TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FMRI-YR5- 22	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CONTROL OF AUTOMATED TRUCKS CONSIDERING STOCHASTIC BEHAVIORS OF HUMAN-DRIVEN VEHICLES IN MIXED TRAFFIC		5. Report Date: May 2022 6. Performing Organization Code:
7. Author(s) Xiao Xiao, Yulong Zhang, Bruce Wang,		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas A&M University Freight Mobility Research Institute		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 69A3551747120
12. Sponsoring Agency Name and Address Freight Mobility Research Institute Florida Atlantic University 777 Glades Rd., Bldg. 36, Boca Raton, FL 33431		13. Type of Report and Period: Final 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Freight traffic affects the performance of the road network significantly due to their different driving characteristics compared to passenger cars. For example, trucks have extra braking distance and time for deceleration and are slower when starting up. In Texas, freight traffic can be significant on the freeway, and the operation of trucks is significant in keeping traffic safe and efficient. Recently, connected and automated vehicle technology has added possibilities to control trucks wisely to improve safety and mobility. Strategies have been developed in the FMRI first and second-year projects to formulate multiple trucks' trajectories considering mixed traffic conditions. The stability problem of vehicle streams has been studied in the third-year project. However, in previous research, deterministic behaviors of human-driven vehicles in mixed traffic were assumed. In reality, truck drivers may act differently (accelerating, decelerating, reacting) according to their varying driving habits, which will lead to uncertainties in the vehicle dynamic system. To make the research more complete and more general, this year, behaviors of human-driven vehicles are considered. This project investigates the method for CAV truck controlling in a truck-only lane. By controlling CAV trucks, the mixed traffic is stabilized and optimized in its mobility given different levels and distribution types of the uncertainty of human-driven vehicles.

The outcomes show a control method for CAVs enables the traffic with safe and stable performances considering human drivers. Due to the limitation of time (one year), the research only focuses on theoretical modeling at the present stage. In the implementation stage in the future, local agencies or industry partners may be involved.

17. Key Words Platooning, CAV, Mixed Traffic	18. Distribution Statement No restrictions. This document is available to the public through Fmri.fau.edu		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

FREIGHT MOBILITY RESEARCH INSTITUTE
College of Engineering & Computer Science
Florida Atlantic University

Project ID: Y6R5-22

CONTROL OF AUTOMATED TRUCKS CONSIDERING STOCHASTIC BEHAVIORS OF HUMAN-DRIVEN VEHICLES IN A MIXED TRAFFIC

Final Report

by

Xiao Xiao
Texas A&M University, College Station
400 Bizzell St, College Station, TX 77843
E-mail: xx1991@tamu.edu

Yunlong Zhang, Ph.D.
Texas A&M University, College Station
400 Bizzell St, College Station, TX 77843
E-mail: yzhang@civil.tamu.edu

Bruce Wang, Ph.D.
Texas A&M University, College Station
400 Bizzell St, College Station, TX 77843
E-mail: bwang@civil.tamu.edu

for

Freight Mobility Research Institute (FMRI)
Florida Atlantic University
777 Glades Rd.
Boca Raton, FL 33431

May, 2021

ACKNOWLEDGEMENTS

This project was funded by the Freight Mobility Research Institute (FMRI), one of the twenty TIER University Transportation Centers that were selected in this nationwide competition, by the Office of the Assistant Secretary for Research and Technology (OST-R), U.S. Department of Transportation (US DOT).

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXCUTIVE SUMMARY

Freight traffic affects the performance of the road network significantly due to their different driving characteristics compared to passenger cars. For example, trucks have extra braking distance and time for deceleration and are slower when starting up. In Texas, freight traffic can be significant on the freeway, and the operation of trucks is significant in keeping traffic safe and efficient. Recently, connected and automated vehicle technology has added possibilities to control trucks wisely to improve safety and mobility. Strategies have been developed in the FMRI first and second-year projects to formulate multiple trucks' trajectories considering mixed traffic conditions. The stability problem of vehicle streams has been studied in the third-year project. However, in previous research, deterministic behaviors of human-driven vehicles in mixed traffic were assumed. In reality, truck drivers may act differently (accelerating, decelerating, reacting) according to their varying driving habits, which will lead to uncertainties in the vehicle dynamic system. To make the research more complete and more general, this year, behaviors of human-driven vehicles are considered. This project investigates the method for CAV truck controlling in a truck-only lane. By controlling CAV trucks, the mixed traffic is stabilized and optimized in its mobility given different levels and distribution types of the uncertainty of human-driven vehicles.

The outcomes show a control method for CAVs enables the traffic with safe and stable performances considering human drivers. Due to the limitation of time (one year), the research only focuses on theoretical modeling at the present stage. In the implementation stage in the future, local agencies or industry partners may be involved.

1.0 INTRODUCTION

In an era of transitioning from conventional human-driven vehicles to CAVs, upgrading infrastructure is a time-consuming process. It is necessary to develop techniques that fit existing features, such as signals, when transitioning from human-driven vehicles to CAVs (Guanetti et al., 2018). AVs and HVs will be exiting in a traffic stream simultaneously as expected in a long period. When the traffic consists of both HVs and AVs, as well as cars and trucks, the steady state becomes different and complex, and it is challenging to design controllers. Some previous studies are to coordinate human-driven vehicles and CAVs to optimize mobility and emissions. (Dresner and Stone, 2008; Carlino et al., 2013). When HVs are considered, the sequence of the mixed traffic needed to be assumed in design of an active control; (Zhao et al., 2018) used scenarios in the experiment to show the possible combination of HVs and CAVs. Using a car-following model, in this case, is efficient in modeling AVs. Among all AV control algorithms, the IDM model is one of the most popular car-following models designed for adaptive cruise control (ACC) for AVs.

The operation strategy of connected and automated vehicles at intersections can either be modeled in a centralized way, as the studies using dynamic programming or cooperative control mentioned before, or a decentralized way. For example, (Du et al., 2018) developed a multi-layer coordination strategy for CAVs at intersections without the help of signals. (Yao and Li, 2020) proposed a decentralized control method for CAVs at intersections to optimize their own travel time, fuel consumption, safety risks, and show that is more computationally efficient than centralized control. (Mahbub et al., 2020) developed a coordination method for CAVs at a corridor considering multiple traffic scenarios using a two-level optimization. A decentralized control can be applied to address similar problems (Kuwata and How, 2006). (Ravikumar et al., 2021) developed a centralized coordination method for scheduling CAVs in a mixed environment when human-driven vehicles are included using mixed-integer linear programming (MILP). (Wu et al., 2014) introduced a sequence-based system by using an onboard signalization and modeling based on Petri Nets (PN) model that accommodated both CAVs and human-driven vehicles and showed improvement compared to current intersection controls.

Previous studies used a centralized method to solve the problem that multiple vehicles along multiple intersections (Liu et al., 2019). It can reach a global minimum value while a decentralized method cannot. However, HVs, which were uncontrollable in a platoon, cannot react according to other CAVs in a real-time manner. To solve this problem, the stability of heterogeneous (mixed of cars and trucks) mixed (mixed of AVs and HVs) traffic is analyzed. The relationship between tracking speed and stability is investigated under the different ratios of AVs or Trucks. Previous publications have modeled the planning using optimal control for CAV traffic (Xiao et al., 2021) and stability problem under mixed traffic condition (Xiao et al., 2023), this research provide one-step further results and analysis based on previous models.

The project objective aligns with the FMRI area of Information Technology, where the research defines the most efficient means for performance-based freight fluidity network management. The research develops methods for understanding, operating, and modeling multimodal freight transportation networks, which also fits the FMRI area of Freight Network Modeling and Operations.

2.0 METHOLOGY

This chapter describes the method to analyze the stability problem for mixed traffic with passenger cars and trucks as AVs (automated vehicles) or HVs (human driven vehicles). Subsequently, the simulation framework is developed based on the analytical results. Both AVs and HVs are supposed to travel on the IDM model. The aim is to guarantee mobility and stability for traffic.

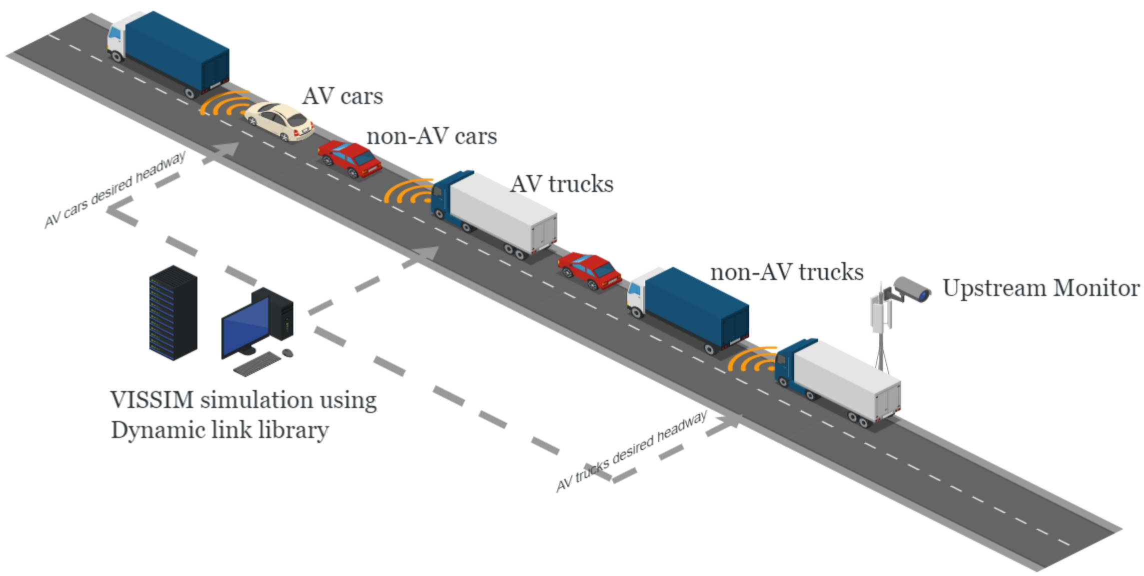


Figure 1 The schematic concept for mixed traffic with automated cars and trucks (drawn by icograms)

2.1 STABLITY AND THROUGHPUT FOR FREIGHT TRAFFIC

The problem concerns a situation when traffic is composed of AVs, HVs, passenger cars, trucks, technical flow is demonstrated in o Figure 2.

A string stability condition theory is developed based on existing theory by considering AV and HV with different vehicle types at the same time. Parameters that determine stability regions are maximal acceleration, comfortable deceleration, and desired headway when taking IDM as an example. The threshold exists for each parameter as the minimum value that can lead to stable traffic. In the process of analysis, other parameters are fixed while letting one or two parameters varied. The relationship between AV drive intervals and stability is investigated using different AV market penetration rates and different truck rates.

By applying CAV technology, an adaptive tracking method to ensure traffic stability and throughput in a mixed traffic environment of passenger cars and trucks as either AV or HV.

Finally, the proposed method is validated in an urban street built in VISSIM by applying the VISSIM External Driver Model Dynamic-link library (DLL).

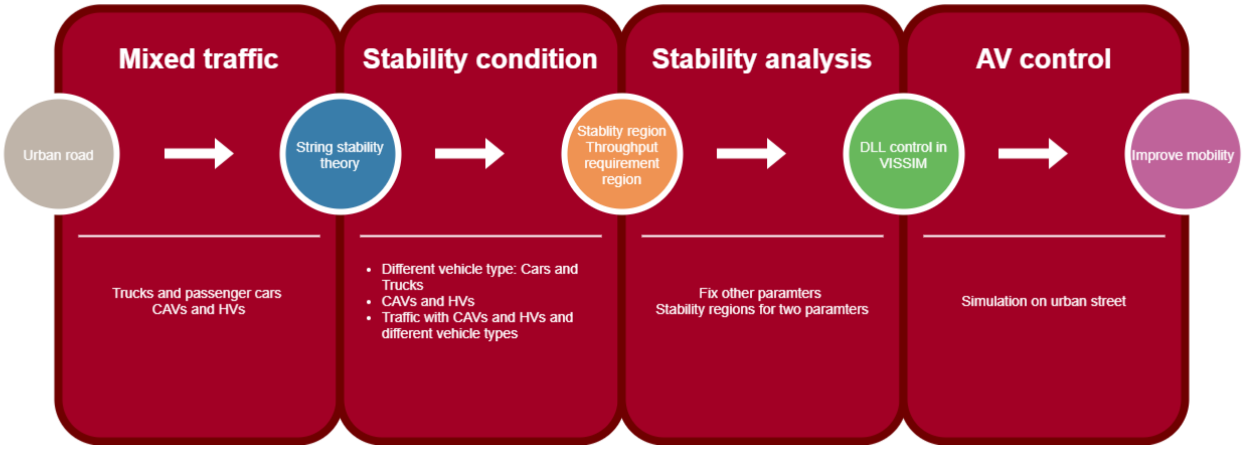


Figure 2 The technical flow of the system

In this part, the stability condition is formulated. The acceleration of a microscopic car-following model concerning relative spacing and speed with reaction time can be described as Ngoduy, "Analytical Studies on the Instabilities of Heterogeneous Intelligent Traffic Flow.".

$$\frac{dv_n(t)}{dt} = f_n(v_n(t-\tau_n^v), s_n(t-\tau_n^s), \Delta v_n(t-\tau_n^{\Delta v})) \tag{1}$$

where s_n is the spacing between the subject vehicle and the preceding vehicle, v_n is the speed of the subject vehicle, Δv_n is the relative speed between the subject vehicle and the preceding vehicle. $\tau_n^v\ \tau_n^s\ \tau_n^{\Delta v}$show the reaction time for relative speed, spacing, and speed respectively. Assuming $\tau_n^v = \tau_n^s = \tau_n^{\Delta v} = \tau_H$,for a car-following model, the derivation of the speed in its equilibrium state can be expressed as :

$$\dot{v_n} = f(s_e, v_e, u_e)_t + \left.\frac{\partial f}{\partial s}\right|_e (s - s_e) + \left.\frac{\partial f}{\partial v}\right|_e (v - v_e) + \left.\frac{\partial f}{\partial \Delta v}\right|_e (\Delta v - u_e) \tag{2}$$

s_e, v_e, u_e are the equilibrium spacing, speed and deviation of speed difference, $f(s_e, v_e, u_e)_t = 0$ and $u_e = 0$.

Define the Taylor expansion coefficients for the derivative terms:

$$f_s = \left.\frac{\partial f}{\partial s}\right|_e \tag{3}$$

$$f_v = \left.\frac{\partial f}{\partial v}\right|_e \tag{4}$$

$$f_{\Delta v} = \frac{\partial f}{\partial \Delta v}\Big|_e \tag{5}$$

IDM model writes:

$$\dot{v} = \alpha\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*}{s}\right)\right] \tag{6}$$

$$s^* = s_0 + Tv - \frac{v*\Delta v}{2\sqrt{\alpha\beta}} \tag{7}$$

where α, β are the maximal acceleration and comfortable deceleration respectively. T is the desired headway. Except for v_e, all other parameters of cars and trucks are different. Let $f_{C,v}$ $f_{C,\Delta v}$ $f_{C,s}$ represent the Taylor expansion coefficients for cars and $f_{T,v}$ $f_{T,\Delta v}$ $f_{T,s}$ for trucks:

$$f_{C,v} = \frac{\alpha_C}{s_{C,e}}\left(\frac{s_{C,0}+T_C v_e}{s_{C,e}}\right)^2, f_{T,v} = \frac{\alpha_T}{s_{T,e}}\left(\frac{s_{T,0}+T_T v_e}{s_{T,e}}\right)^2 \tag{8}$$

$$f_{C,v} = -\alpha_C\left[\frac{4}{v_{C,0}}\left(\frac{v_e}{v_{C,0}}\right)^3 + \frac{2T_C(s_{C,0}+T_C v_e)}{{s_{C,e}}^2}\right], f_{T,v} = -\alpha_T\left[\frac{4}{v_{T,0}}\left(\frac{v_e}{v_{T,0}}\right)^3 + \frac{2T_T(s_{T,0}+T_T v_e)}{{s_{T,e}}^2}\right] \tag{9}$$

$$f_{C,\Delta v} = \sqrt{\frac{\alpha_C}{\beta_C}}\frac{v_e}{v_{C,0}}\frac{s_{C,0}+T_C v_e}{s_{C,e}}, f_{T,\Delta v} = \sqrt{\frac{\alpha_T}{\beta_T}}\frac{v_e}{v_{T,0}}\frac{s_{T,0}+T_T v_e}{s_{T,e}} \tag{10}$$

To improve mobility while serving the flow demand, the desired headway is related to demand. Due to the inverse relation between flow and headway, the desired headway has an upper bound. In the following part, the stability conditions for heterogeneous traffic with cars and trucks, for mixed traffic with AVs and HVs, for mixed traffic and heterogeneous traffic are demonstrated respectively.

The string stable condition can be derived from the analysis of the signal between two consecutive vehicles in a single follower problem. The energy in the frequency domain caused by the perturbation should decrease to ensure string stability. The theory has been widely studied. This research directly adopts some of the conclusions from previous studies and makes progress based on that. According to (Ngoduy, 2015b), the stability condition for heterogeneous traffic with cars and trucks.

$$r_C\left(\frac{1}{2} - \frac{f_{C,\Delta v}}{f_{C,v}} - \frac{f_{C,s}}{{f_{C,v}}^2}\right) + r_T\left(\frac{1}{2} - \frac{f_{T,\Delta v}}{f_{T,v}} - \frac{f_{T,s}}{{f_{T,v}}^2}\right) > 0 \tag{11}$$

where the ratio of trucks is denoted as r_T and cars denoted as r_c, which add up to 1.

$$r_C + r_T = 1 \tag{12}$$

To satisfy the throughput which represents demand, the average desired headway should be smaller than the inverse of flow demand.

$$(r_1 h_1 + r_2 h_2) \le \bar{h} = \frac{3600}{q} \tag{13}$$

According to (Ngoduy, 2013) When traffic is composed of HVs and AVs, the reaction time for human drivers is considered to differentiate them:

$$r_A + r_H = 1 \tag{14}$$

$$r_A\left(\frac{1}{2}-\frac{f_{A,\Delta v}}{f_{A,v}}-\frac{f_{A,s}}{{f_{A,v}}^2}\right)+r_H\left(\frac{1}{2}-\frac{f_{H,\Delta v}}{f_{H,v}}-\frac{f_{H,s}}{{f_{H,v}}^2}+\frac{f_{H,s}}{f_{H,v}}*\tau_H\right)>0 \tag{15}$$

To server the demand, the average desired headway should be smaller than the inverse of flow demand.

$$r_H h_H + r_A h_A \le \bar{h} = \frac{3600}{q} \tag{16}$$

2.2 CONDITION WITH A MIXED TRAFFIC OF AVS AND HVS IN DIFFERENT VEHICLE TYPES

Based on previous studies, the stability condition for Heterogeneous and mixed traffic are given: Let r_A show the ratio of AVs and r_T the ratio of trucks. r_1 r_2 r_3 r_4 show the ratio of HV cars, HV trucks, AV cars and AV trucks respectively:

$$r_1 = (1-r_A)(1-r_T) \tag{17}$$

$$r_2 = (1-r_A)*r_T \tag{18}$$

$$r_3 = r_A*(1-r_T) \tag{19}$$

$$r_4 = r_A*r_T \tag{20}$$

The string stability condition for heterogeneous and mixed traffic considering a linear combination of all the vehicle types with the weighting of their ratios is given as:

$$r_1\left(\frac{1}{2}-\frac{f_{1,\Delta v}}{f_{1,v}}-\frac{f_{1,s}}{{f_{1,v}}^2}\right)+r_2\left(\frac{1}{2}-\frac{f_{2,\Delta v}}{f_{2,v}}-\frac{f_{2,s}}{{f_{2,v}}^2}\right)+r_3\left(\frac{1}{2}-\frac{f_{3,\Delta v}}{f_{3,v}}-\frac{f_{3,s}}{{f_{3,v}}^2}+\frac{f_{3,s}}{f_{3,v}}\tau_3\right)+r_4\left(\frac{1}{2}-\frac{f_{4,\Delta v}}{f_{4,v}}-\frac{f_{4,s}}{{f_{4,v}}^2}+\frac{f_{4,s}}{f_{4,v}}\tau_4\right)>0 \tag{21}$$

Similarly, the average desired headway should be smaller than the inverse of flow demand.

$$r_1*h_1+r_2*h_2+r_3*h_3+r_4*h_4 \le \bar{h} = \frac{3600}{q} \tag{22}$$

For cars and trucks, the dynamic parameters such as acceleration and deceleration should be in the feasible region:

$$\alpha_C, \beta_C \in \Phi_C; \alpha_T, \beta_T \in \Phi_T \tag{23}$$

where Φ_C and Φ_T show the feasible region of vehicle dynamic parameters of cars and trucks.

2.3 OPTIMAL CONTROL FOR VEHICLE TRAJECTORY WITH A MIXED TRAFFIC OF AVS AND HVS IN DIFFERENT VEHICLE TYPES

Human vehicles and mixed traffic scenarios are also considered to add to previous model for vehicles passing multiple intersections as described in previous FMRI reports. These models and formulations are added to previous models to consider the human vehicles and mixed traffic:

The total travel time of vehicles along a lane can be written as:

$$\begin{aligned}
\min_{z_{n,i}} \sum_{n=1}^{N} \sum_{i=1}^{I} T_{n,i} \\
&= \min \underbrace{\left(\sum_{i=1}^{I} T_{1,i} + \sum_{i=1}^{I} T_{2,i} + \cdots + \sum_{i=1}^{I} T_{m,i} \right)}_{CAVs} \\
&+ \underbrace{\left(\sum_{i=1}^{I} T_{m+1,i} + \cdots \sum_{i=1}^{I} T_{m+2,i} + \sum_{i=1}^{I} T_{n,i} \right)}_{HVs} \\
&= \min \left(\sum_{1}^{m} \big(\tau_1(n) + \tau_2(n) \ldots + \tau_i(n) \big) + \sum_{1}^{m} (\Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)) \right) \\
&+ \sum_{m+1}^{n} (\tau_1(n) + \tau_2(n) \ldots + \tau_i(n)) + \sum_{m+1}^{n} (\Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n))
\end{aligned}$$

The obligate time to pass a block is $\tau_i(n)$ and time loss is denoted as $\Delta_i(n)$.
Apparently, the only controllable part is $\sum_1^m(\Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$

The previous proposed scenarios reduce the time loss of CAVs term to the largest extend, and the CAVs term does not lead to an increase of HVs term. This means, only if the vehicles are planned as the proposed scenarios, the total travel time of the whole traffic stream can be minimized. For convenience, the planning start from the vehicle which with an earliest starting time.

All the vehicle trajectories in time and space are represented in a manner of Taxicab geometry. In a Taxicab geometry, the metric of distance between two points A and B is the sum of the absolute differences of their Cartesian coordinates:

$$d(A,B) = |X_B - X_A| + |Y_B - Y_A|$$

The optimization to minimize travel time writes:

$$\min_{z_{n,i}} \sum_{n=1}^{N} \sum_{i=1}^{I} T_{n,i} = \min \sum_{n=1}^{N} \Delta X_n$$

Due to the nature of transportation, a vehicle moves from A to B and takes some time. In taxicab geometry, for each move in y-axis, a move in x-axis which is no less than the move in y-axis occurs:

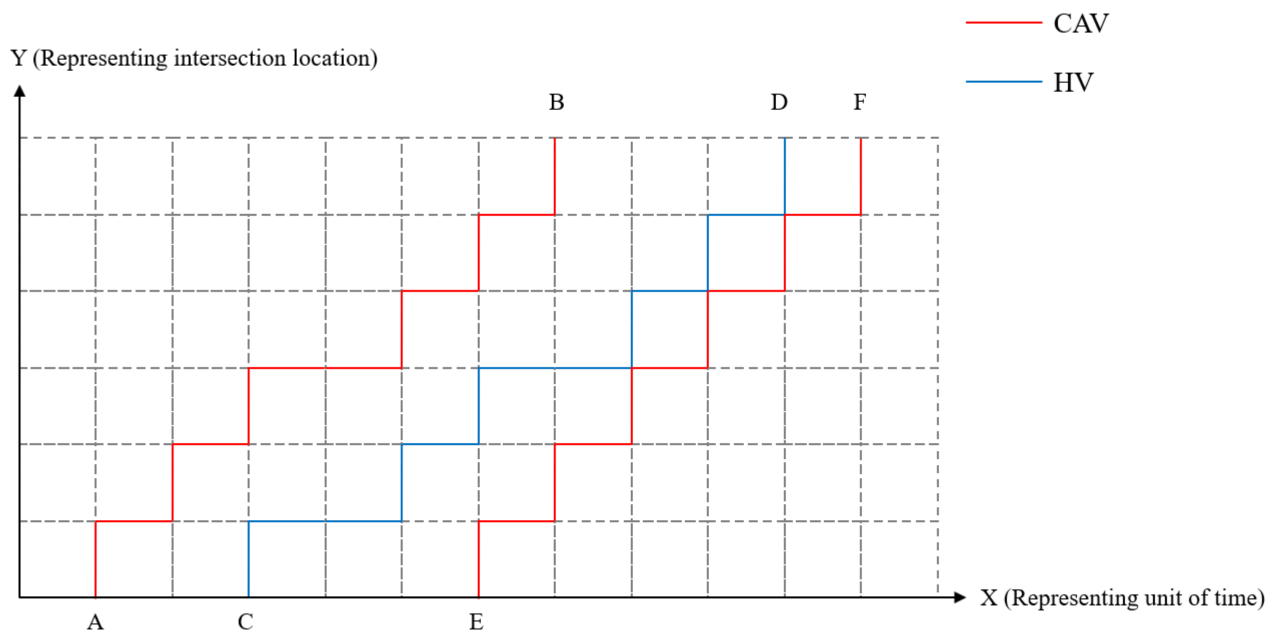


Figure 3 Schematic representation of the problem of mixed traffic of HV and AV.

Define the minimal time to pass a block is $\tau(i)$ and time loss as $\Delta_i(n)$. A time spent at one intersection is:

$$x(2) - x(1) = y(2) - y(1) + \tau(1) + \Delta_i(n)$$

Going through intersection 1 to intersection i:

$$x(2) - x(1) = y(2) - y(1) + \tau(1) + \Delta_1(n)$$
$$x(3) - x(2) = y(3) - y(2) + \tau(2) + \Delta_2(n)$$
$$\cdots$$
$$x(i-1) - x(i-2) = y(i-1) - y(i-2) + \tau(i-1) + \Delta_{i-1}(n)$$
$$x(i) - x(i-1) = y(i) - y(i-1) + \tau(i) + \Delta_i(n)$$

Adding up all the equations and it shows:

$$x(i) - x(1) = y(i) - y(1) + \big(\tau(1) + \tau(2) + \cdots + \tau(i)\big) + \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$

Considering all the vehicles:

$$x1(i) - x1(1) = y1(i) - y1(1) + \big(\tau(1) + \tau(2) + \cdots + \tau(i)\big) + \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$
$$x2(i) - x2(1) = y2(i) - y2(1) + \big(\tau(1) + \tau(2) + \cdots + \tau(i)\big) + \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$

$$\dots$$
$$xn(i) - xn(1) = yn(i) - yn(1) + \left(\tau(1) + \tau(2) + \cdots + \tau(i)\right) + \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$

If each vehicle has to travel the same distance in Y axis, $|y(B) - y(A)|$ for each vehicle is identical. So $\sum_{n=1}^{N} \Delta Y_n$ is also a constant, denoted as C_1.
$\tau(1) + \tau(2) + \cdots + \tau(i)$ is the inevitable time cost at one single intersection. Assuming that in a heavy or moderate traffic condition, the arrival of vehicles follows a uniform distribution. When the timing plan and the volume of traffic is determined. It is also a Constance, denoted as C_2.

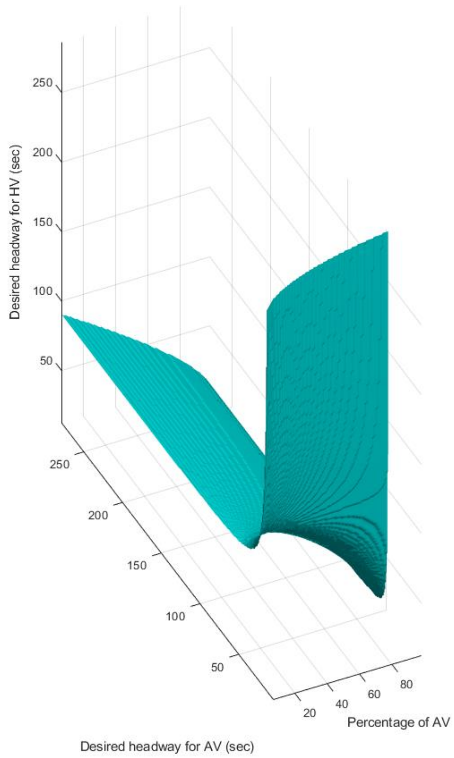
$$\sum_{n=1}^{N} \Delta X_n = C_1 + C_2 + \sum_{1}^{n} \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$

$$\sum_{1}^{n} \Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)$$
$$= \underbrace{\sum_{1}^{m} \left(\Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)\right)}_{CAVs} + \underbrace{\sum_{n-m+1}^{n} \left(\Delta_1(n) + \Delta_2(n) \ldots + \Delta_i(n)\right)}_{HVs}$$

3.0 RESULTS

3.1 STABILITY REGION OF PARAMETERS FOR HETEROGENEOUS TRAFFIC OF AVS AND HVS

The stability regions for AV and HV desired headway under the different percentages of AV are presented. All vehicles are assigned with the same parameters except for their reaction time. HVs are assumed to react with a delay time while AVs do not have that delay.



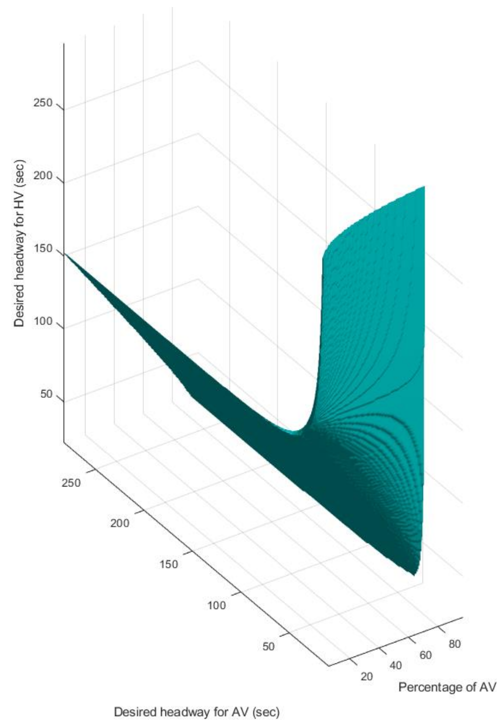


Figure 4 The stability region of maximal acceleration under different penetration rate of AV. reaction time 0.5 sec (left) and 1.0 sec (right) (fixing comfortable deceleration for vehicles as 2 m/s^2; maximal acceleration for vehicles as 1.4 m/s^2)

The results in Figure 4 show that the thresholds for desired headways for both AVs and HVs decrease with the increase of the AV ratio. This shows the selection of desired headway becomes more flexible when the AV ratio is high. The existence of reaction time increases the slope of this trend and increases the lower bound of the thresholds for both AVs and HVs.

3.2 CASE STUDY: VISSIM COMPARISON

The simulation is implemented using parameters shown in Table 2. The proposed method, controlling AV using a fixed headway and IDM model are implemented on Link 1, link 2, link 3 respectively. It shows that the average speed using proposed method is highest compared to other two counterparts.

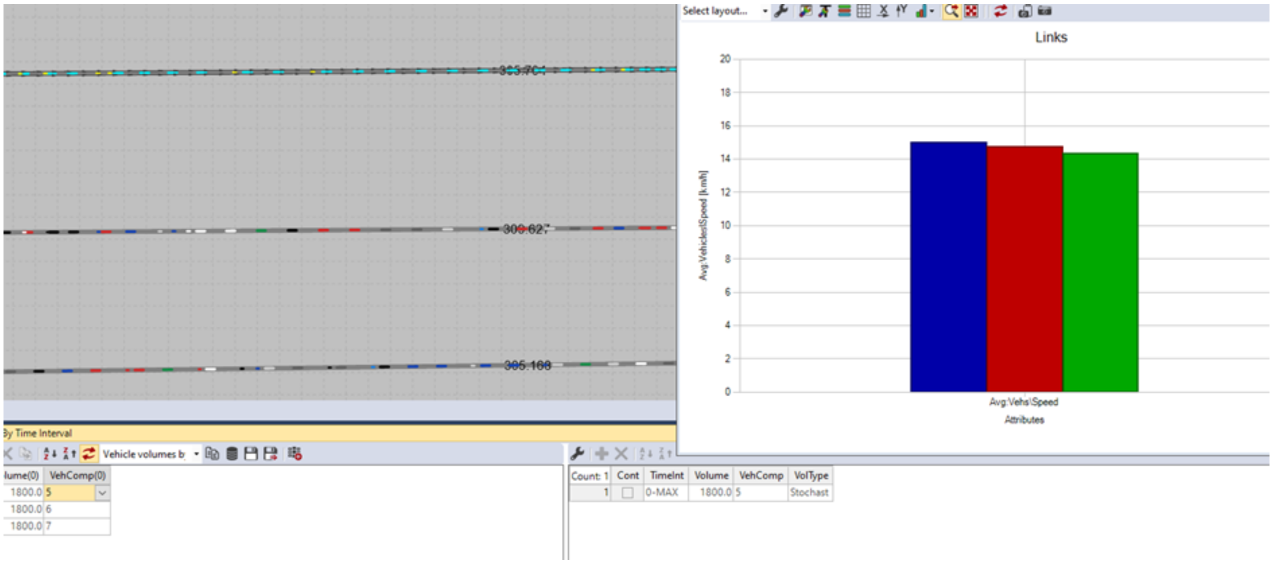
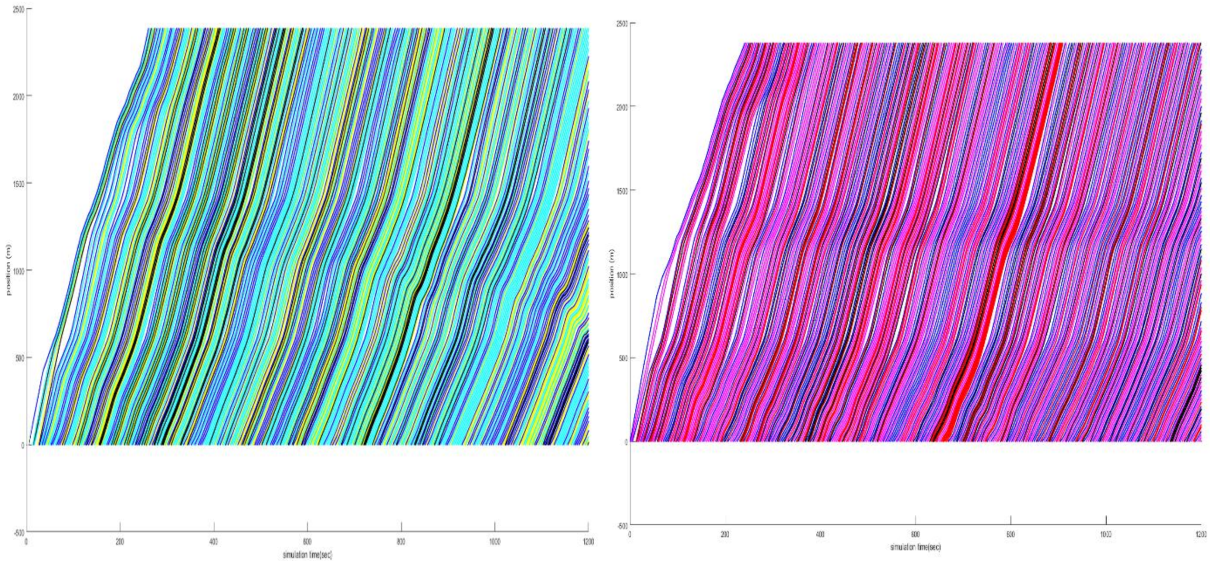


Figure 5 VISSIM simulation and average speed using proposed method compared to fixed AV headway and IDM car following model.

Table 1: VISSIM simulation setup

Length of the link tested (m)	2000
Demand (veh/h)	1800
Desired speed (km/h)	50
Simulation time (sec)	1800
Percentage of trucks	60%
Percentage of AVs	60%
Desired headway for HV car (sec)	1.5
Desired headway for HV Truck (sec)	2
Desired headway for AV car baseline (sec)	1
Desired headway for AV Truck baseline (sec)	1.5

The trajectories of HV cars, HV trucks, AV cars (baseline), AV trucks(baseline) are demonstrated in black, blue, green, and yellow, respectively. AV cars, AV trucks using the proposed method are demonstrated in pink and red, respectively.



(a) (b)

Figure 6 The trajectory from VISSIM simulation Baseline (a) and proposed method perturbation in an area.

In Figure 6, the influences of HV trucks on the traffic is significant in baseline (a). AVs do not adjust their desired headway in the baseline, the traffic becomes unstable with time increases. After time 1000 sec, the oscillation happens. With the proposed method shown in Figure 6 (b), AVs update the desired headways accordingly over time. Early (during time 0 sec and 600 sec), the AV headways are small. When the instability is about to happen, the AV headways become large to avoid oscillation. As a result, traffic is stable and causes less delay. Comparing the aggregated performance for all vehicles, the average delay reduction is 23.19% while the average speed benefit is 9.09% when comparing to the baseline.

3.3 CASE STUDY: OPTIMAL CONTROL RESULTS FOR MIXED TRAFFIC

A result in Figure 7 show the AV has shape the mixed traffic with human vehicles. The proposed method was also tested when different vehicle types were assumed (one can be assumed as car and another truck). There were two types of vehicles with different dynamic properties, such as the maximal speed and maximal acceleration, safety spacing etc. All vehicles were assumed as CAVs. We also assumed the input headway was 5-second and 3-seconds respectively.

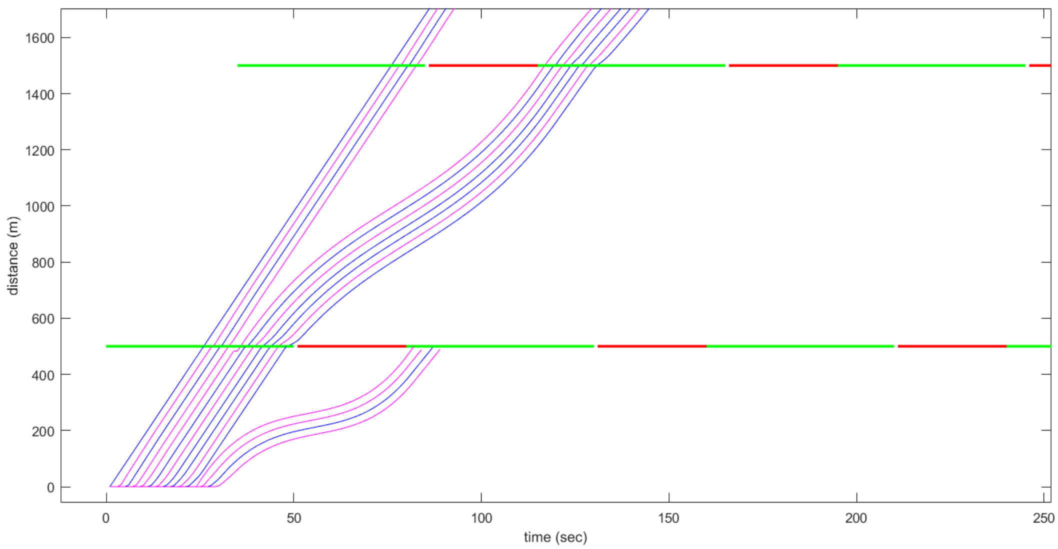


Figure 7 The trajectory from when the traffic is composed of HV and AV

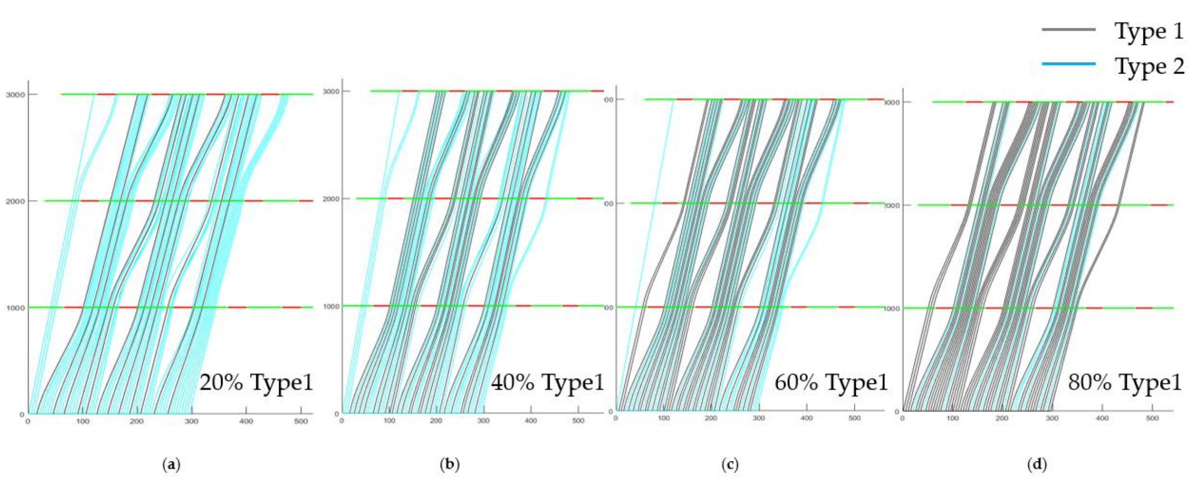


Figure 8 A comparison of trajectories between vehicle type 1 (black) and type 2 (blue) (If all vehicles are CAVs). From left to right, Type 1 percentage: 20%, 40%, 60%, and 80%, headway 5-second; (x-axis – time (sec), y -axis – distance (m))

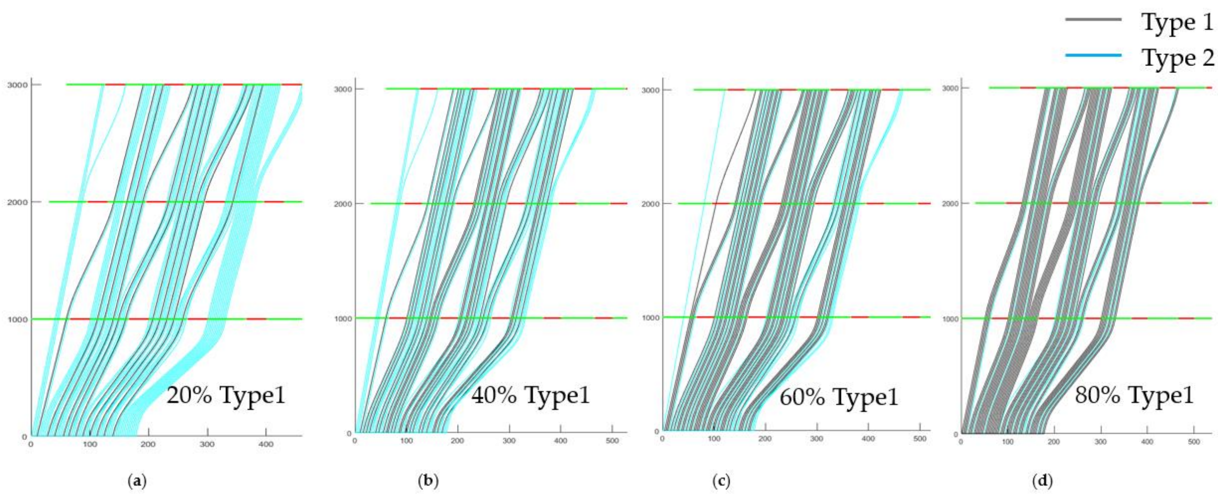


Figure 9 A comparison of trajectories between vehicle type 1 (black) and type 2 (blue) (If all vehicles are CAVs). From left to right, Type 1 percentage: 20%, 40%, 60%, and 80%, headway 3-second; (x-axis – time (sec), y -axis – distance (m))

Under heavy traffic condition that the headway was small, when two types of CAVs were mixed, the vehicles with lager maximal speed tended to perform as its optimal trajectory if the preceding vehicle was not the other type of CAV. Otherwise, the vehicle was bounded by the maximal speed of its preceding vehicle. Generally, due to the distributed structure of our method, the overall traffic stream seemed harmonious.

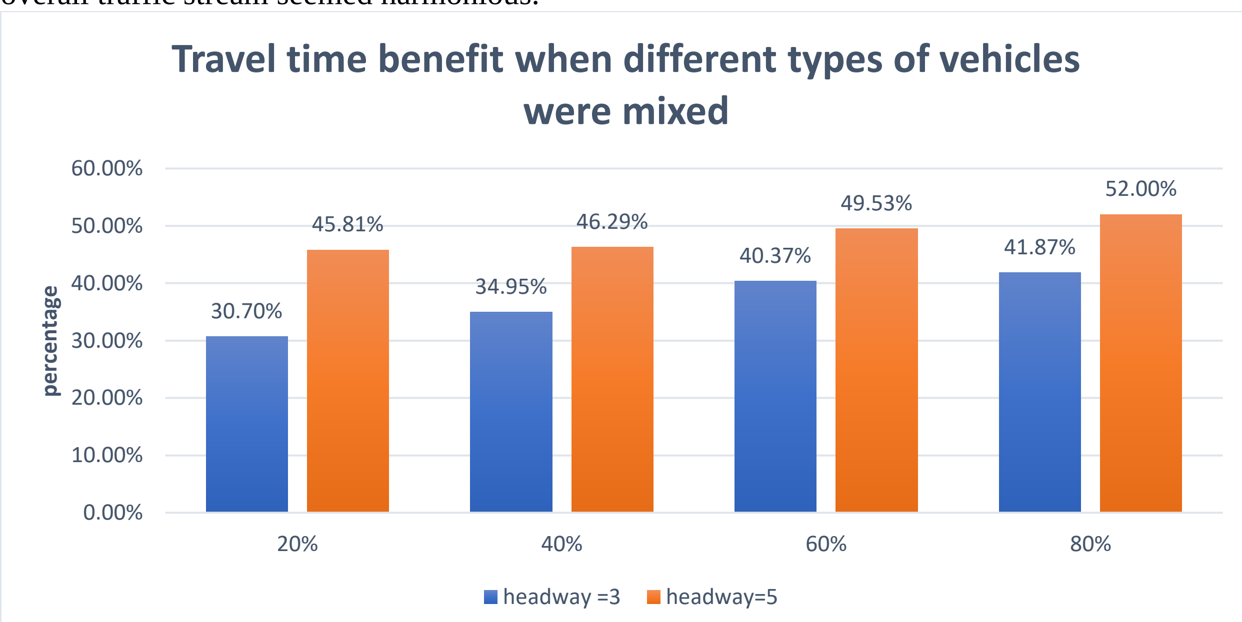


Figure 10 Travel time benefit when the traffic was mixed of two types of CAVs.

When two types of CAVs were mixed, the performances were stable. According to Figure 10the proposed method could reduce the travel time from 30.70 % to 41.87 % when the input headway was 3-second and ranged from 45.81 % to 52.00% when the input headway was 5-second. This result showed the important potential of implementation of the method under mixed traffic condition.

4.0 CONCULUSIONS

Extended stability regions for parameters maximal acceleration, comfortable deceleration, and desired headway are studied. The threshold exists for each parameter as the minimum value that can lead to stable traffic. For maximal acceleration, the thresholds shrink when the percentage is in the middle (around 40% - 60%). The threshold of comfortable declaration decreases with the increase of the ratio of trucks for trucks and increases for cars. When the ratio of trucks is too large, the feasible values for comfortable deceleration almost no exists. The threshold of truck desired headway decreases with the increase of the ratio of trucks and it is the opposite for cars. When considering mixed traffic with AVs and HVs, the reaction time for HVs significantly increases the threshold of desired headway for AVs and HVs. AV ratios lower the thresholds.

The extended optimal control results considered a mix of CAVs and HVs with arbitrary with cars and trucks and show the method can control mixed traffic well as previous models. The limitation was that the status of CAVs and HVs were assumed as deterministic and only a single lane was considered in the problem.

5.0 REFERENCES

Carlino, D., Boyles, S.D., Stone, P., 2013. Auction-based autonomous intersection management, in: 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013). IEEE, pp. 529–534.

Dresner, K., Stone, P., 2008. A multiagent approach to autonomous intersection management. Journal of artificial intelligence research 31, 591–656.

Du, Z., HomChaudhuri, B., Pisu, P., 2018. Hierarchical distributed coordination strategy of connected and automated vehicles at multiple intersections. Journal of Intelligent Transportation Systems 22, 144–158. https://doi.org/10.1080/15472450.2017.1407930

Guanetti, J., Kim, Y., Borrelli, F., 2018. Control of connected and automated vehicles: State of the art and future challenges. Annual reviews in control 45, 18–40.

Kuwata, Y., How, J., 2006. Decentralized cooperative trajectory optimization for UAVs with coupling constraints, in: Proceedings of the 45th IEEE Conference on Decision and Control. IEEE, pp. 6820–6825.

Liu, M., Wang, M., Hoogendoorn, S., 2019. Optimal Platoon Trajectory Planning Approach at Arterials. Transportation Research Record 2673, 214–226. https://doi.org/10.1177/0361198119847474

Mahbub, A.I., Malikopoulos, A.A., Zhao, L., 2020. Decentralized optimal coordination of connected and automated vehicles for multiple traffic scenarios. Automatica 117, 108958.

Ravikumar, S., Quirynen, R., Bhagat, A., Zeino, E., Di Cairano, S., 2021. Mixed-integer Programming for Centralized Coordination of Connected and Automated Vehicles in Dynamic Environment, in: 2021 IEEE Conference on Control Technology and Applications (CCTA). IEEE, pp. 814–819.

Wu, J., Perronnet, F., Abbas-Turki, A., 2014. Cooperative vehicle-actuator system: a sequence-based framework of cooperative intersections management. IET Intelligent Transport Systems 8, 352–360.

Xiao, X., Zhang, Y., Wang, X.B., Guo, X., 2023. Adaptive Headway Control Algorithm for Mixed-Traffic Stabilization and Optimization with Automated Cars and Trucks. Transportation Research Record: Journal of the Transportation Research Board 2677, 234–246. https://doi.org/10.1177/03611981231156587

Xiao, X., Zhang, Y., Wang, X.B., Yang, S., Chen, T., 2021. Hierarchical longitudinal control for connected and automated vehicles in mixed traffic on a signalized arterial. Sustainability 13, 8852.

Yao, H., Li, X., 2020. Decentralized control of connected automated vehicle trajectories in mixed traffic at an isolated signalized intersection. Transportation research part C: emerging technologies 121, 102846.

Zhao, W., Ngoduy, D., Shepherd, S., Liu, R., Papageorgiou, M., 2018. A platoon based cooperative eco-driving model for mixed automated and human-driven vehicles at a signalised intersection. Transportation Research Part C: Emerging Technologies 95, 802–821.