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16. Abstract

On an arterial with significant freight traffic, traffic stability is a issue that can influence mobility. The stability functions of car-following models in mixed traffic have been extensively studied, but most of them focus on the feasible region of the parameters. Few studies use theory to control AV to improve traffic stability concerning the requirement of throughput at the same. With the development of connected and automated car (CAV) technology, vehicles can communicate information in real-time between the vehicle and the infrastructure to make decisions with less reaction time.

Applying CAV technology, this project develops an adaptive headway method to ensure traffic stability and throughput in a mixed traffic environment of passenger cars and trucks. The relation between AV driving headway and stability is investigated under different AV market penetration rates and different truck percentages. According to the analysis, traffic can only be stable if the truck ratio is less than 80%. The proposed method is validated with a VISSIM simulation. The proposed method can reduce oscillations, reduce the delay by 23.19%, and increase average speed by 9.09% compared to the case of baseline where the desired head of AV is fixed. The results of the project will extend to the situation when the signal exists in the urban road in future work.

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OPTIMAL AND ROBUST CONTROL OF VEHICLE PLATOONING ON SIGNALIZED ARTERIAL WITH SIGNIFICANT FREIGHT TRAFFIC

Final Report

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DISCLAIMER

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EXCUTIVE SUMMARY

On an arterial with significant freight traffic, traffic stability is a issue that can influence mobility. The stability functions of car-following models in mixed traffic have been extensively studied, but most of them focus on the feasible region of the parameters. Few studies use theory to control AV to improve traffic stability concerning the requirement of throughput at the same. With the development of connected and automated car (CAV) technology, vehicles can communicate information in real-time between the vehicle and the infrastructure to make decisions with less reaction time.

Applying CAV technology, this project develops an adaptive headway method to ensure traffic stability and throughput in a mixed traffic environment of passenger cars and trucks. The relation between AV driving headway and stability is investigated under different AV market penetration rates and different truck percentages. According to the analysis, traffic can only be stable if the truck ratio is less than 80%. The proposed method is validated with a VISSIM simulation. The proposed method can reduce oscillations, reduce the delay by 23.19%, and increase average speed by 9.09% compared to the case of baseline where the desired head of AV is fixed. The results of the project will extend to the situation when the signal exists in the urban road in future work.

1.0 INTRODUCTION

Due to the complexity of mixed traffic characteristics, significant freight traffic can have a significant impact on the efficiency of the entire urban road network in terms of mobility and safety. Trucks need extra space and time for deceleration and increasing speed, and their interactions with passenger cars can be more sensitive in influencing traffic. A traffic bottleneck is likely to appear on a road segment where freight traffic is significant, and the investigation of the control and operation of significant freight traffic is necessary. The investigation of the first-year project FMRI showed that the coordination of signals fails if the demand consists of a large proportion of the trucks. The strategies were developed in the second year FMRI project to formulate multiple truck routes to transmit consecutive signals individually and cooperatively, taking into account mixed traffic conditions. However, a new problem has remained: since trucks are driven to formulate platoons to improve mobility, the stability problem exists in the process of platooning when the platoon is in an urban street. A stability analysis is needed for mixed urban traffic with operationally significant freight traffic that can improve the mobility and safety of mixed truck-car traffic by ensuring both passage and stability.

While the stability function for a car tracking model in mixed traffic has been extensively studied, most focus on the feasible area of parameters. Few studies check AVs using the theories to improve traffic stability. When the traffic consists of AVs, HVs, cars, and trucks, the stability conditions become complex. In addition, the change of traffic flow parameters, such as equilibrium speed, will lead to a change of the stability conditions, making the problem more difficult.

Therefore, this project focuses on the analysis of the string stability of mixed traffic with both HVs and AVs, cars, and trucks; applies traffic stability conditions to improve traffic mobility by using the traffic stability region as a limitation of the desired headway time for AVs. The traffic demand is intended to limit the lower limit of the desired headway time. The method is evaluated in VISSIM under different scenarios. The results of the project will extend to the situation when the signal exists in the urban road in future work. A method has been developed to improve the stability of heterogeneous and mixed traffic by updating the parameters (desired headway) in a car-following model. Current research work resulted in a publication in (Xiao et al., 2023).

Some previous studies have investigated the stability of heterogeneous traffic consisting of cars and trucks. Due to their different acceleration and braking capabilities, the behaviors of trucks are much more affecting than cars in a traffic stream (Aghabayk et al., 2011). The maximal acceleration and deceleration are different, as well as safety headway (Bokare and Maurya, 2017). Some empirical studies have shown the relation between vehicle type and traffic stability, and the existence of trucks can benefit or worsen traffic stability under different situations (Chen et al., 2016). The theoretical stability condition for heterogeneous traffic flow mixed of cars and trucks was also studied (Ngoduy, 2015).

With the development of automated vehicle technology, the stability of mixed traffic AVs (automated vehicles) and HVs (human-driven vehicles), has been studied and the two vehicle types are differentiated by the reaction time (Ngoduy, 2013). With the application of V2V and V2I technology, more information can be obtained in real-time for AVs, which has changed the traffic stability condition (Talebpour and Mahmassani, 2016).

The control logic of AVs can be modeled in several ways. Take ACC (adaptive cruise control) system as an example, these are: linear control system, model predictive control system, car-following models, including state feedback algorithms such as Optimal Velocity Model (OVM) and Intelligent Driver Model (IDM), artificial intelligence (AI) techniques, rules-based controllers and other methods such as fuzzy logic or machine learning. Among them, active control is suitable for the development of a platoon. Many control strategies have been developed to improve mobility to reduce the stop-and-go waves and other adverse traffic effects on highways (Lee and Park, 2012; González et al., 2015; Rios-Torres and Malikopoulos, 2016). The performance of traffic for the mixed traffic with CAVs is analyzed (Guo et al., 2020). The stability problem for control law actively and cooperatively such as CACC has been studied (Wang et al., 2014a, 2014b; Wang et al., 2017; Gong et al., 2018; Wang et al., 2019; Zhou et al., 2019).

Traffic is considered as string stable if a perturbation decays as it propagates upstream (Treiber and Kesting, 2013). Traffic instability can result in oscillations and a decrease in capacity. Stable traffic can ensure a high flow efficiency by relieving oscillations (Wilson and Ward, 2011). The perturbation that causes traffic instability can result from the deviation of speed or spacing difference from a steady-state state (Tian et al., 2019). Therefore, the stability analysis studying how the perturbation evolves can be important in ensuring mobility and benefiting efficient traffic operation.

Parameters in car-following models are closely related to traffic stability. Reaction time influences the stability of traffic flow (Kesting and Treiber, 2008). The headway has been used as an important factor in keeping the string stability of traffic flow when considering the design of automated vehicles (Yanakiev and Kanellakopoulos, 1995). With the help of simulation software such as VISSIM, updating the parameters to ensure traffic stability becomes possible. What is more, the headway is related to the demand according to traffic flow theory (Treiber and Kesting, 2011). To fulfill the required demand, the desired headway should also be small enough.

Traffic stability has been well studied. Three types of car-following models concerning different information topology are basic car-following models (B-CF), time-delayed car following models (TD-CF), multi- anticipative/cooperative car following models (MAC –CF) (Sun et al., 2018). Stability analysis methods include the Transfer function-based method (Chandler et al., 1958), Characteristic equation(Treiber and Kesting, 2013) , and Laplace transform-based method (Wilson and Ward, 2011), etc.

2.0 METHODOLOGY

2.1 GENERALIZED STABILITY CONDITION

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, 2013).

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

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. τ_n^v τ_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:

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

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

$$f_{\Delta v} = \left.\frac{\partial f}{\partial \Delta v}\right|_e \tag{5}$$

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:

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

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

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

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 SYSTEM DESGIN AND SIMULATION

The maximal acceleration α , comfortable deceleration β and the desired headway T from IDM models are investigated in the analysis. In the simulation part, For AV trucks, the desired headway is noted as $T_{T,A}$, for AV car it is noted as $T_{C,A}$. These two variables are adjusted using equations considering stability and throughput. Other parameters such as maximal acceleration and comfortable deceleration based on specific vehicle types are assumed to be known.

The procedure of the adaptive headway methods for AVs is described in Figure 1. Current equilibrium speed v_e and demand q are obtained each time step from the environment. With the updated values, the stability condition is also updated at each time step, giving feasible desired headway for AV cars and AV trucks, respectively. The AVs then update their desired headways according to the minimal feasible value so that the stability condition and demand requirement are satisfied simultaneously. The driving behaviors are modeled in External Driver Model in VISSIM.

The desired speed can be set as a speed limit. The equilibrium speed is the average speed when the traffic is in a steady state. The demand is believed to be as high as 1800 vehicle / hour / lane and the equilibrium speed is less than the desired speed according to the traffic flow theory. The equilibrium speed is set to 0.6 of the desired speed in the analysis portion.

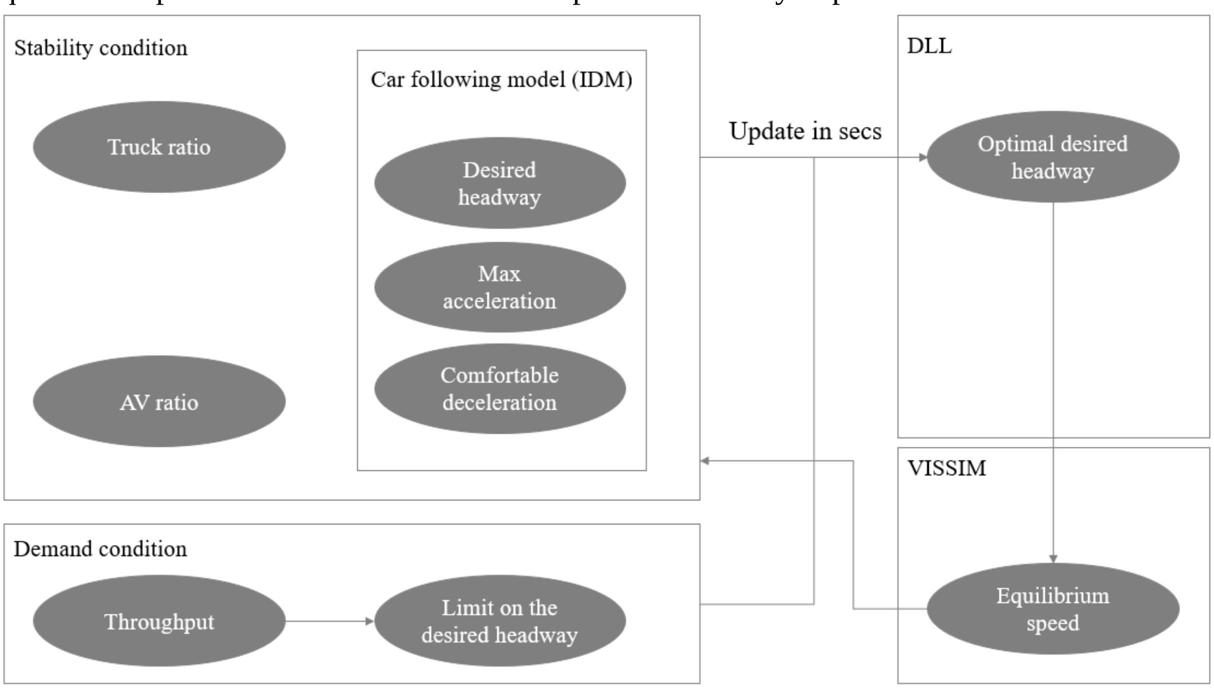


Figure 1 The design of the system to keep stability and throughput

3.0 RESULTS OF STABILITY ANALYSIS

The stability regions for parameters for cars and trucks under different truck ratios are shown below. Maximum acceleration, comfortable deceleration, and desired headway distance of cars and trucks respectively are selected to test their feasible region. When examining one of them, two other parameters were established.

3.1 STABILITY REGION OF PARAMETERS FOR HETEROGENEOUS TRAFFIC OF DIFFERENT VEHICLE TYPE: CARS AND TRUCKS

Figure 2 shows the combination of maximum acceleration of cars and maximum acceleration of trucks that can lead to stable traffic among different percentages of trucks. Traffic is only stable if the maximum acceleration of both vehicle types is greater than certain thresholds. The thresholds shrink when the percentage is in the middle (around 40% - 60%). This indicates that when truck and passenger car proportions are close, the achievable maximum acceleration increases sharply.

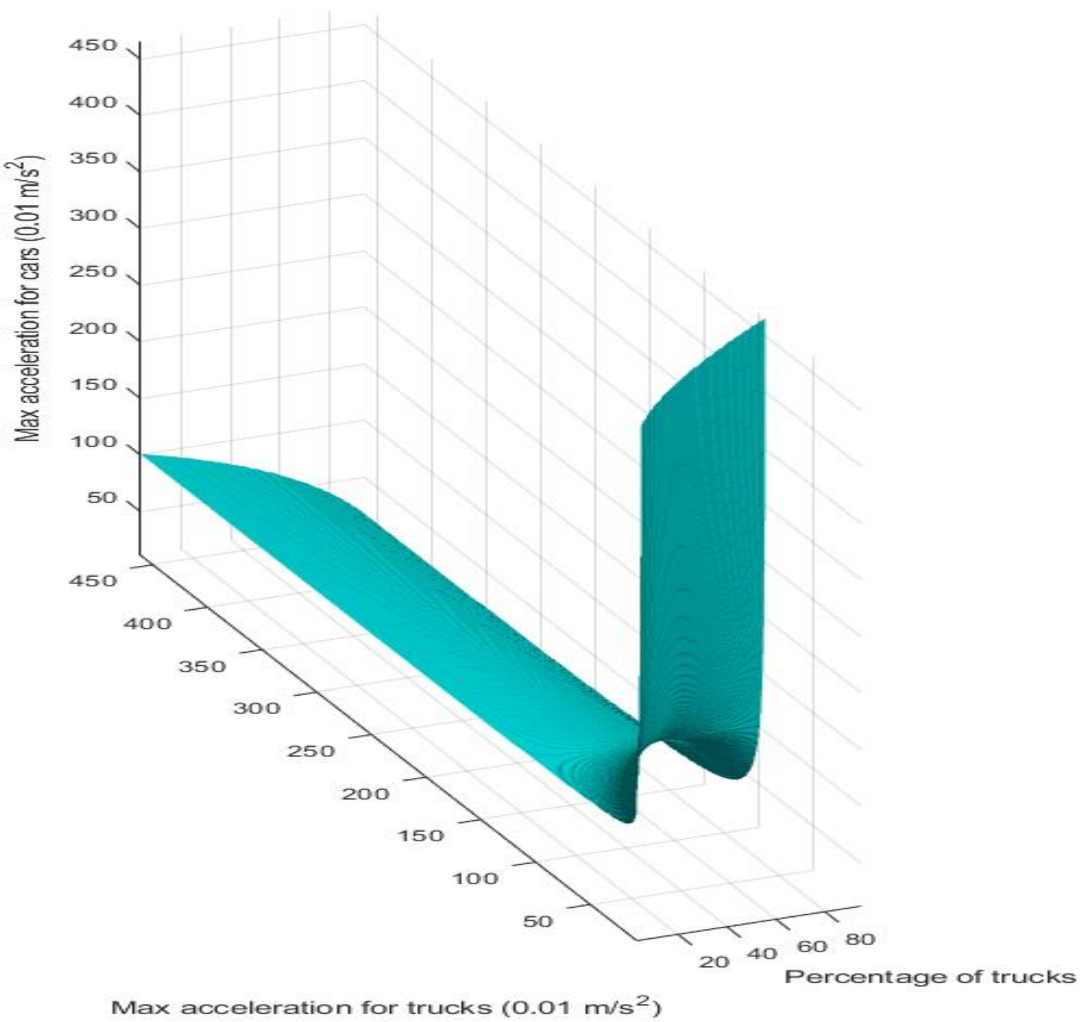


Figure 2 The stability region for maximal acceleration under different penetration rate of trucks (fixing comfortable deceleration for car and trucks as 2 m/$s^2$and 2 m/s^2; desired headway for cars and trucks as 1 sec and 1.5 sec)

Figure 3 shows the combination of comfortable deceleration of cars and trucks that can lead to stable traffic among different percentages of trucks. Traffic can only be stable if the comfortable delays for both cars and trucks exceed their thresholds given the ratio between trucks. In general, the existence of trucks destabilizes traffic proportionally. This trend becomes more obvious as the truck ratio increases. If the proportion of trucks is too large (> 80%), it is almost impossible to keep stable traffic. Because the thresholds for delays are becoming very large.

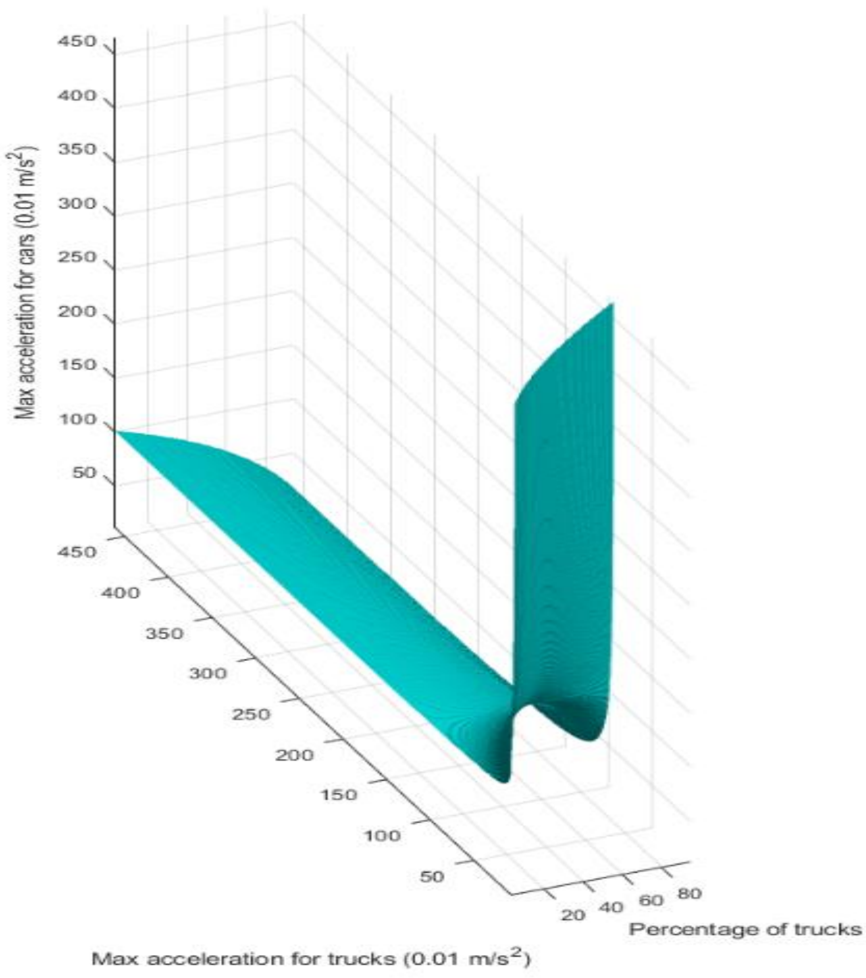


Figure 3 The stability region for comfortable deceleration under different penetration rate of trucks. (fixing maximal acceleration for car and trucks as 1.4 m/s^2 and 0.7 m/s^2; desired headway for cars and trucks as 1 sec and 1.5 sec)

Figure 4 shows the thresholds of the combination of desired tracking movements. With the increase in the truck ratio, the minimum desired following distance for trucks increases, and the minimum desired following distance for cars decreases. As with maximum acceleration, the edge of the thresholds shrinks with the desired headway time when the truck ratio is in the middle (40% - 60%).

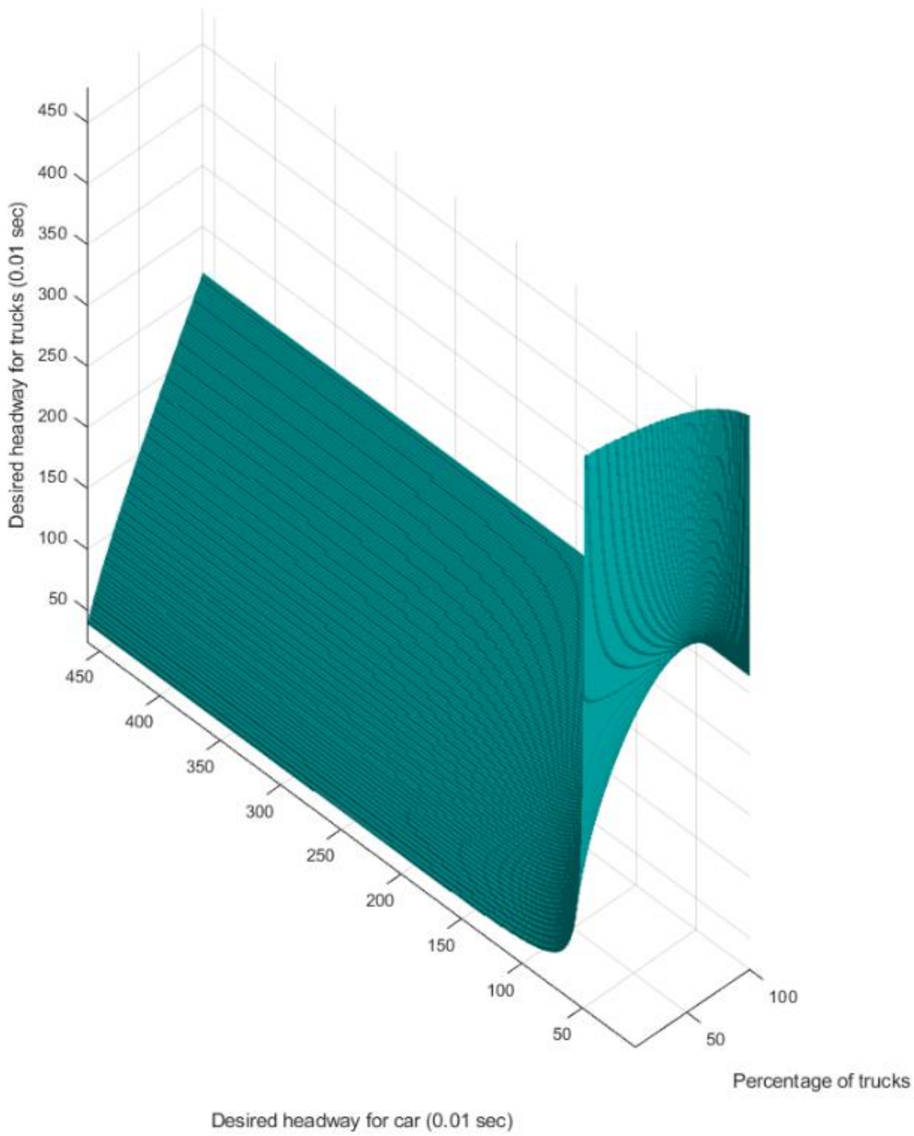


Figure 4 The stability region for desired headway under different penetration rate of trucks (fixing comfortable deceleration for car and trucks as 2 m/$s^2$and 2 m/s^2; maximal acceleration for car and trucks as 1.4 m/s^2 and 0.7 m/s^2)

Three parameters were examined respectively. The influence on the traffic stability of parameters such as maximum acceleration and comfortable deceleration has been demonstrated in the previous analysis. Nevertheless, once the vehicle types have been determined, the acceleration and deceleration are fixed. They are not changeable parameters. Therefore, in the next section regarding AVs, only the stability region of the desired headway time will be examined.

3.2 STABILITY REGION OF PARAMETERS FOR HETEROGENEOUS AND MIXED TRAFFIC

This part gives the stability region when traffic is composed of HVs and AVs, cars, and trucks. The parameters for the car-following model used in this part are listed in Table 1: The setting of acceleration and deceleration of cars and trucks for IDM is according to (Kesting et al., 2010). The desired headways for AV cars and AV trucks that can lead to stable traffic are shown as the region above the pink surface in Figure 6. The desired headways for AV cars and AV trucks that can fulfill the demand are shown as the region below the green surface (demand region). The region over the green surface shows the combination that can satisfy the stability requirement and the region under the pink surface demonstrates the combination that satisfies the requirement of throughput.

Table 1: Vehicle parameters setup

Parameters	**Car**	**Truck**
Desired speed (km/h)	50	50
Max acceleration (m/s^2)	50	50
Comfortable deceleration (m/s^2)	1.4	0.7
Jam distance (m)	2	2
Average reaction time (sec)	1	2
Equilibrium speed (km/h)	1	1

According to Figure 5 , when the ratio of the truck is less than 20%, the combination of desired headway of AV cars and AV trucks satisfying stability requirement satisfy the requirement of throughput automatically. With the increase of truck ratio, many combinations of the desired headways for two types of AVs will go outside the feasible region.

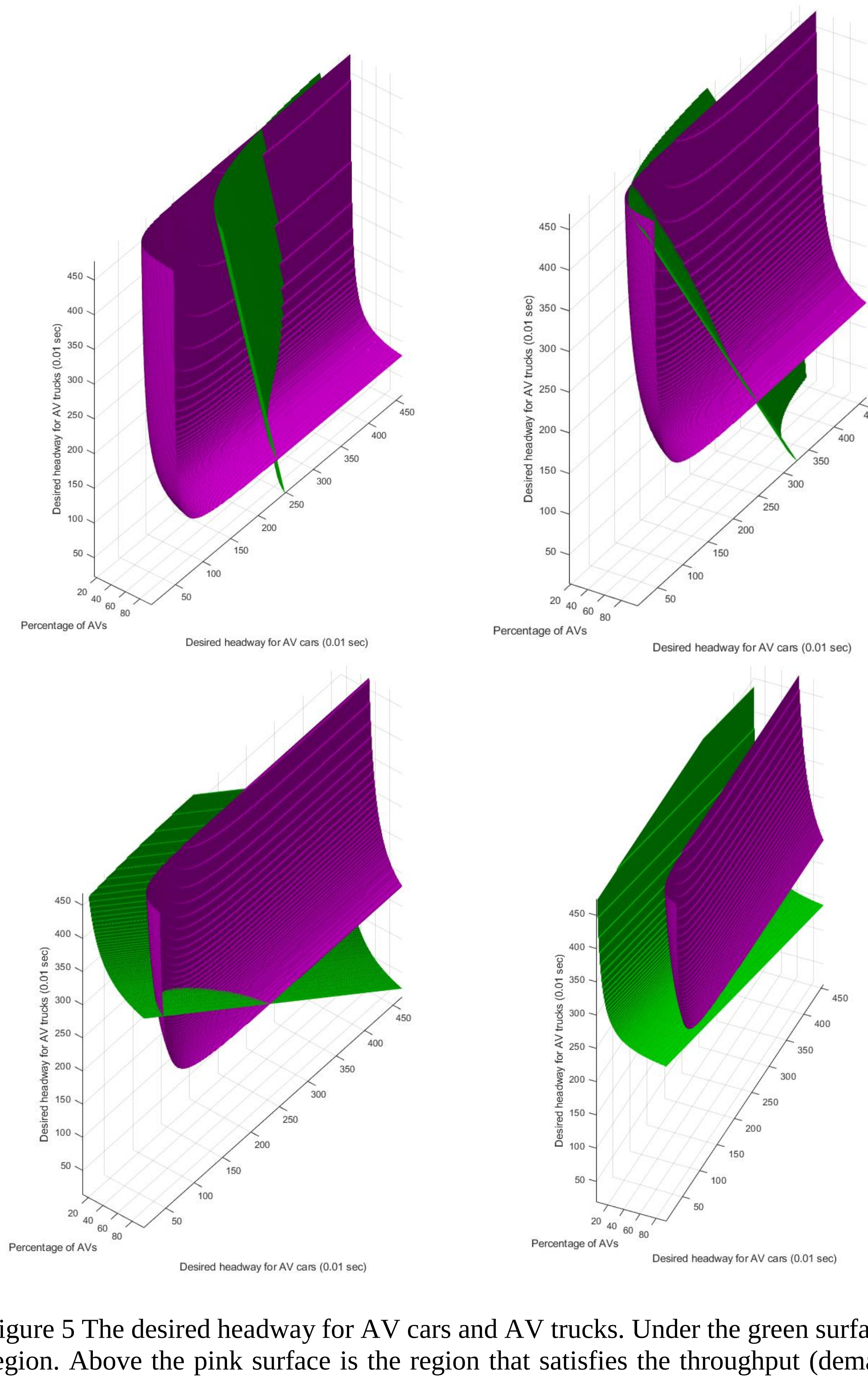


Figure 5 The desired headway for AV cars and AV trucks. Under the green surface is the stability region. Above the pink surface is the region that satisfies the throughput (demand), Truck ratio 20%, 40%, 60%, and 80% respectively.

When the ratio of trucks is larger than 80%, the pink surface is completely above the green surface, which shows that any desired headway combinations of AV cars and AV trucks that can fulfill the demand will not lead to stable traffic, and any stable traffic is at the cost of throughput. When the ratio of trucks is moderate around 60%, the two surfaces cross each other, the adjustment of the desired headway of AVs becomes meaningful and useful in keeping stable while maintaining throughput.

4.0 RESULTS OF CASE STUDIES

This part shows the simulation results using the proposed method in VISSIM. A baseline case is that AVs drive with no reaction time but adopt fixed desired headway. An assumption is made that at certain locations (location = 800 to 1000 m, location = 1600 to 1800 m), HV trucks decelerate down to 60% of the desired headway and accelerate back to their desired speed. Parameters are listed in Table 2.

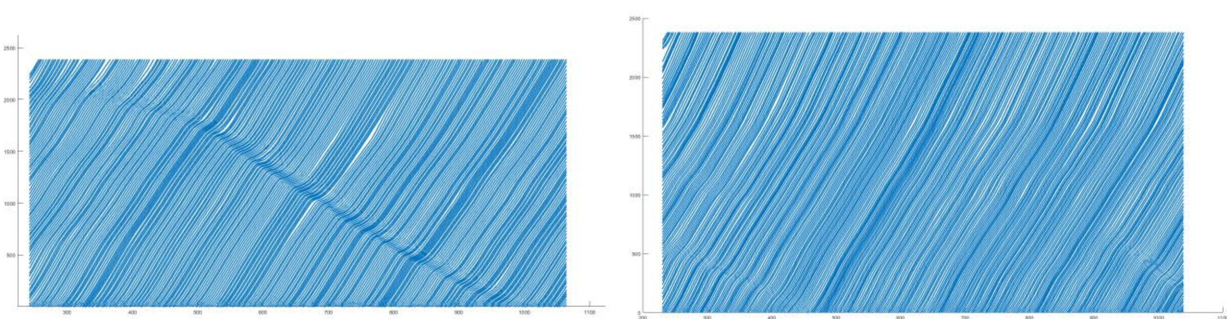
4.1 EXPERIMENT SETUP

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.

Table 2: VISSIM simulation setup

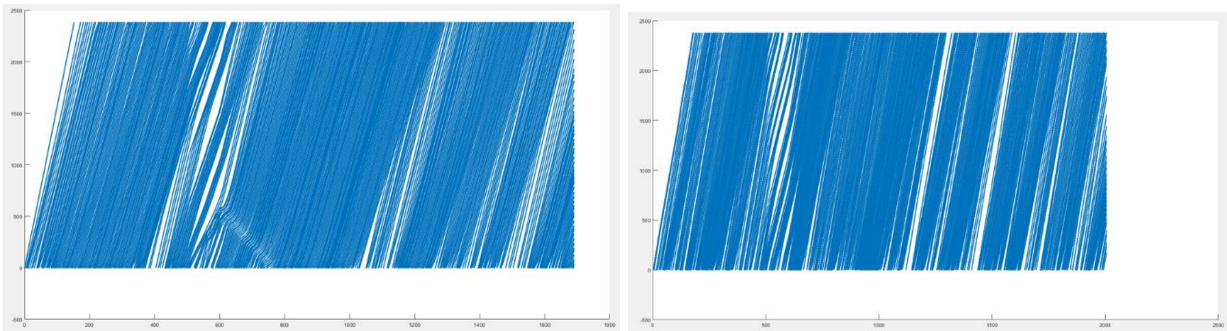
Length of the link tested (m)	2000
Demand (veh/h)	1800
Desired speed (km/h)	50
Simulation time (sec)	1800
Percentage of trucks	60%
Percentage of AVs	60%
Desired headway for HV car (sec)	1.5
Desired headway for HV Truck (sec)	2
Desired headway for AV car baseline (sec)	1
Desired headway for AV Truck baseline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

The baseline is a case when all AVs are having a fixed desired headway. As shown in different cases from Figure 6 to Figure 8 , the output for control method using baseline is shown in (a). In this case, a small perturbation is applied downstream to cause oscillation, which propagates backward upstream.



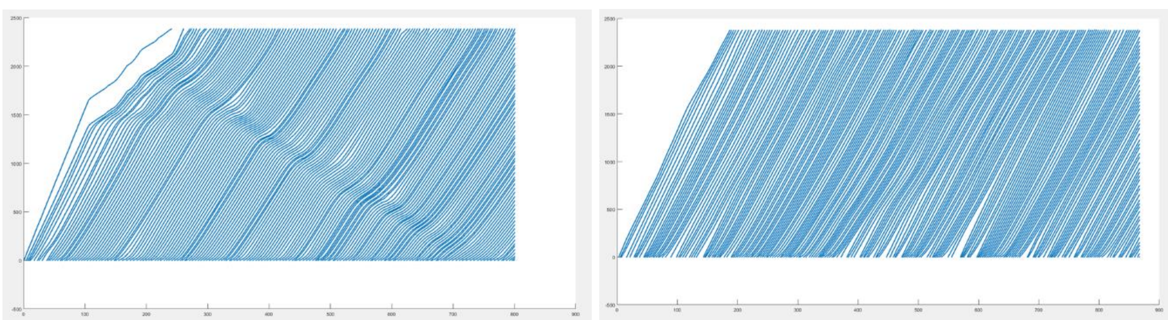
(a) (b)

Figure 6 The trajectory from VISSIM simulation Baseline (a) and proposed method under a perturbation at downstream.



(a) (b)

Figure 7 The trajectory from VISSIM simulation Baseline (a) and proposed method under a perturbation at downstream.



(a) (b)

Figure 8 The trajectory from VISSIM simulation Baseline (a) and proposed method under a perturbation at downstream.

In the baseline case (a), since AVs do not adjust their desired headway in the baseline, the perturbation propagates upstream traffic. becomes unstable with time increases. When using the proposed method, as shown in Figure 6(b), the proposed method helps AV trucks to adjust their headways. As a result, the traffic is stable that the perturbation does not propagate, and no obvious oscillation occurs.

5.0 CONCLUSIONS

5.1 GENERAL SUMMARY

The literature review is presented in Chapter 1 by covering the topics of: control strategies for heavy-duty vehicles (Trucks), control strategies for AVs, stability analysis for mixed traffic. Next, a stability condition for different combinations of vehicles is defined in Chapter 2. It starts with the analysis of the influence truck percentage has on the individual signalized intersection and a coordinated signal corridor. Including a generalized condition, a condition to consider mixed traffic of AVs and HVs, a condition to consider traffic with different vehicle types, and a condition to combine all situations. In Chapter 3. Analytical results provide stability regions for each parameter. In Chapter 4, the results are used for the AV control in VISSIM simulation and some case studies are provided.

5.2 RESULTS AND SUGGESTIONS

When traffic is composed of AVs, HVs, cars, trucks, the stability condition becomes very different and complex. The theory of string stability of traffic under heterogeneous or mixed traffic using a car-following model has been studied but seldomly combined and applied in AV control. An adaptive desired headway method for automated vehicles for this problem is developed.

When investigating the situation concerning both AV ratio and truck ratio, the feasible region is studied for desired headways for AV cars and AV trucks, considering both stability and throughput. For each truck ratio, the threshold decrease (meaning the value of the parameters has more choices) as the increase of AV ratio. The surface of the threshold that satisfying two requirements are changing their relative position with the increase of the truck ratio. When the ratio of trucks is large, it is hard to keep traffic stable and the throughput large at the same time.

The proposed method is validated in VISSIM. Compared to the baseline case when the desired headway is fixed for AVs, the results show that the proposed methods can significantly improve stability when perturbations occur. The methods can save delays by 23.19% and increase the average speed by 9.09% compared to the same baseline.

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