information propagation performance, there would be an optimal communication scheme, that is, how many receivers within the communication a sender should choose to communication with, that will ensure both efficiency and improvement requirements. Furthermore, the unstable conditions for this CAV system is also worth of exploring as it is very important for model reliability validation. Last, due to the scarcity of real-world CAV trajectories, the parameters used in the simulation are adopted from HDV trajectory data. Using calibrated parameters for real-world CAV trajectories would enhance the simulation fidelity.

Division of Labor

- Yangjiao Chen: Conceptualization, methodology, implementation, simulation test, analysis, and writing.
- Yifan Li: Simulation test, writing.
- Jiajie Wen: Conceptualization, methodology, implementation, simulation test, analysis, and writing.
- Zhe Zhang: Implementation, code testing, and report editing.

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Appendix I. Information Propagation Cases

Case 9: IDM with constant speed leader, communication range=200, initial distance=20

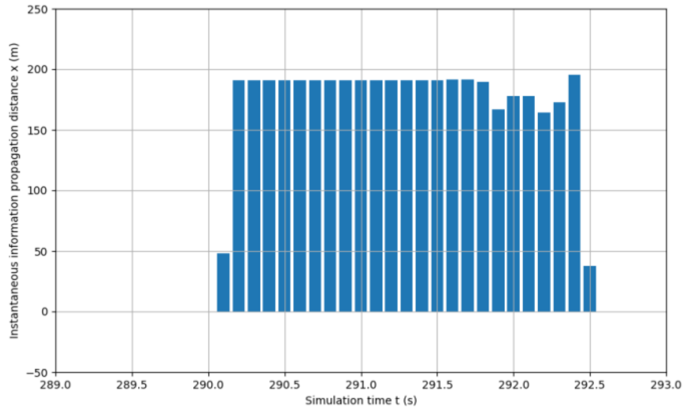


Figure 28. Instantaneous information propagation distance vs. time, case 9

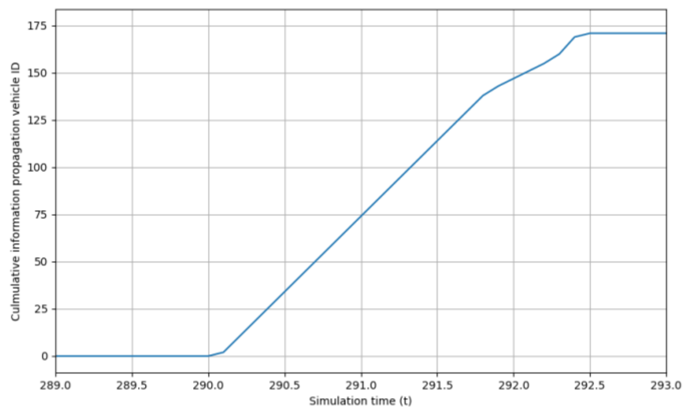


Figure 29. Information propagation vehicle ID vs. time, case 9

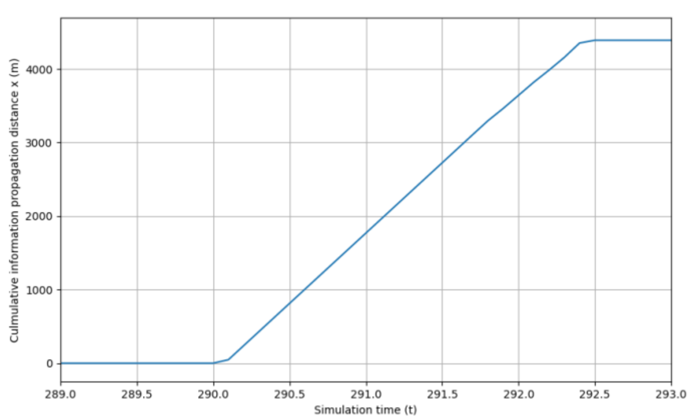


Figure 30. Cumulative info propagation distance vs. time, case 9

Case 10: IDM with constant speed leader, communication range=500, initial distance=20

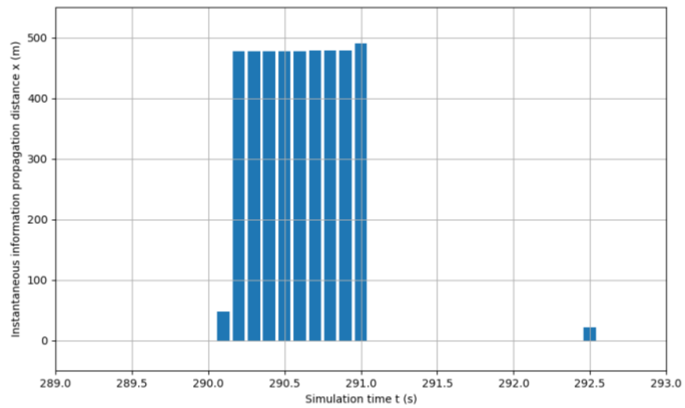


Figure 3128. Instantaneous information propagation distance vs. time, case 10

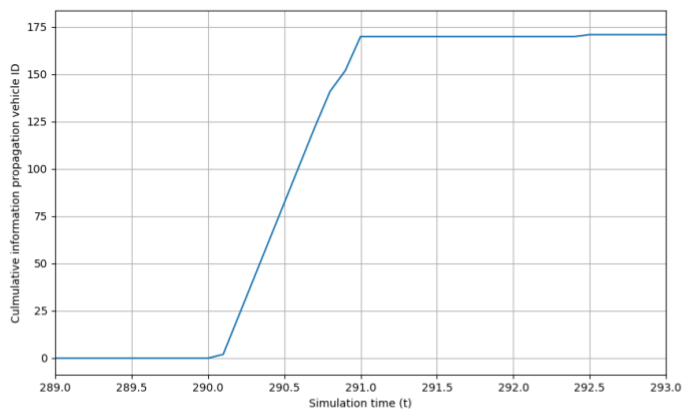


Figure 32. Information propagation vehicle ID vs. time, case 10

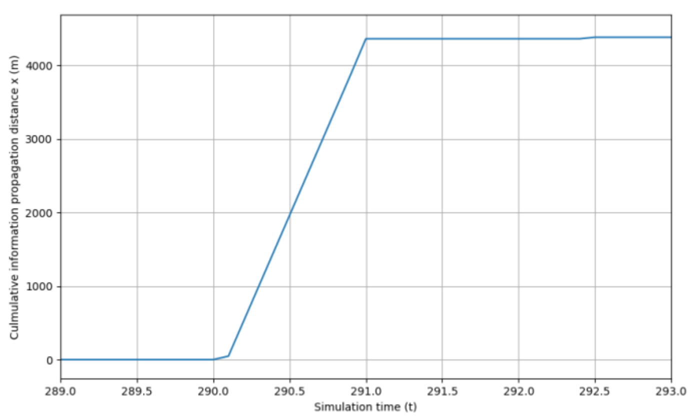


Figure 33. Cumulative info propagation distance vs. time, case 10

Case 11: CIDM with constant speed leader, receive_info_num_cars = 3, communication range=500, initial distance=20

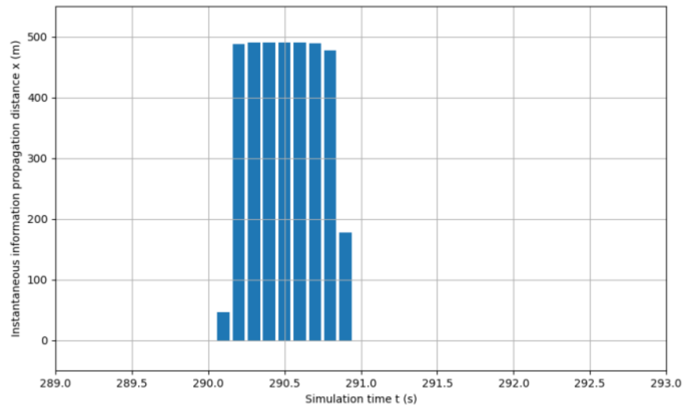


Figure 34. Instantaneous information propagation distance vs. time, case 11

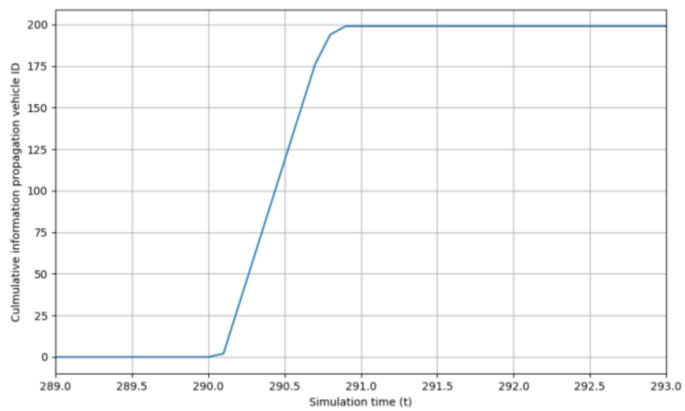


Figure 3529. Information propagation vehicle ID vs. time, case 11

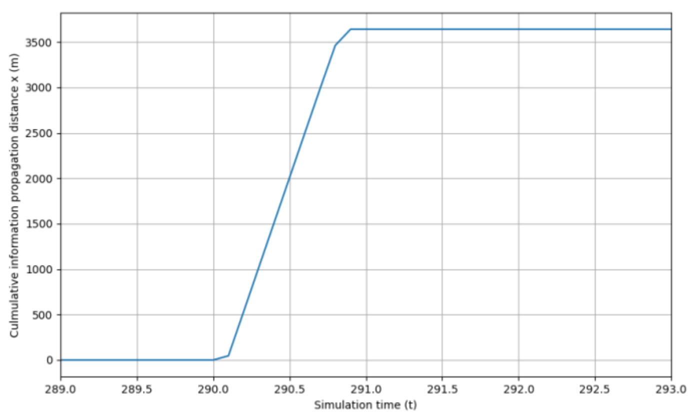


Figure 3630. Cumulative info propagation distance vs. time, case 11

Case 12: CIDM with constant speed leader, receive_info_num_cars = 3, communication range=200, initial distance=20

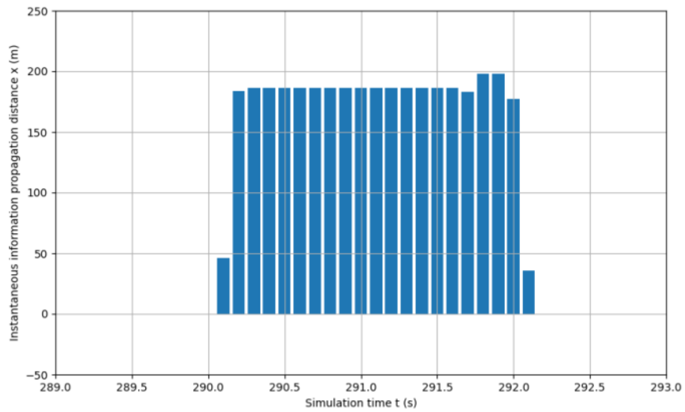


Figure 3731. Instantaneous information propagation distance vs. time, case 12

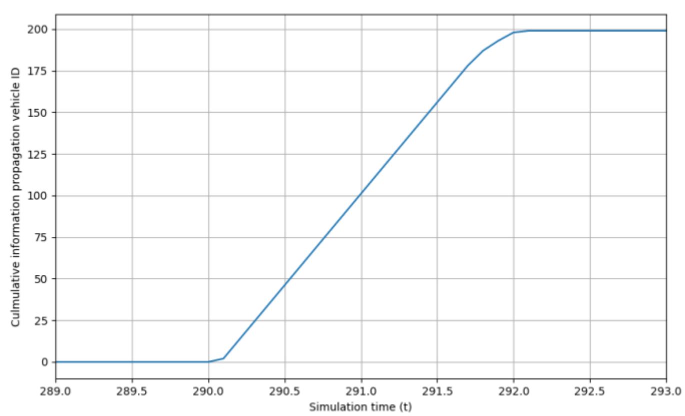


Figure 38. Information propagation vehicle ID vs. time, case 12

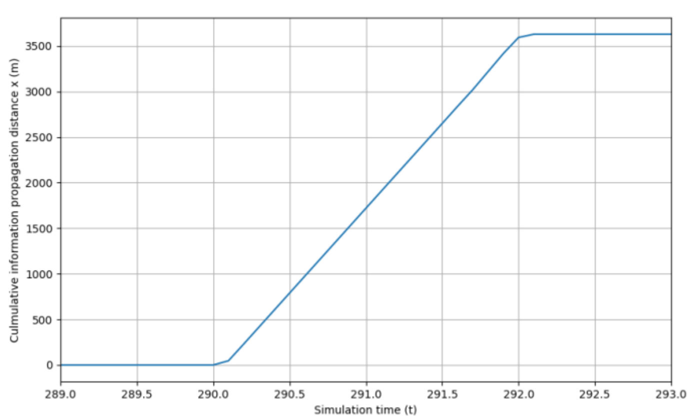


Figure 3932. Cumulative info propagation distance vs. time, case 12

Case 13: CIDM with constant speed leader, receive_info_num_cars = 9, communication range=600, initial distance=20

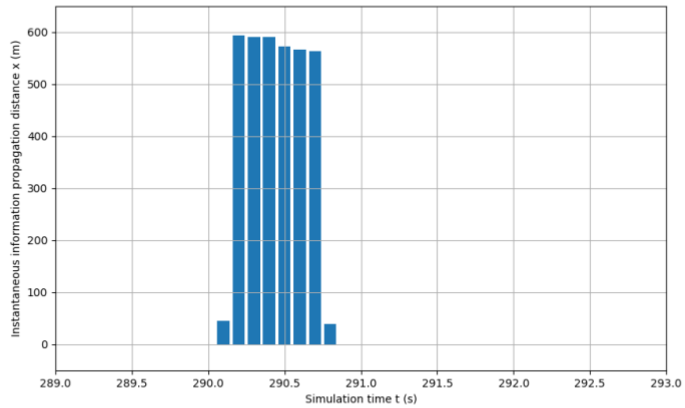


Figure 40. Instantaneous information propagation distance vs. time, case 13

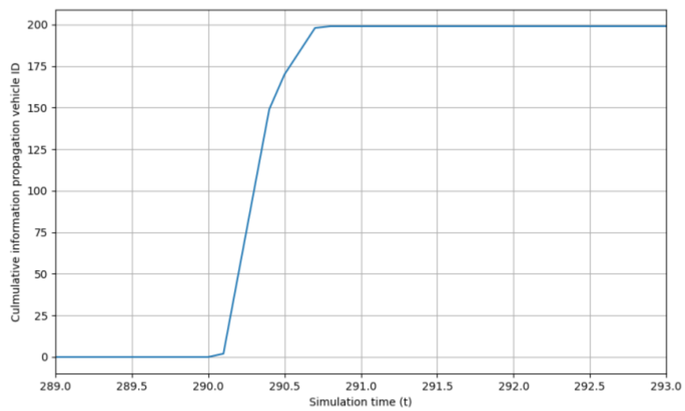


Figure 41. Information propagation vehicle ID vs. time, case 13

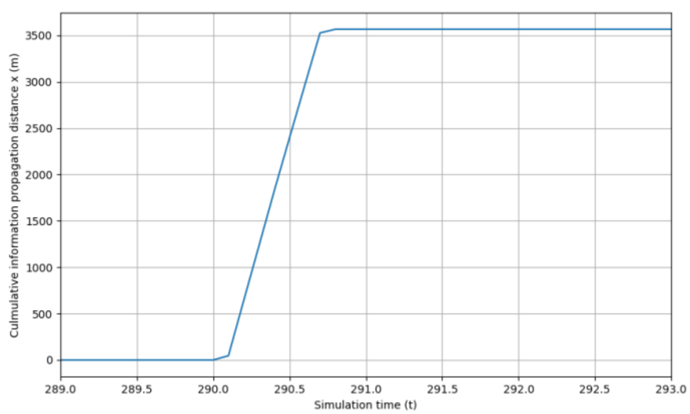


Figure 42. Cumulative info propagation distance vs. time, case 13

Case 14: CIDM with constant speed leader, receive_info_num_cars = 9, communication range=600, random initial distance

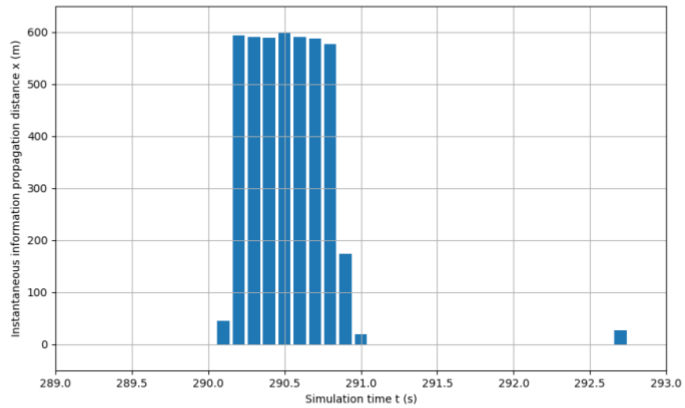


Figure 4333. Instantaneous information propagation distance vs. time, case 14

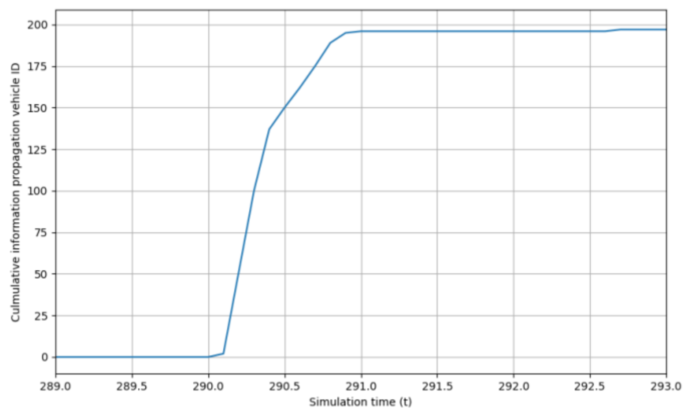


Figure 4434. Information propagation vehicle ID vs. time, case 14

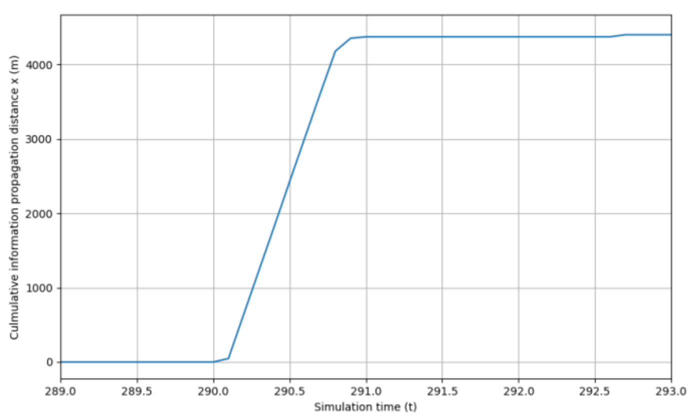


Figure 4535. Cumulative info propagation distance vs. time, case 14

Case 15: CIDM with constant speed leader, receive_info_num_cars = 3, communication range=200, random initial distance

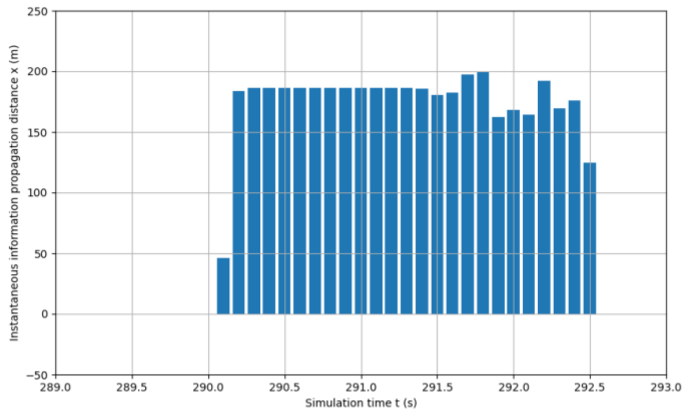


Figure 46. Instantaneous information propagation distance vs. time, case 15

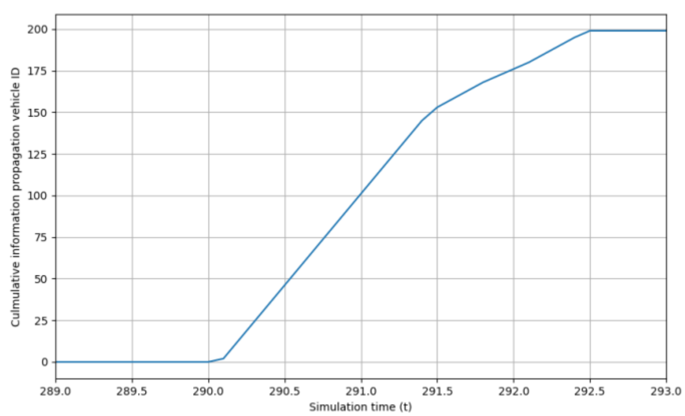


Figure 47. Information propagation vehicle ID vs. time, case 15

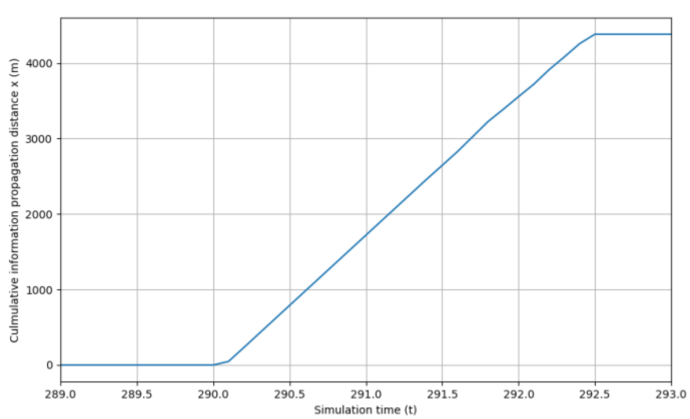


Figure 48. Cumulative info propagation distance vs. time, case 15

Case 16: CIDM with constant speed leader, receive_info_num_cars = 1, communication range=200, random initial distance

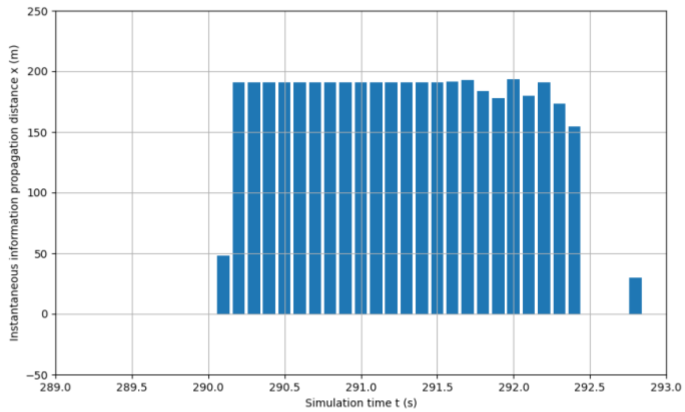


Figure 4936. Instantaneous information propagation distance vs. time, case 16

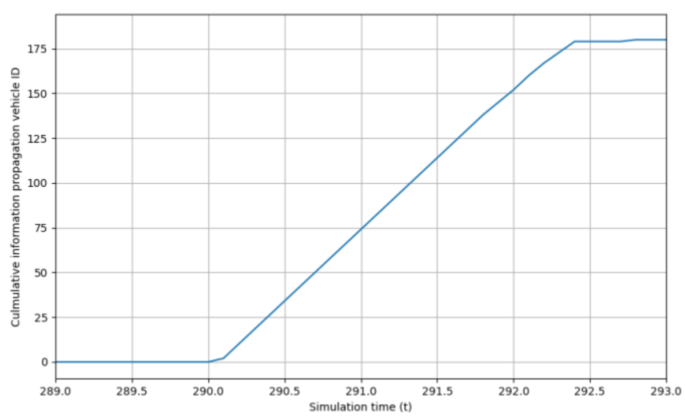


Figure 5037. Information propagation vehicle ID vs. time, case 16

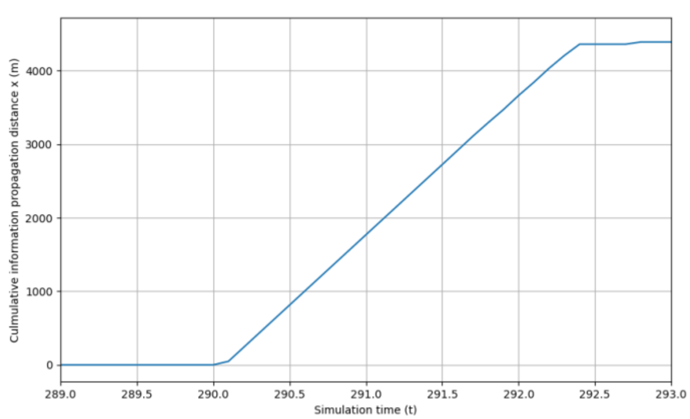


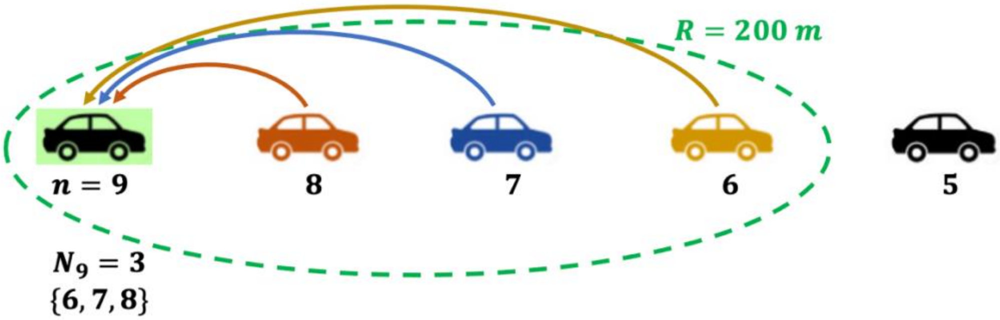
Figure 5138. Cumulative info propagation distance vs. time, case 16

Appendix II: Pseudocode of Main Functions

```
function test()
     Set up the simulation by calling the simulation class
     Run the simulation by calling the window class

class Simulation()
     Initialize parameters
     Create the road
     Call vehicle generator
     For each vehicle:
          calculate leading vehicles in communication range
          Log the location

class Window()
     Visualize the simulation by drawing the window that
     displays it
     Run the simulation in a loop
     Plot the simulation when the simulation finishes

class Road()
     Update the position/velocity/acceleration of the vehicles
     base on their order on the road
     Update the information status of whether the vehicle
     receive the information at time t

class VehicleGenerator()
     Generate a platoon of vehicles with appropriate spacing

class Vehicle()
     define constants and initial condition
     calculate vehicle motion using the C-DIM equations

function update()
     if the space between two vehicles is less than r:
          update vehicle class attributes (position, velocity,
          and acceleration) to stop or slow down based on its
          leading vehicle’s attributes

# Generate a list of selected vehicles that are in communication
range
function multicast(other car’s position)
     for each car on the road:
          if the car is in the current car’s communication
          range:
          put the car in the candidate list
               Sort the candidate list by its position
```

```
Return first k closest cars
```

Appendix III: Broadcast vs. Multicast Example Illustration



Let n be the total number of vehicles, and N be the number of vehicles within the communication range $R = 200$m. For $n = 9, N = 3$, vehicles 8, 7, 6 are within the communication range. Thus the acceleration of vehicle 9 is:

$$\dot{v}_9(t) = a\left(1 - \left(\frac{v_9(t)}{v_0}\right)^4 - \left(\frac{s^*\left(v_9(t), \Delta v_{9,8}(t), \Delta v_{9,7}(t), \Delta v_{9,6}(t)\right)}{\alpha_{9,8}w_{9,8}s_{9,8}(t) + \alpha_{9,7}w_{9,7}s_{9,7}(t) + \alpha_{9,6}w_{9,6}s_{9,6}(t)}\right)^2\right)$$

$$s^*\left(v_9(t), \Delta v_{9,8}(t), \Delta v_{9,7}(t), \Delta v_{9,6}(t)\right) = s_0 + Tv_9(t) + \frac{v_9(t)}{2\sqrt{ab}}\left(\beta_{9,8}w_{9,8}\Delta v_{9,8}(t) + \beta_{9,7}w_{9,7}\Delta v_{9,7}(t) + \beta_{9,6}w_{9,6}\Delta v_{9,6}(t)\right)$$

When R changes, N change. Furthermore, when switching from broadcast to multicast, w change as well. The acceleration of a vehicle changes with different communication range R and multicast design.

Broadcast Method:

If vehicle i is in the communication range of vehicle 9, $w_{9,i} = 1$, otherwise $w_{9,i} = 0$.

$$\dot{v}_9(t) = a\left(1 - \left(\frac{v_9(t)}{v_0}\right)^4 - \left(\frac{s_0 + Tv_9(t) + \frac{v_9(t)}{2\sqrt{ab}}\left(\beta_{9,8}\Delta v_{9,8}(t) + \beta_{9,7}\Delta v_{9,7}(t) + \beta_{9,6}\Delta v_{9,6}(t)\right)}{\alpha_{9,8}s_{9,8}(t) + \alpha_{9,7}s_{9,7}(t) + \alpha_{9,6}s_{9,6}(t)}\right)^2\right)$$

$$\Delta v_{9,8} = v_9 - v_8$$
$$s_{9,8} = x_8 - x_9 - l$$
$$\Delta v_{9,7} = v_9 - v_7$$
$$s_{9,7} = x_7 - x_9 - l$$

$$\Delta v_{9,6} = v_9 - v_6$$
$$\mathrm{s}_{9,6} = x_6 - x_9 - l$$

Weighting factors:

$$\alpha_{9,8} + \alpha_{9,7} + \alpha_{9,6} = 1 \tag{1}$$
$$\beta_{9,8} + \beta_{9,7} + \beta_{9,6} = 1 \tag{2}$$

(We can choose many options of α, β as long as $(1)(2)$ are satisfied.
For example, $\alpha_{9,8} = 0.5, \alpha_{9,7} = 0.3, \alpha_{9,6} = 0.2, \beta_{9,8} = 0.5, \beta_{9,7} = 0.3, \beta_{9,6} = 0.2)$

Multicast Method:

Define an example strategy: $w_{9,8} = 1, w_{9,7} = 1, w_{9,6} = 0$ (there can be many multicast designs).

$$\dot{v}_9(t) = a\left(1 - \left(\frac{v_9(t)}{v_0}\right)^4 - \left(\frac{s_0 + Tv_9(t) + \frac{v_9(t)}{2\sqrt{ab}}\left(\beta_{9,8}\Delta v_{9,8}(t) + \beta_{9,7}\Delta v_{9,7}(t) + \cancel{\beta_{9,6}\Delta v_{9,6}(t)}\right)}{\alpha_{9,8}s_{9,8}(t) + \alpha_{9,7}s_{9,7}(t) + \cancel{\alpha_{9,6}s_{9,6}(t)}}\right)^2\right)$$

$$\dot{v}_9(t) = a\left(1 - \left(\frac{v_9(t)}{v_0}\right)^4 - \left(\frac{s_0 + Tv_9(t) + \frac{v_9(t)}{2\sqrt{ab}}\left(\beta_{9,8}\Delta v_{9,8}(t) + \beta_{9,7}\Delta v_{9,7}(t)\right)}{\alpha_{9,8}s_{9,8}(t) + \alpha_{9,7}s_{9,7}(t)}\right)^2\right)$$

$$\Delta v_{9,8} = v_9 - v_8$$
$$\mathrm{s}_{9,8} = x_8 - x_9 - l$$
$$\Delta v_{9,7} = v_9 - v_7$$
$$\mathrm{s}_{9,7} = x_7 - x_9 - l$$

Weighting factors:

$$\alpha_{9,8} + \alpha_{9,7} = 1$$
$$\beta_{9,8} + \beta_{9,7} = 1$$

(We still have many options of α, β. For example, $\alpha_{9,8} = 0.6, \alpha_{9,7} = 0.4, \beta_{9,8} = 0.6, \beta_{9,7} = 0.4)$

Parameters:

$$v_0 = 120\ km/h$$
$$s_0 = 2\ m$$
$$T = 1.1\ s$$
$$a = 1\ m/s^2$$
$$b = 2\ m/s^2$$

$$l = 5\ m$$

Weighting factors:

$$\alpha_{9,8} + \alpha_{9,7} + \alpha_{9,6} = 1. \quad (1)$$
$$\beta_{9,8} + \beta_{9,7} + \beta_{9,6} = 1. \quad (2)$$

We can choose many options of $\alpha, \beta\ as\ long\ as$ (1)(2) are met. For example,

$$\alpha_{9,8} = 0.5, \alpha_{9,7} = 0.3, \alpha_{9,6} = 0.2,$$
$$\beta_{9,8} = 0.5, \beta_{9,7} = 0.3, \beta_{9,6} = 0.2.$$

The acceleration of a vehicle changes with different communication range R and multicast design.

$$R\ change \Rightarrow N\ change, further\ change\ broadcast\ to\ multicast \Rightarrow w\ change$$