Traffic Flow Control for Connected and Automated Vehicles Using Spring Mass Damper System

By

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A dissertation submitted in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

(Civil and Environmental Engineering)

at the

UNIVERSITY OF WISCONSIN-MADISON

2017

Date of final oral examination: 12/15/2017

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ABSTRACT

This study presents a strategy for platoon formation and evolution of connected and autonomous vehicles (CAVs) for all traffic condition (stable and unstable traffic) and various vehicle composition based on a Spring-Mass-Damper (SMD) system.

First, this study presents a strategy for platoon formation and evolution of connected and autonomous vehicles (CAVs) in free-flow traffic. CAV platoon formation and evolution are controlled by the spring constant and damping coefficient of the SMD system. Valid domains of these control parameters are derived based on physical vehicle properties (e.g., bounded acceleration/deceleration) for realistic control. The result suggests that the most efficient platooning can be achieved by the maximum relationship (where the spring constant is set at its maximum for given flow) between the spring constant and flow with critical-damping. However, the cubic relationship, coupled with over-damping, is more desirable in low flow states to allow more freedom for vehicles to cut in and out.

Second, this study proposes the control method that aims to improve the platoon efficiency and stability after a cut-in movement (e.g., lane change and merging from on-ramp). The method seeks to resolve a disturbance created by a cut-in vehicle by systematically setting spring constant and damping coefficient based on the prevailing traffic condition. The control method is evaluated through simulation based on the changes of speed and spacing, recovery time to reach the desired speed, disturbance propagation, and platoon flow. The simulation result shows that the control method can effectively reduce the disturbance caused by a cut-in movement and improve platoon flow.

Lastly, heterogeneous CAVs and mixed traffic of CAVs and manual vehicle are dealt as a way of extending this study. In case of the heterogeneous CAVs, based on their capabilities such as maximum acceleration and the desired time gap, the optimal order of CAVs that shown the best efficiency is found. For the mixed traffic, due to the different characteristics of CAVs and manual vehicles, the impact of CAVs on the manual vehicle occurs. Thus, this study proposes the range of the spring constant and damping coefficient to absorb the impact.

KEYWORDS

Swarm intelligent, Spring-mass-damper system, Spring constant, Damping coefficient, Connected and autonomous vehicle, Platooning.

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1. INTRODUCTION

1.1 Background

Traffic congestion and vehicle crashes have negative impacts on our lives regarding its mortality and loss of work productivity. The number of people who died from vehicle crashes has increased steadily from approximately 35,365 in 2013 to 40,200 in 2016 (National Safety Council, 2016). The estimates of medical expenses and work loss due to vehicle crashes were $44 billion in 2013 (Centers for disease control and prevention, 2013) and it was estimated more than $50 billion in 2016. Additionally, people have to waste their time and fuel on the road if they face traffic congestion. The cost due to wasted time and fuel has gradually increased from 2009, and, in 2014, was estimated at $160 billion as Figure 1.1 (The Texas A&M Transportation Institute and INRIX, 2015). If this trend continues, Centre for Economics and Business Research (2014) expected that it increases to $186 billion by 2030.

(a) (b)

FIGURE 1.1 Trend of the motor-vehicle death and congestion cost
(a) motor vehicle fatality in the US (Centers for disease control and prevention, 2013);
(b) congestion cost in the US (The Texas A&M Transportation Institute and INRIX, 2015)

In this regard, Connected and Autonomous Vehicle (CAV) is one of the possible solutions in terms of efficiency and safety. Due to embedded sensors of CAV such as a video camera, lidar identify the situation of traffic, CAVs can brake or change direction itself to avoid the collision without the control by a human driver. Additionally, because the vehicles are connected, information such as position, speed, and acceleration of near vehicles can be shared, so it is possible that CAVs drive safe by reducing potential danger and also travel with short spacing (improved capacity). To know the status of current automation for vehicles, the levels of driving automation from the Society of Automotive Engineers (SAE) is suggested as below:

- Level 0 – No Automation: The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems
- Level 1 – Driver Assistance: The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task
- Level 2 – Partial Automation: The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task
- Level 3 – Conditional Automation: The driving mode-specific performance by an Automated Driving System of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene

- Level 4 – High Automation: The driving mode-specific performance by an Automated Driving System of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene
- Level 5 – Full Automation: The full-time performance by an Automated Driving System of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver

In the market, automated systems in vehicles at level 2 are used such as emergency braking system, lane departure assistance. Some automakers prepare to release an automated vehicle that satisfies the level 3 in a few years, and various experiments for the level 4 are in progress. Considering the technologies of automation for vehicles in the market, today we are in somewhere between the level 2 and 3.

In research area, various studies about control CAVs have been conducted. In terms of improving capacity, VanderWerf et al. (2002) showed through simulation that traffic capacity increased significantly when traffic was composed of 100 % ACC or CACC vehicles due to shorter time gaps. Particularly, traffic capacity more than doubled with CACC vehicles. Shladover et al. (2012) showed a similar result: as the penetration rate of CACC vehicles increased, the lane capacity increased rapidly. They showed, however, that ACC vehicles did not significantly increase the lane capacity.

For longitudinal control of CAVs, ACC and CACC are widely used. Basically, the control logics drive CAVs to maintain a constant time headway with a leading vehicle. In detail, Shladover et al. (2012) developed two control algorithms for ACC and CACC vehicles: (i) speed control for gap/spacing > 120 m (representing light traffic) and (ii) gap control for gap/spacing < 100 m (heavy traffic). They simulated these algorithms using traffic simulator AIMSUN with four types of vehicles: manual vehicles, ACC vehicles, manual vehicles with communication capability, and CACC vehicles. The result showed that as the percentage of CACC vehicles increased, lane capacity increased, suggesting that communication capability is critical for increasing capacity. Similarly, Milanés et al. (2014) also developed two control algorithms, one for free-flow conditions and the other for higher flow conditions, considering cut-in and cut-out maneuvers. They conducted a field experiment with four CACC vehicles and demonstrated a shorter response time and string stability (i.e., reduced gap/spacing and speed variability). Milanés and Shladover (2014) increased the number of test vehicles up to ten and conducted various experiments, involving the IDM controller, an ACC controller, and the CACC controller by Milanés et al. (2014). The IDM controller showed the longest response time, while the CACC controller recorded the shortest delay. They also found that the group of ACC vehicles did not show string stability and actually had a negative effect on highway capacity. In contrast, CACC vehicles were found to improve stability and traffic flow. Wang et al. (2014a, 2014b) developed their ACC and CACC control logics that optimize the cost function of safety, efficiency, comfort, and Eco-driving. Each parameter of the cost function for the four purposes played an important role in the movement of ACC and CACC vehicles. In Gong et al. study (2016), new car-following regime for CAVs was suggested. Optimization is conducted to minimize traffic perturbation and keep a stable gap of vehicles. This logic was more stable and showed less traffic oscillation than existing CACC of Schakel et al. (2010).

Though not as extensive, some studies developed control models for CAV platooning based on the concept of spring-mass-damper system. This concept goes back to Yanakiev and Kanellakopoulos (1998) who modeled the AV behavior within a platoon as a spring-mass-damper system. They considered two types of vehicle interactions: interaction only with the AV ahead, and interactions with the AVs ahead and behind. They also considered two different spacing policies: constant spacing and spacing varying according to the speed. They proved string stability in all combinations of vehicle interactions and spacing policies. Yi and Chong (2005) developed an impedance control model, in which each CAV in a platoon is connected with spring-damper. Similarly, Contet et al. (2006) proposed a 'multi-agent system model' to represent CAV platooning based on the spring-mass-damper concept. They assumed that a platoon of vehicles is a virtual train, such that vehicles could merge only at the end of the platoon and could not split promptly. Thus, with a long platoon, merging vehicles may have to wait for a long time to get a chance. These studies, however, fixed parameter values for the system (spring constant and damping coefficient) to describe the movement of a platoon. In contrast, Munigety et al. (2015) showed how vehicles move differently as the parameters varied; however, they only simulated a two-body system and did not consider CAVs.

In order to develop a control logic that includes all traffic condition, the cut-in movement could be considered. Content et al. (2006) developed a 'multi-agent system model' based on the Spring-Mass-Damper (SMD) system concept. In this model, a vehicle platoon was considered as a virtual train so that cut-in vehicles could join the platoon only at the end. With this arrangement, however, some cut-in vehicles may have to wait awhile, particularly if the platoon is long. Milanés et al. (2014) demonstrated that their CACC algorithm worked properly for a cut-in vehicle and a cut-out vehicle: a platoon of two CACC vehicles recovered the desired time gap when a vehicle merged into and left the platoon. Milanés and Shladover (2016) considered more cut-in cases in terms of the existence of Vehicle to Vehicle (V2V) communication. Specifically, if a cut-in vehicle had no V2V capability, the first follower of the cut-in vehicle would be an ACC vehicle because it cannot communicate with the cut-in vehicle.

When a V2V-equipped vehicle merges into the platoon of CACC vehicles, the platoon showed better stability. While these studies evaluated the performance of the existing CACC control algorithm in the presence of cut-in and cut-out movements, they did not explore different strategies that could be more stable or efficient.

Studies about an impact of heterogeneous vehicles such as heavy-duty trucks have been done regardless of CAVs. Due to their huge dimension and limited movement, they kept larger spacing between the front vehicle and the rear vehicle, and traveled with little variation of speed (Moridpour et al., 2014). Specifically, Sarvi and Ejtemai (2011), Chen et al. (2016) found out that heavy vehicles had longer time and distance headway, and also when a passenger car followed a heavy vehicle, it needed larger both headway. Because of these characteristics of heavy vehicles, they showed a dampen effect as reduction of speed variation (Chen et al., 2016). Considering these effects of heavy vehicles, studies about truck platooning were accomplished to improve efficiency and reduce fuel consumption by minimizing air drag with close gap between trucks (Bonnet and Fritz, 2000; Tsugawa et al. 2015). As a way of extending the studies, not many, but some studies about heterogeneous CAVs have been carried out. For example, Shaw and Hendrick (2007) designed a controller for a platoon of heterogeneous vehicles consist of slow, medium, and fast vehicles. They used constant spacing policy, and there were restrictions to achieve string stability such as the number of vehicles in a platoon and the order of vehicle types. Nieuwenhuijze et al. (2012) applied CACC to a heavy-duty truck and found out that the truck could reduce the benefit of CACC, as the truck needed large time headway due to its limited acceleration capability. When short time headway like passenger vehicles were used, string stability was not satisfied.

Considering the heterogeneity that is mixed with CAVs and manual vehicles, many researchers (Shladover et al, 2012; Chang, 1997; Huang et al, 2000) presented that as the ratio of CAVs or Autonomous Vehicles (AVs) increased, capacity also increased and traffic stream was more stable. Chen et al. (2017) assumed that platoons of AVs and manual vehicles were separated, and spacing between the vehicle was fixed. Since the spacing between AVs was shorter than manual vehicles, capacity could increase proportionally to not only penetration rate of AV, but also the number of AVs in the AV platoon. For multiple lanes, as the ratio of AV changed, they proposed an optimal lane policy for which lanes should be dedicated to which vehicles (AV / passenger vehicles) or both.

1.2 Problem Statement

The studies about longitudinal control of CAVs showed more efficient and stable for traffic than the car-following scheme of manual vehicles. They focused on only developing the control models and prove the stability of individual vehicles. Besides, they had limited consideration of various traffic condition including the stable and unstable state. For example, fixed parameters were used regardless of traffic condition, and although Shladover et al. (2012) and Milanés et al. (2014) suggest two logics for different traffic, the logics did not cover all traffic states from free flow and capacity to congestion. Additionally, the models were not developed with regard to various vehicle types. For instance, when a platoon of heterogenous CAVs or mixed traffic (of manual vehicles and CAVs) was formed, they did not suggest how the models could be adjusted to perform efficiently, and different types of vehicles should be controlled. Most of all, they focused on controlling individual vehicles and did not consider the process of platoon formation and evolution.

There were some studies dealt with CAV platooning. However, these studies focused on the mechanism to join or leave a platoon after vehicles are already clustered and did not address how vehicles swarm to form a platoon in the first place. As the penetration rate of CAVs on the road increases, a general control logic for how CAVs are clustered and how platoons evolve with traffic conditions are needed. Also, they used fixed parameter values for the system (spring constant and damping coefficient) to describe the movement of a platoon.

The papers that considered cut-in movement of CAVs described how control logic worked by what kinds of cut-in vehicles were merged into, but they did not suggest a different strategy or control method for the cut-in movement. Moreover, they dealt with the stability of vehicles, not traffic flow in aspects of capacity.

When the papers considered heterogeneous CAVs including automated passenger cars, heavy-duty trucks, and so on, only coupled vehicles (the heavy-duty truck following a passenger vehicle) was analyzed, not more than two vehicles. Besides, they focused on stability to find out an impact of the heavy-duty truck. However, analysis of capacity resulted from heterogeneous CAVs and platoon formation and evolution as procedure for reaching capacity with considering the characteristic of heterogeneous CAVs are necessary.

The previous papers that studied mixed traffic showed the only improvement of capacity due to the shorter response time of CAVs and more stable traffic flow that perturbation decreased as going backward. Based on the different characteristic of a CAV and manual vehicle, acceleration of CAVs and manual vehicle, variation of traffic flow in mixed traffic should be analyzed.

1.3 Research Objective and Scope of Work

As the early stage, studies of CAVs including heterogeneous CAVs and manual vehicle are conducted. They dealt with the change of capacity and achievement of stability without considering platooning procedure from light traffic to heavy traffic. Bringing the characteristic of various vehicle types such as acceleration and response time, this study analyzes the best platoon formation and evolution of heterogeneous traffic of CAVs including manual vehicles as well as capacity with achieving stability. Strategy in this study is based on swarm intelligence that describes the clustering behavior in natural and artificial systems such as bird flocking and fish schooling. In this concept, animals (CAVs in this study) behave according to some rules to move together as a platoon without collisions. The rules can be expressed by a Spring-Mass-Damper (SMD) system, which is physically stable. Therefore, as a control logic of CAVs, the Spring-Mass-Damper (SMD) system is used. Valid domains of these control parameters are derived based on physical vehicle properties, such as bounded acceleration/deceleration, for realistic control.

This study also aims to develop a strategy for systematic CAV platoon formation and evolution within free-flow regimes for better platooning efficiency and stability. Particularly, the proposed strategy controls platoon formation and evolution by controlling the spring constant and damping coefficient of SMD system. Various relationships between the control parameters of SMD system and traffic flow are examined via simulations to obtain insight into desirable parameter setting. This study finds that that the most efficient platooning can be achieved by the "maximum" relationship between the spring constant and flow, where the spring constant is set at its maximum for each flow level, and critical-damping. However, a cubic relationship, coupled with over-damping, is more desirable in low flow states to allow more freedom for vehicles to cut in and out.

As a next step, another objective of this research is to develop control logic that specifically deals with CAV platoon control with vehicle cut-in movements. Ultimate aim is to develop a control framework that improves efficiency and stability during the transition and that can apply in a wide range of traffic conditions. This study already developed a SMD-based model to describe platoon formation and suggest an optimal strategy for platooning in light to near-capacity traffic states. Such strategy considered balance between freedom for cut-in and cut-out movements, and efficient and rapid platooning. This model enables simple dynamic control via dynamic setting of two control parameters. To cover all range of traffic condition, this study provides a systematic way of setting these control parameters with cut-in movements to minimize their impact on platoon efficiency and stability. Testing through simulations shows that a CAV platoon can be controlled effectively with the proposed control logic.

From the capability of various vehicle types, this study draws their expected movement in SMD system. The best sequence of the heterogeneous CAVs in a platoon is analyzed for improving efficiency, and using this sequence, this study finds out how capacity and clustering time which is taken to reach capacity is changed by the proportion of each types of CAV. This study opens a new chapter of CAV platooning in process of reaching capacity by considering capability of different CAVs such as acceleration and response time beyond the analysis of capacity and stability.

This paper studies the acceleration of a CAV and manual vehicle based on their different characteristic. Traffic flow of the mixed traffic could be varied in light and heavy traffic due to their different acceleration to achieve equilibrium state. We find out a negative impact of CAVs in a cut-in procedure (e.g., an occurrence of void) and develop a control method to prevent the impact. To this end, the combination of low spring constant and high damping coefficient of Spring-Mass-Damper system is presented with considering of road design and traffic condition.

To sum up, the structure of this research is expressed as Figure 1.2. Using SMD system, CAVs are controlled. This study suggests different control methods or strategies by vehicle composition and traffic condition. For traffic condition, this study shows the platooning procedure of CAVs in light traffic. Furthermore, how to minimize the impact of the cut-in vehicle with improving capacity is dealt for heavy traffic. In terms of vehicle composition, control methods for heterogeneous CAVs and mixed traffic are introduced.

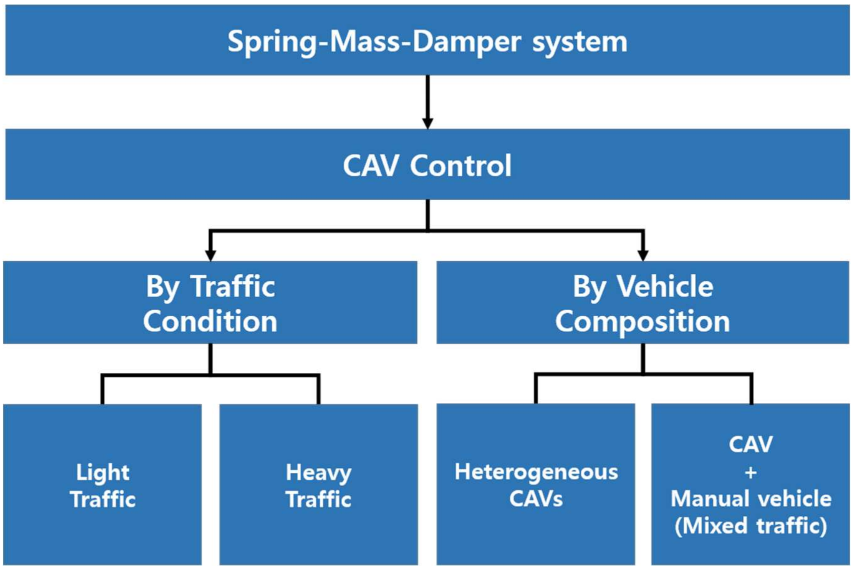


FIGURE 1.2 Structure of this research

1.4 Expected Contribution

There are two major expected contribution of this study: one is about CAV platooning control for a wide range of traffic condition; the other is for vehicle composition in terms of CAVs.

For CAV platoon:

- Considering groups of several CAVs, not individual vehicles, this study develops control strategy for platoon formation and evolution in light traffic and heavy traffic.
- A simple single algorithm for different traffic condition using SMD system is developed by varying parameters of the system suitably.
- Better condition to accommodate cut-in movement is maintained in procedure of CAV platooning
- When a CAV cuts in, the impact of a cut-in movement such as capacity drop and disturbance could be minimized and deter propagation of the impact to upstream at the same time while capacity increases with guaranteeing safety and stability.

For CAV composition:

- Considering various vehicle types, this study analyzes the movement of individual vehicle and the platoon of heterogeneous CAVs based on their capability and specification such as maximum acceleration and response time.
- To improve efficiency of the heterogeneous CAV platoon, the best order of the heterogenous CAVs is suggested, and by increasing the penetration rate of each types CAV, this study describes how the capacity and clustering time would be changed.
- Therefore, it is expected that this study opens the door that various vehicles which have different capability can be controlled as CAVs, and estimate how heterogeneous CAVs perform.

- In addition, this study compares the characteristic of CAVs and manual vehicles by analyzing car-following equations of a CAV and manual vehicle.
- Through this comparison, how platoons of CAVs and manual vehicles would be formed is presented in light traffic. When the traffic flow can be unstable by cut-in movement, this study shows that different movement of CAVs has an impact on mixed traffic of CAVs and manual vehicles.
- Finally, this study develops a control method to prevent the negative impact of the cut-in movement on a manual vehicle. To this end, this study finds out that the cut-in movement actually has an impact on a manual vehicle. An equation that identifies how much spacing is insufficient is created. Based on this shortage spacing, this study presents that how CAVs in front of a manual vehicle should be controlled to absorb the impact.

1.5 Thesis Organization

This study proposes how a CAV platoon is formed and evolved by different traffic condition and vehicle composition. In this dissertation, there are 8 chapters, and what each chapter contains is expressed as follow.

In chapter 2, various CAV controls are introduced. As car-following regime of CAVs, studies about ACC and CACC are reviewed. Most of the studies considered one type of CAV for control logic, but some studies suggested CAV control with several types of CAVs. In terms of a CAV platoon, the studied that suggest how CAVs were connected were presented. As a way of extending their control range from longitudinal to lateral, how lane changing movement was handled in CAVs traffic is shown.

Chapter 3 explains the model that is used in this study. As the reason why SMD system is used for CAV control, swarm intelligent is introduced. Moreover, there is description of SMD system such as formulas, characteristic of the parameters, and types of damping, etc. Based on the formulas and types of damping, the parameters could be set, and using those parameters, this chapter shows the model can achieve string stability.

Chapter 4 is the first step of dealing CAV platooning. How a platoon of CAVs is formed and evolved from light traffic to capacity (stable traffic state) is suggested. Based on the relationship between the parameters and flow, simulation to know platoon formation is conducted. From this result, optimal strategy for CAV platooning is proposed.

Chapter 5 is the second step that covers heavy traffic (unstable traffic state). In this traffic condition, when a vehicle join a platoon, an impact of the cut-in vehicle occurs. To prevent it, the control concept and relationship between the parameters and traffic condition are suggested. After simulation, it is found out that this control method can minimize the impact and improve capacity with maintaining safety

Chapter 6 is about vehicle composition of CAVs. If there are several types of CAVs that have different physical dimension and capability of movement, how they can be controlled is suggested in this chapter. By its order and ratio of each heterogeneous CAV, changing of efficiency is presented.

Chapter 7 presents control method of CAVs in mixed traffic of a manual vehicle and CAVs. Based on different characteristic of two vehicles, traffic flow of mixed traffic is analyzed. In heavy traffic, spring constant and damping coefficient of CAVs are set to absorb the impact of a cut-in movement with considering traffic condition and the distance between on-ramps.

Chapter 8 recapitulates the strategies and results of previous chapters as conclusion and discusses the possible future works.

2. LITERATURE REVIEW

In this chapter, various CAV controls are dealt. For car-following regime of CAVs, studies about ACC and CACC are introduced. Most of the studies considered one type of CAV for control logic, but some studies suggested CAV control with several types of CAVs. In terms of a platoon, consecutive CAVs were treated as a group and explained its movement. As a way of extending their control range from back-and-forth (longitudinal) to up-and-down (lateral), how lane changing movement was handled in CAVs traffic is studied.

2.1 Adaptive Cruise Control / Connected Adaptive Cruise Control

This section introduces control logic that how CAVs follow the leading one. First, studies about the control logic of homogeneous traffic condition (one type of CAVs) is described. Second, considering heterogeneous traffic condition (several types of CAVs), papers about car-following control of CAVs are suggested.

2.1.1 Homogeneous Traffic Condition

Most control algorithms aim to maintain a constant time headway between vehicles in a platoon. For instance, Shladover et al. (2012) developed two control algorithms for ACC and CACC vehicles: (i) speed control for gap/spacing > 120 *m* (representing light traffic) and (ii) gap control for gap/spacing < 100 *m* (heavy traffic). They simulated these algorithms using traffic simulator AIMSUN with four types of vehicles: manual vehicles, ACC vehicles, manual vehicles with communication capability, and CACC vehicles. The result showed that as the percentage of CACC vehicles increased, lane capacity increased. It is possible to set short time gap due to communication capability of CACC vehicles. If all vehicles in the highway were controlled with CACC, estimated lane capacity was about 4,000 *veh/hr* which is twice the capacity of manual vehicles. On the other hand, the impact of ACC vehicles was not significant because of their similar time gap to manual vehicles in terms of capacity increase.

Similarly, Milanés et al. (2014) also developed two control algorithms, one for free-flow conditions and the other for higher flow conditions, considering cut-in and cut-out maneuvers. They conducted a field experiment with four CACC vehicles and demonstrated a shorter response time and string stability (i.e., reduced gap/spacing and speed variability). Milanés and Shladover (2014) increased the number of test vehicles up to ten and conducted various experiments, involving the IDM controller, an ACC controller, and the CACC controller by Milanés et al. (2014). The IDM controller showed the longest response time, while the CACC controller recorded the shortest delay. They also found that the group of ACC vehicles did not show string stability and actually had a negative effect on highway capacity. In contrast, CACC vehicles were found to improve stability and traffic flow.

Wang et al. (2014a, 2014b) developed their ACC and CACC control logics that optimize the cost function of safety, efficiency, comfort, and Eco-driving. Each parameter of the cost function for the four purposes played an important role in the movement of ACC and CACC vehicles. In case of ACC, when the cost function was optimized for Eco-driving, they saved 18% fuel consumption due to smooth acceleration to follow the leading vehicle. Comparing between ACC and CACC, CACC could accelerate and decelerate more smoothly, and react more sensitively when the CACC vehicle started accelerating.

While these pioneering studies have made important contributions to AV and CAV research, they focused on controlling individual vehicles and did not consider the process of platoon formation and evolution.

2.1.2 Heterogeneous Traffic Condition

Except passenger vehicles of CAVs, studies about truck platooning were accomplished to reduce fuel consumption by minimizing air drag with close gap between trucks. Bonnet and Fritz (2000) were conducted an experiment with two heavy-duty truck that have no physical link. These trucks were connected with “Electronic Tow Bar” and moved on driving track with close spacing and constant speed. When they traveled with 80 km/h and 10 m gap, fuel consumption reduced 10% than when they move separately. Tsugawa et al. (2011) also carried out experiment about truck platooning with three fully automated truck. If these trucks were driven with 10 m gap and 80 km/h speed, 14% of fuel could be saved. And, when the penetration rate of automated trucks was 40 %, they found out that12% of $\boldsymbol{CO_2}$ is reduced along the road from the simulation.

As a way of extending the studies, multiple CAVs were considered. Shaw and Hendrick (2007) designed a controller for a platoon of heterogeneous vehicles consist of slow, medium, and fast vehicles. They used constant spacing policy, and there were restrictions to achieve string stability such as the number of vehicles in a platoon and the order of vehicle types.

Nieuwenhuijze et al. (2012) applied CACC to a heavy-duty truck and let it follow the leading passenger car. They did several experiments to know how the heavy-duty truck follow the leading vehicle that vary its speed by change time headway of the heavy-duty truck. When the time headway of passenger car (0.6 sec) was applied, the heavy-duty truck showed large distance error and failed to achieve string stability due to its deficient acceleration capability and the gear changes. When large time headway (1.5 sec) was used for the heavy-duty truck, it could follow the leading one smoothly without dramatic distance error and showed string stability. However, in this case, the truck could reduce the benefit of CACC in terms of improving capacity. In the paper, only coupled vehicles as the heavy-duty truck following a passenger vehicle was analyzed, not more than two vehicles. And they focused on stability as an impact of the heavy-duty truck.

2.2 Platooning Connected and Automated Vehicles (CAVs)

Though not as extensive, some studies developed control models for CAV platooning. This concept goes back to Yanakiev and Kanellakopoulos (1998) who modeled the AV behavior within a platoon as a spring-mass-damper system. They considered two types of vehicle interactions: interaction only with the AV ahead (uni-direction), and interactions with the AVs ahead and behind (bi-direction). They also considered two different spacing policies: constant spacing and spacing varying according to the speed (constant time headway). They tested string stability in all combinations of vehicle interactions and spacing policies. As a result, when a platoon was controlled by uni-direction and constant spacing policies, it was not possible to achieve string stability. If bi-direction and constant spacing policies were used, the platoon showed string stability but under-damping (oscillation) occurred. However, when constant time headway policy is used, regardless of interaction, the platoon could achieve string stability.

Yi and Chong (2005) developed an impedance control model, in which each CAV in a platoon is connected with spring-damper. They considered not only back and forth (longitudinal) but also right and left (lateral) movement of a platoon, and showed this model operated stable even though the signal from vehicle such as relative position and speed has noises and there was uncertainty in the model.

Similarly, Contet et al. (2006) proposed a ‘multi-agent system model’ to represent CAV platooning. They added friction force term in the spring-mass-damper equation, and calculated the value of the parameters in the model by using the relation among the parameters. They assumed that a platoon of vehicles is a virtual train, such that vehicles could merge only at the end of the platoon and could not split promptly. Thus, with a long platoon, merging vehicles may have to wait for a long time to get a chance. these studies focused on the mechanism to join or leave a platoon after vehicles are already clustered and did not address how vehicles swarm to form a platoon in the first place. As the penetration rate of CAVs on the road increases, it is needed a general control logic for how CAVs are clustered and how platoons evolve with traffic conditions.

2.3 Lane Change of CAVs

This section introduce studies about how cut-in vehicle joins a platoon and the impact of it, but do not deal with exact movement of the cut-in vehicle such as steering control and acceleration / deceleration of the cut-in vehicle to join the platoon. As mentioned previous section, Content et al. (2006) developed a 'multi-agent system model' by using Spring-Mass-Damper (SMD) system. In this model, a platoon of vehicles was considered as virtual train so that cut-in vehicles could join the platoon only at the end. This limitation would make waiting time for cut-in vehicles if the length of the platoon was long.

Milanés et al. (2014) represented that their CACC worked properly for a cut-in vehicle and cut-out vehicle. CACC platoon of two vehicles recovered desired time gaps both when the cut-in vehicle was merged and left the platoon. Milanés and Shladover (2016) added more cut-in cases in terms of the existence of Vehicle to Vehicle (V2V) communication. If a cut-in vehicle had no V2V-equipment, the first follower of the cut-in vehicle among CACC vehicles would be ACC vehicle because it could not communicate with the cut-in vehicle. In this case, after the cut-in vehicle join the platoon, oscillation with under-damping (overshooting) occurred. On the contrary, when a V2V-equipped vehicle was merged into the platoon of CACC vehicles, the platoon could maintain their CACC so showed more stable movement than the case of not the V2V-equipped cut-in vehicle. The amplitude of oscillation was reduced and the shape of oscillation was similar to critical damping (little overshooting). They also conducted another experiment that a vehicle was inserted a platoon of ACC vehicles. This case also showed large oscillation with under-damping, and magnitude of the oscillation increased to upstream. String stability of the platoon did not guarantee. This paper described how control logic worked by what kinds of cut-in vehicles were merged into, but it did not suggest a different strategy or control method for the cut-in case. Moreover, it dealt with the stability of vehicles, not traffic flow in aspects of capacity.

2.4 Summary

Control logics such as CACC and ACC drive CAVs to maintain a constant time headway with a leading vehicle. In detail, Shladover et al. (2012) and Milanés et al. (2014) suggested two control modes of ACC and CACC by traffic condition: (i) one is for light traffic and (ii) the other is under Car-Following (CF) regime with achieving string stability. Milanés and Shladover (2014) showed the algorithms of Milanés et al. (2014) worked well in the real world by using ten consecutive vehicles which ACC and CACC were applicable to. When CACC was used, the platoon of the vehicles presented better stability and traffic flow than the cases of ACC and Intelligent Driver Model (IDM). To extend these control logics to heterogeneous CAVs, capability of acceleration and gear change should be considered. For this reason, automated heavy-duty truck need larger time headway so that the benefit of CACC could be reduced in terms of efficiency (Nieuwenhuijze et al. ,2012). As another direction of expansion, how to handle cut-in vehicles could be considered. Milanés and Shladover (2016) showed the impact of the cut-in vehicle on the CACC platoon was different whether the cut-in vehicle has an equipment for communication. When the equipped vehicle was inserted the platoon, the oscillation of speed change was not significant. These papers focused on developing model that could improve capacity and achieve stability. In aspect of traffic flow, how CAVs form and evolve platoons should be considered for stable traffic state and unstable traffic states.

3. SPRING-MASS-DAMPER SYSTEM

In this chapter, a model used for controlling CAVs is described. This study applies SMD system since it is analogous to the self-organization behavior of fish and bird as swarm intelligent (Reynolds, 1987). How SMD system is formed and meaning of each term are presented. In detail, characteristic of the parameters in SMD system is explained, and by the values of the parameters, damping type is decided. Lastly, when the values of the parameters are set by the specification of a vehicle in the market, stability of SMD system is shown.

3.1 Swarm Intelligent

Swarm intelligence describes self-organization behavior of a group/colony in natural and artificial worlds. Many models and algorithms of swarm intelligence were invented based on the clustering behavior of animals or insects, by learning how their self-organizing movements manifest into collective, group behavior. Some of the most popular natural cluster systems are bird-flocking and fish-schooling. Birds or fish gather and move as a group by a set of rules (Reynolds, 1987): (i) their grouping target is the one that moves in the same direction; (ii) they attempt to avoid collision with others; (iii) they move at the same speed as their neighbors; and (iv) they try to be close to one another. According to rules (ii)-(iv), three different zones can be defined: *repulsion* zone, *alignment* zone, and *attraction* zone, respectively, as illustrated in Figure 3.1 (Couzin et al., 2002; Bode et al., 2011). The *repulsion* zone is the inner-most zone, where birds or fish try to avoid collisions. In the *alignment* zone, they try to synchronize their speed and maintain minimum spacing among them. Lastly, in the *attraction* zone, which is the outer-most zone, they attract others to travel closer. This flocking algorithm was used to describe clustering behavior and showed better performance than other popular clustering algorithms such as K-means algorithm (Amintoosi et al., 2004; Cui et al., 2006).

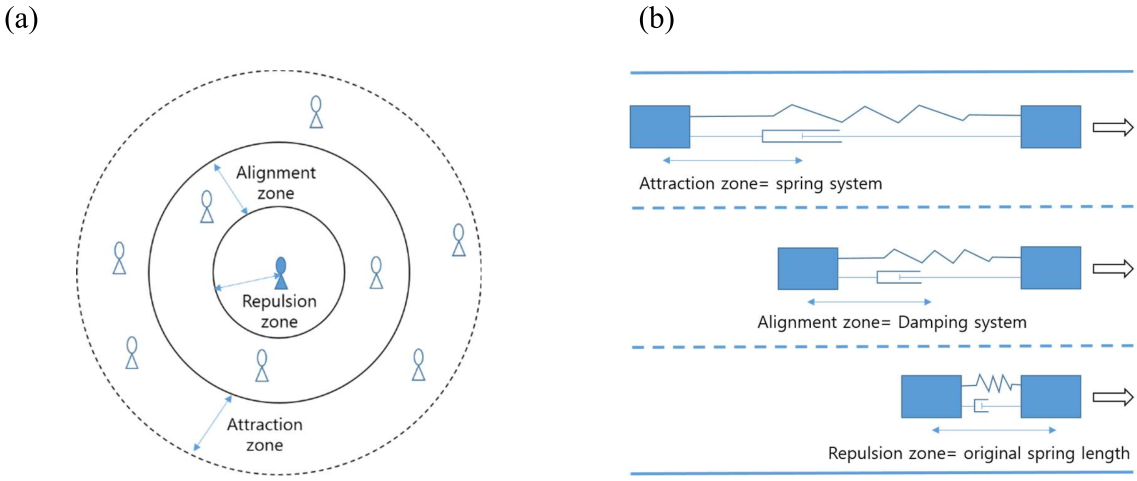


FIGURE 3.1 Illustration of swarm intelligence: (a) The zones of fish schooling (adopted from (Couzin et al., 2002)); (b) Matching zones for CAVs

In this study, swarm intelligence is used to develop a decentralized platooning concept for CAVs. For the purpose of developing a theoretical framework, we assume a full CAV environment with 100% penetration. Particularly, the system dynamics of CAV platooning is described by the dynamics in the three zones similarly defined; see Figure 3.1(b). In the *attraction* zone, a CAV is independently traveling and seeks to join the closest platoon nearby by accelerating. It starts to reach certain spacing from the leading CAV. In the *alignment* zone, a CAV travels in a platoon and is controlled to maintain the same speed as the CAV ahead with neutral spacing. If a CAV gets too close to the lead vehicle, entering the *repulsion* zone, it decelerates to avoid collision. This self-organizing control dynamics can be effectively modeled as a spring-mass-damper system, as described in detail in the following section.

3.2 Equation of Spring-mass-damper System

In this section, this study describes in detail the spring-mass-damper system to model the control process of CAV platooning. We also analyze the constraints of the system parameters to obtain insight into the valid domains of control and system stability.

The concept of spring-mass-damper system is widely used to describe how objects reduce their oscillations based on spring constant, damping coefficient, and mass (14). In the spring-mass-damper system for CAVs (see Figure 2.1(b)), the attraction zone and alignment zone can be represented by the spring system and damping system, respectively. In the attraction zone, the spring system governs and controls a following vehicle to accelerate and approach the original spring length (e.g., critical spacing). In alignment zone, the damping system controls the following vehicle to reduce the speed difference with the leading one and maintain the original spring length. In the repulsion zone, the spring shrinks and a repulsive force pushes the vehicle to decelerate to recover the original spring length. For safe and stable platooning, it is not desirable to enter the repulsion zone. This will be considered in our parameter constraints.

Here this study presents the formulation of CAV control, assuming n vehicles considered for platooning. Figure 3.2 illustrates the spring-mass-damper system for three bodies/vehicles (as an example), with each connected with a spring and a damper. This study further assumes that there is no friction between the bodies and the surface and that a CAV is controlled based only on the condition of its leader (i.e., no influence from a CAV behind). Then, the forces acting on the vehicles are expressed as follows:

$$m_1\ddot{x}_1 = c(v_d - \dot{x}_1)\ , \tag{1}$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2 - l) + b_1(\dot{x}_1 - \dot{x}_2) = k_1\Delta x_2 + b_1\dot{\Delta x}_2 \tag{2}$$

…

$$m_n\ddot{x}_n = k_{n-1}(x_{n-1} - x_n - l) + b_{n-1}(\dot{x}_{n-1} - \dot{x}_n) = k_{n-1}\Delta x_n + b_{n-1}\Delta\dot{x}_n \quad (3)$$

where m_i is mass of the ith vehicle in platoon (i=1 for the first lead vehicle in platoon); x_i, $\dot{x}_i$ and $\ddot{x}_i$ are respectively the position, speed and acceleration of the ith vehicle; v_d is the desired speed of the lead vehicle; c is the coefficient that represents how fast the lead vehicle reaches v_d; k_i and b_i are respectively the spring constant and damping coefficient for the ith vehicle; and l is the original, unstretched spring length. In our context, l can be considered as the critical spacing, the minimum neutral spacing for speed, v. (Note that v can be greater than v_d to enable platooning.) The first term of equations (2) and (3) represents the spring force, proportional to the deviation from the critical spacing, and the second term represents the damping force, proportional to the relative speed.

This study assumes that l is determined in a similar fashion as Newell's simplified car-following model (Newell, 2002): i.e.,

$$l = S_o + \tau * v, \quad (4)$$

where S_o is the minimum spacing, and τ is the response time. Then, $\Delta x_i = x_{i-1} - x_i - l$ represents the deviation from the critical spacing for the ith vehicle. Note that in our CAV control framework, all vehicles are controlled in the same manner, and thus the parameters, S_o and τ, are not vehicle specific. Also note that τ can be set aggressively (0.5-1 sec is possible with CACC vehicles (Shladover et al., 2010; Nowakovski et al., 2010; Nowakowski et al., 2011), as opposed to 1.5-2 sec for non-automated vehicles (Ahn et al., 2004) since vehicles are automated, and thus l would be much smaller than spacing in regular traffic. In this study, 1 sec was used for τ. For the same reason, S_o is assumed to be tight 7 m.

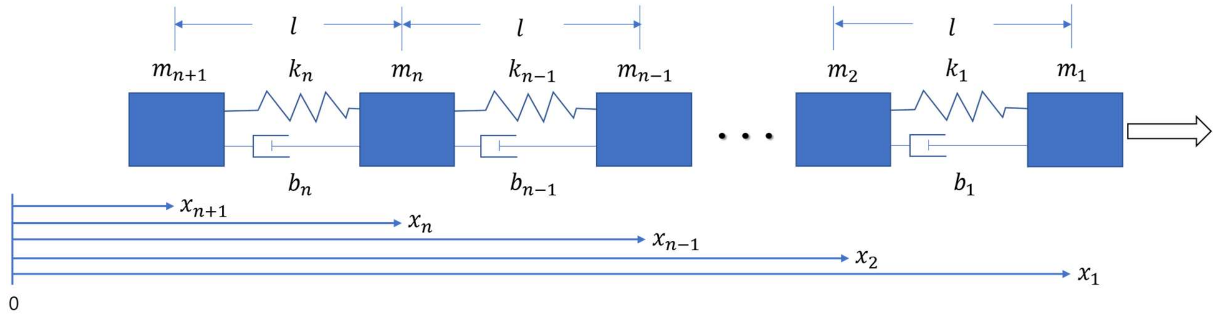


FIGURE 3.2 *n* body *n*-1 spring and damper system

3.3 Characteristics of Parameters

The spring constant, k_i, represents the spring stiffness. A spring with a larger k_i is harder to stretch or shrink, but once stretched or shrunk, there is a greater force to recover its original length. Thus, a large k_i represents a stiff spring with high acceleration of the body (high frequency). In contrast, a small k_i represents a limp spring with low acceleration (low frequency). Accordingly, the spring constant can be regarded as the sensitivity of CAV response to reach its critical spacing. The damping coefficient, b_i, represents the degree of resistance that mitigates the spring force. The damping force makes a body approach another body (a lead CAV in our context) smoothly and maintain the same speed as the lead CAV. Thus, with a large b_i, it would take long to reach the original spring length and the same speed as the lead CAV. In contrast, with a small b_i, a vehicle would oscillate in its position and speed until it reaches l. Thus, the damping coefficient represents the degree of CAV tendency to retain the same speed as its leader and determines control stability.

3.4 Type of damping

Harmony between the spring constant and damping coefficient is important for the stability and efficiency of CAV platooning. There are critical values of these parameters, representing the fastest approach to l without collision or oscillations. When these critical values are achieved, the movement of the system is referred to as critical-damping (Taylor, 2005). For example, a simple one-body spring-mass-damper system can be expressed as

$$F = m\ddot{x} + b\dot{x} + kx = 0. \tag{5}$$

According to Taylor (2005), if $b^2 - 4mk = 0$, the system can fulfill critical-damping. The case of $b^2 - 4mk > 0$ represents over-damping: it would take longer to reach l than it would under critical damping, but there is no oscillation. Finally, $b^2 - 4mk < 0$ represents under-damping: vehicles would oscillate back and forth (possibly entering the repulsion zone) before reaching l, which is undesirable. Ideally, the spring constant and damping coefficient should be set to satisfy the condition of critical-damping for optimal efficiency and stability. However, to be conservative, these parameters may be set to satisfy over-damping for better stability. Our CAV system, which is a n body n -1 spring and damper system, cannot be described by the simple formulation in equation (5) because Δx depends on the speed, $\dot{x}$. Instead, from Yanakiev and Kanellakopoulos (1998), condition of critical-damping and over-damping to achieve string stability can be obtained as:

$$b \geq max\left(\frac{m}{\tau}, \sqrt{km}\right) \tag{6}$$

Specifically, the system will be critical-damping if $b = max\left(\frac{m}{\tau}, \sqrt{km}\right)$, and over-damping if $b > max\left(\frac{m}{\tau}, \sqrt{km}\right)$ as Figure 3.3. Hereafter, this study set $b_{crit} = max\left(\frac{m}{\tau}, \sqrt{km}\right)$

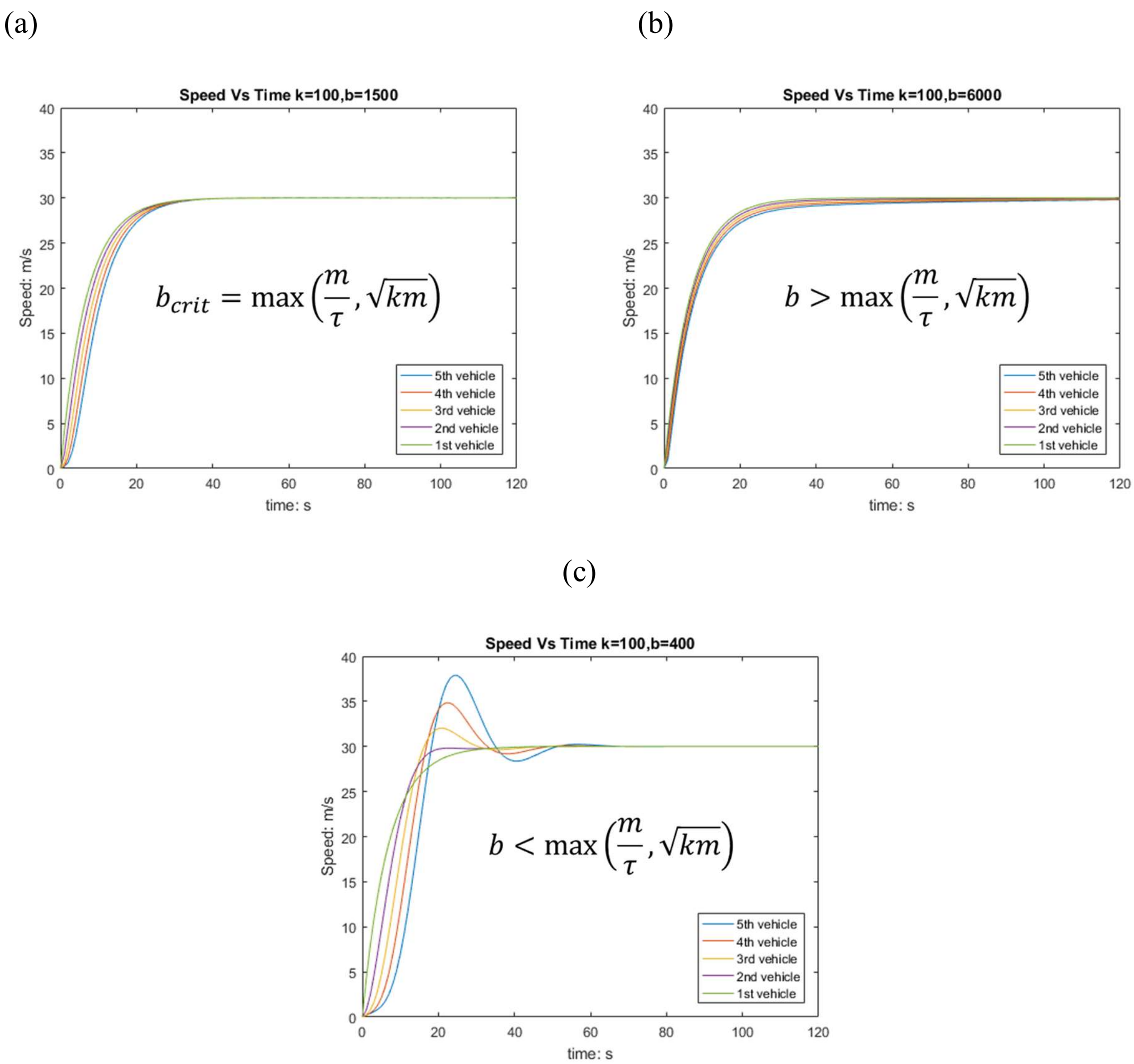


FIGURE 3.3 Types of damping (a) Critical-damping; (b) Over-damping; (c) Under-damping

3.5 Parameter setting

Here this study determines reasonable ranges for parameter c and control parameters k and b. The constraints are derived from the maximum acceleration and deceleration characteristics of CAVs. As an example, this study uses the specifications for 2016 Chevrolet Malibu 2.0T since this vehicle model is common in the United States and has average specifications. Table 3.1

presents the specification of the sample vehicle. From this specification, the maximum acceleration, a_{max}, and deceleration, d_{max}, are calculated as 4.43 m/s^2 and 9.42 m/s^2, respectively.

TABLE 3.1 Specification of 2016 Chevrolet Malibu 2.0T (Car and Driver, 2016)

Specification	**Value**
Weight	1,500kg (3,307 lb)
Length	5m (193.8 inch)
Accelerating time from zero mph to 60 mph	6.1 sec
Decelerating distance from 70 mph to zero mph	51m (167 ft)

Based on these acceleration/deceleration characteristics, this study obtains the constraints for c, k and b. Specifically, for the first lead vehicle, acceleration can be written based on Equation (1) as

$$\ddot{x}_1 = \frac{c}{m_1}(v_d - \dot{x}_1)\ . \tag{7}$$

Assuming that the maximum acceleration is attained when $\dot{x}_1 = 0$, c is obtained as follows:

$$\frac{c}{m_1} v_d \leq a_{max}\ ,$$

$$c\ \leq \frac{m_1 a_{max}}{v_d}\ . \tag{8}$$

For the typical acceleration/deceleration characteristics in Table 1 ($m = 1500\ kg$ and $a_{max} = 4.43\ m/s^2$) and the desired speed, v_d, of 30 m/s (corresponding to the typical free-flow speed of 65-70 mph on US highways), this study obtains $c\ \leq 221.5\ kg/s$. Furthermore, assuming that the maximum deceleration is attained when the first lead vehicle wants to stop, i.e., $v_d = 0$, another constraint for c is obtained as follows:

$$\frac{c}{m_1}(-\dot{x}_1) \geq -d_{max}\ ,$$

$$c \leq \frac{m_1 d_{max}}{\dot{x}_1} . \quad (9)$$

For the typical values in Table 1 and $\dot{x}_1 = 30\ m/s$, this study obtains $c\ \leq 471\ kg/s$. The upper bound for c can be determined based on the two constraints, Equation (8) and (9). Since $a_{max} < d_{max}$ typically, the upper bound for c is governed by Equation (8). Combining with the obvious lower bound of zero, the range of c can be expressed as:

$$0 < c\ \leq \frac{m_1 a_{max}}{v_d} . \quad (10)$$

For the typical characteristics, this study obtains $0 < c\ \leq 221.5\ kg/s$.

In our CAV control system, spring constant k and damping coefficient b should be controlled within a reasonable physical range. For simplicity, this study assumes that all CAVs are identical; i.e.,

$$m_i = m,\ for\ i = 1,\ldots,n\ , \quad (11)$$

$$k_i = k, b_i = b\ for\ i = 1,\ldots,n-1\ . \quad (12)$$

The range of b for critical-damping and over-damping can be determined based on equation (6). For $m = 1500\ kg$ and $\tau = 1\ sec$, this study obtains $b \geq 1{,}500\ kg/s$. Furthermore, it is obvious that $k \geq 0$. To obtain a reasonable upper bound for k, the force $m\ddot{x}$ is set to be maximum with a_{max}: i.e., $m\ddot{x} = ma_{max}$. This study further assumes that (i) the force only comes from the spring force, $k\Delta x$, based on the relationship in Equation (2): i.e., this study set $\Delta\dot{x} = 0$, such that the damping force is equal to zero, and (ii) Δx is set as the boundary value for car-following. Based on these assumptions, the upper bound for k is obtained as follows:

$$m\ddot{x} = ma_{max} = k\Delta x\ ,$$

$$k = \frac{1}{\Delta x} ma_{max}\ ,$$

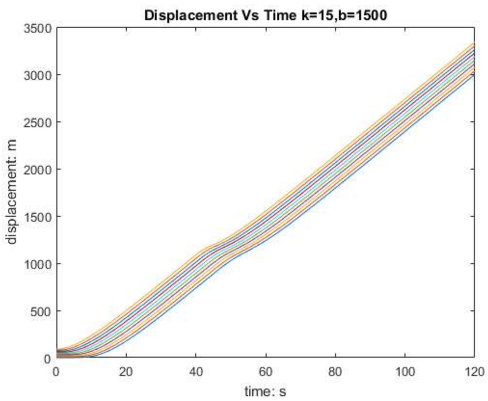
Consequently,

$$0 < k \leq \frac{1}{\Delta x} m a_{max} \ . \tag{13}$$

3.6 Stability Analysis

As discussed in Introduction, Yanakiev and Kanellakopoulos (1998) proved string stability of a platoon if each vehicle in a platoon is controlled based only on the leading vehicle and followed speed-dependent spacing. Thus, it is expected that vehicles under our platooning strategy are string stable, particularly given critical- and over-damping conditions. Figure 3.4 shows an example of string stability under our strategy. In this example, there are 10 vehicles connected virtually by springs and dampers. The parameters are set for critical-damping ($c = 221.5\ kg/s, k = 15\ kg/s^2, b = 1{,}500\ kg/s$). At 40 seconds (after warm-up), the first lead vehicle in the platoon fully brakes for 5 seconds at the rate of $d_{max} = 9.42\ m/s^2$ and then accelerates at the rate of $a_{max} = 4.43\ m/s^2$ to recover its desired speed (30 m/s). The following vehicles also decelerate and then accelerate, but the total speed change decreases as the speed disturbance travels further away from the first vehicle; see Figure 3.4(a) for vehicle trajectories and 3.4(b) for speed changes.

(a) (b)



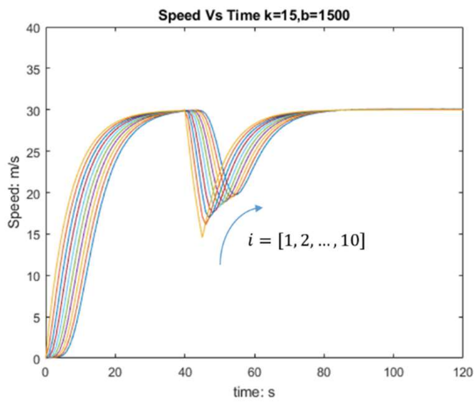


FIGURE 3.4 (a) Change of trajectories; (b) Change of speed

4. PLATOONING FORMATIN AND EVOLUTION OF CAVS

In this chapter, this study aims to develop a strategy for systematic CAV platoon formation and evolution within free-flow regimes for better platooning efficiency and stability. various relationships between the control parameters and traffic flow are examined via simulations to obtain insight into desirable parameter setting. With the set parameters, Optimal strategy for various traffic condition are suggested. For light traffic, the purpose of the control is to allow freedom for cut-in and cut-out movement. At near capacity, platooning procedure is done the most efficiently. In intermediate traffic, CAVs are controlled to balance between freedom and efficiency.

4.1 Platooning Concept of CAVs: Below Capacity

In this section, this study presents a self-organizing CAV platooning concept based on the model developed above. Our concept is similar to variation of molecule arrays from gas to solid, as illustrated in Figure 4.1. Particularly, the CAV platooning process evolves with flow by varying k (and b as a result). In a light, low-density condition (labeled as condition '1' in the figure), k is set low; therefore, CAVs operate (nearly) independently and do not react sensitively to position changes by the lead vehicles. In this condition, vehicles can change their lanes freely. As the flow of CAVs increases, particularly due to inflow from a nearby on-ramp, k can be set higher, so that vehicles travel closer due to stronger interactions (condition '2'). In this condition, vehicles can still cut in from adjacent lanes without much impact on the following vehicles. As more CAVs enter the freeway via downstream on-ramps, vehicles start to form small platoons (condition '3' in the figure). As the flow and k continue to increase, platoons have strong interactions and form larger and tighter platoons (condition '4' in the figure). This process will continue as the flow increases until the upper bound of platoon size is satisfied, and the critical spacing (i.e., l in equation (4)) is reached.

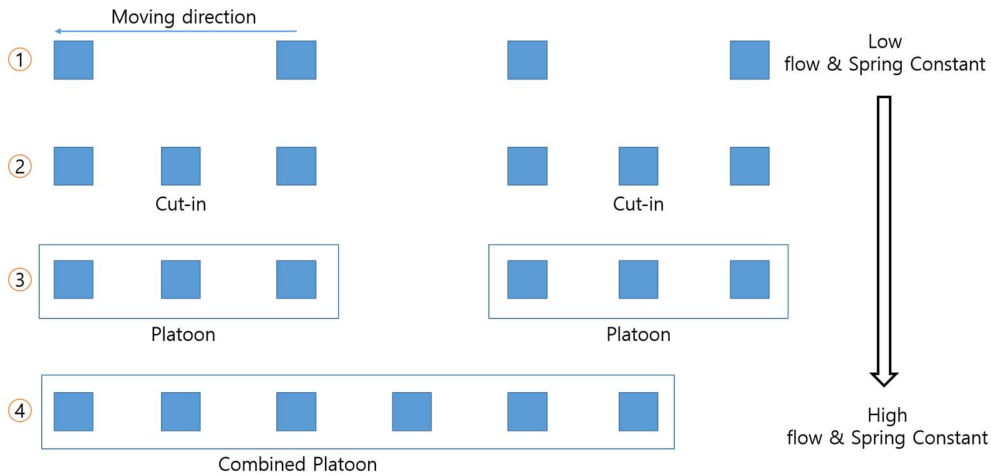


FIGURE 4.1 Evolution of vehicle platooning

4.2 Relationship between Parameters and Flow

In our model, the spring constant, k, is assumed to vary with respect to flow. For the evolution of platoon formation and merging, we consider the free-flow regime. Particularly, we consider three types of relationships between flow and k: *maximum*, *quadratic* and *cubic*. We use the following relations for the three types:

$$\text{Maximum: } k = \frac{1}{\Delta x} m a_{max}, \tag{14}$$

$$\text{Quadratic: } k = \beta_1 * flow^2, \tag{15}$$

$$\text{Cubic: } k = \beta_2 * flow^3 \; . \tag{16}$$

Coefficients, β_1 and β_2, can be determined by setting k equal to the maximum value of k at the maximum flow. Then the damping coefficients are determined to be critical- or over-damping according to equations (6). For the *maximum* relationship, k is set to be the maximum value possible for given flow, as determined by the upperbound in equation (13). Thus, the spring force is the greatest with relationship, and thus we expect vehicles to accelerate and cluster quickly. Conversely, the *cubic* relationship represents the lowest spring force and the slowest platooning process. Thus, we expect the most efficient platooning with the *maximum* relationship; however, vehicles would have more freedom to cut-in and cut-out under the *cubic* relationship. The *quadratic* relationship represents the balanced solution.

4.3 Simulation

For simulation, this study assumes merging area that consist of single lane of mainline and on-ramp. CAVs from mainline and on-ramp follow the Person type III distribution. After all parameters for simulation are set, clustering time of various set parameters are analyzed in simulation.

4.3.1 Simulation Set-up

To gain insight into desirable parameter setting for the suggested procedure of platooning transition, simulations were performed. For the simulation, this study considers a merge area with an on-ramp; see Figure 4.2. This study assumes that (i) the on-ramp and the mainline each consists of one lane; (ii) 30% of the total flow, q, is coming from the on-ramp; and (iii) headway of traffic on the mainline and on-ramp follow the Pearson type III distributions for the spacing or headway (May, 1990). For the location parameter, this study assumes 0.5 since a value between 0 and 1 is normally assumed for roadway traffic (May, 1990). For the standard deviation, this study used the mean and the standard deviation of headway for each flow level in May (1990) and obtained the following general regression model:

$$\text{Ratio of standard deviation to mean} = 0.30680 + 0.30745 * ln(\text{mean}) \tag{17}$$

This model satisfies 95% confidence with the R-squared value of 0.9155. Moreover, for a near-capacity state with flow 2,200 veh/hr, the ratio is equal to 0.46, which is consistent with the ranges reported in the literature (e.g., (Daganzo, 1997)).

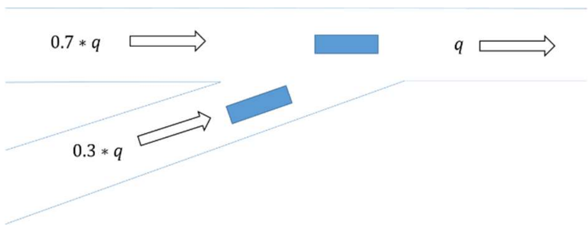


FIGURE 4.2 Flow distribution scheme for simulation

For the simulation scenario, this study considers five free-flow states, from 500 veh/hr to 2,500 veh/hr (below capacity), in an increment of 500 veh/hr. To calculate β_1 and β_2, the capacity, q_{max} is obtained based on the critical density, ρ_{crit}, derived from equation (4) and the free-flow speed of $v_d = 30\ m/s$:

$$q_{max} = \rho_{crit} v_d = \frac{v_d}{S_o + \tau * v_d} \tag{18}$$

Assuming $S_o = 7\ m$ and $\tau = 1\ sec$ as stated earlier, this study obtains $q_{max} = 2{,}920\ veh/hr$. For the case of *maximum*, the 85th percentile spacing, Δx, based on the Pearson type III distribution is used for each flow level. For the relation between flow and k, the coefficient, β_1 and β_2, for each shape is evaluated based on $k_{max} = 121.31\ kg/s^2$ and $q_{max} = 2{,}920\ veh/hr$. This study obtains $1.42 * 10^{-5}$ and $4.87 * 10^{-9}$ for β_1 and $\beta_2$of the quadratic and cubic relations, respectively; see Figure 4.3 for the relations obtained.

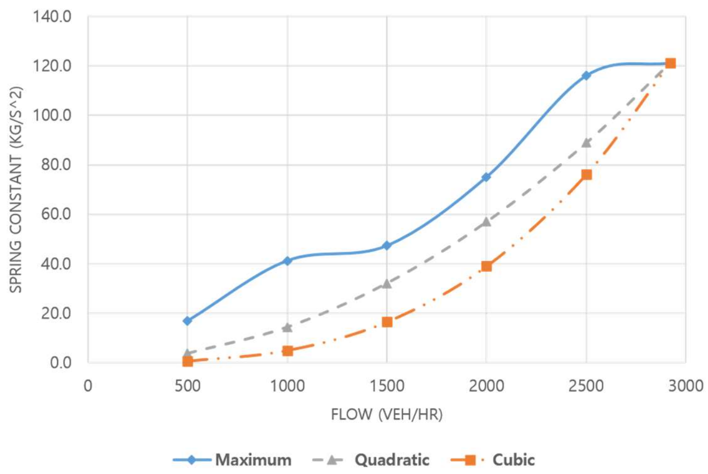


FIGURE 4.3 Spring constant for each scenario

Finally, three damping conditions are considered: in the order of magnitude of b, (i) critical-damping with $b = b_{crit}$, (ii) over-damping ('Over1') with $b = 2b_{crit}$, and (iii) over-damping ('Over2') with $b = 3b_{crit}$.

4.3.2 Simulation Result

Table 4.1 presents how long it takes to cluster to a platoon, in which all vehicles have the same speed and keep the critical spacing. In this simulation, this study sets the tolerance level at 1 m/s and 1 m for speed and spacing, respectively. This study also sets the simulation time at 600 sec. The result shows that the *maximum* case yields the shortest clustering time for all flow states and damping conditions because it has the highest spring constant value for given flow, and thus, it has more force to bring together vehicles. In contrast, the *cubic* case shows the longest clustering time: in fact, vehicles do not cluster until the flow reaches 1500 veh/hr. The *quadratic* case represents an intermediate result between the *maximum* and *cubic* cases. For a given flow level, the clustering time increases with the damping coefficient because it deters clustering by trying to retain the same speed as the leading vehicle and hindering acceleration.

TABLE 4.1 Clustering time by flow, damping type, and relation between k and flow

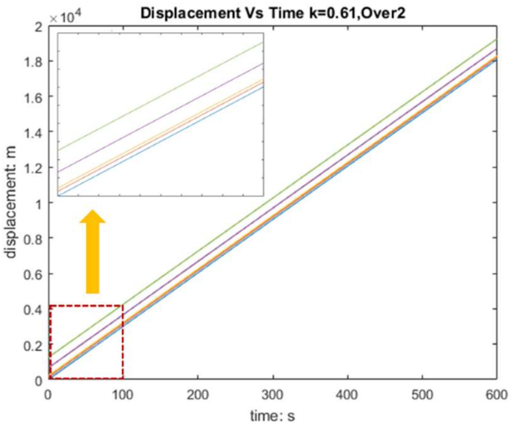
Flow (veh/hr)	Damping type	Clustering time (sec)		
		Maximum	Quadratic	Cubic
500	Critical	572	over 600	over 600
	Over1	over 600	over 600	over 600
	Over2	over 600	over 600	over 600
1000	Critical	189	540	over 600
	Over1	381	over 600	over 600
	Over2	568	over 600	over 600
1500	Critical	179	263	509
	Over1	359	526	over 600
	Over2	537	over 600	over 600
2000	Critical	103	135	195
	Over1	207	270	391
	Over2	308	403	584
2500	Critical	61	79	92
	Over1	121	157	183
	Over2	181	234	273

4.4 Optimal strategy for CAV platooning

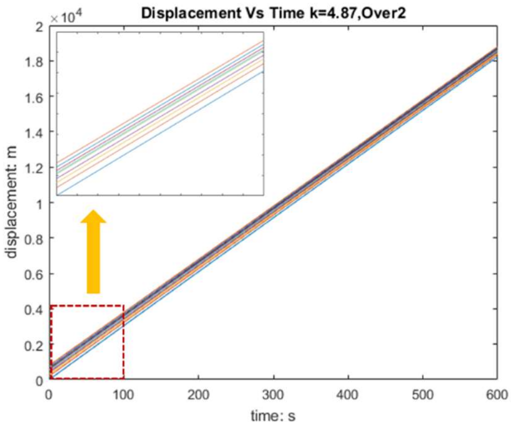
The simulation result reveals that in terms of efficiency (i.e., faster clustering), it is desirable to follow the *maximum* flow-spring constant relationship and critical-damping conditions. However, in low flow states, the *cubic* relationship, coupled with over-damping, would be more desirable since vehicles can move more freely to cut in and out in these conditions and do not have to accelerate significantly or travel at high speed to form a tighter platoon. However, once the flow becomes sufficiently high, it would be desirable to switch to the *quadratic* or *maximum* relationship to improve efficiency (i.e., capacity). Figure 4.4 shows an example result of the simulation. In this example, this study used the *cubic* relation and Over2 damping type for light traffic (500-1000 veh/hr) to largely maintain vehicle freedom. For the intermediate level of flow (1500 and 2000 veh/hr), this study switched to the quadratic relation with Over1 damping type for tighter platooning to increase efficiency while sustaining vehicle freedom to some extent. Lastly, near capacity, 2500 veh/hr, the *maximum* relation with critical damping is employed to maximize the capacity. In low flow states (Figure 4.4(a) and (b)) with small spring constant values and Over2 damping, vehicles gather slowly with large spacing. In moderate flow states (Figure 4.4(c) and (d)) with greater spring constant values and Over1 damping, vehicles form small platoons from the beginning of simulation, and most of vehicles are clustered as one platoon after 300-400 sec. Near capacity (Figure 4.4(e)), where the spring constant is near its maximum, and critical-damping is used, vehicles reach the critical spacing quickly and complete the platooning process after 100 sec.

To fulfill this optimal strategy, vehicles should know the traffic condition (i.e., flow) of sections on a freeway. Thus, it needs communication capability (connectivity) to receive the information of the traffic condition from other facilities such as a traffic management center.

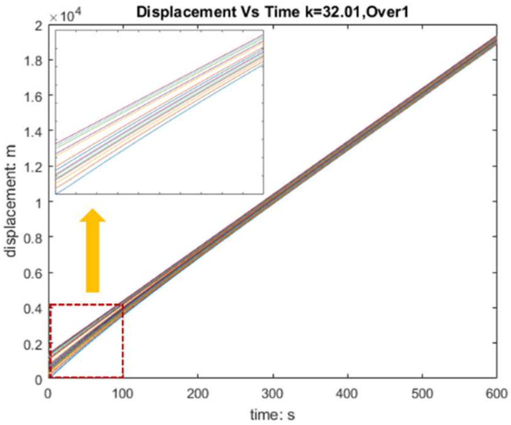
(a)



(b)



(c)



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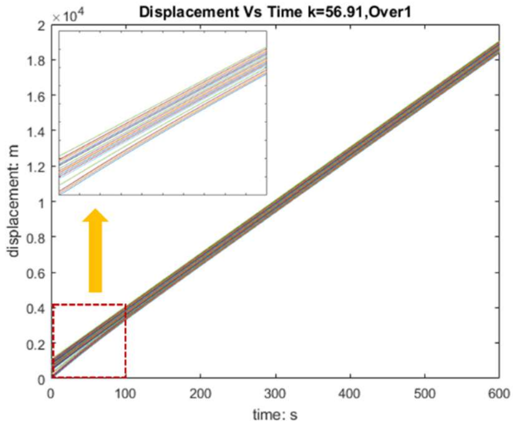

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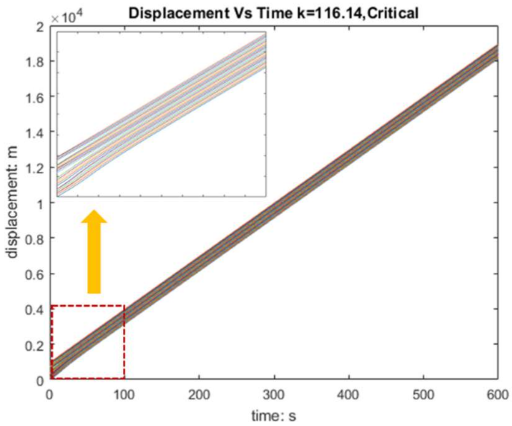


FIGURE 4.4 Example of CAV platooning (a) flow=500 veh/hr; (b) flow=1000 veh/hr; (c) flow= 1500 veh/hr; (d) flow=2000 veh/hr; (e) flow=2500 veh/hr

5. CONTORL CAVS WITH CUT-IN

In this chapter, this study describes how the above control framework is extended to control CAVs in a platoon when it is disturbed by a cut-in vehicle. Note that this study does not focus on controlling the cut-in movement, but controlling vehicles in a platoon, including the cut-in vehicle once it joins the platoon, to minimize the impact of a cut-in. This study assumes that all vehicles including cut-in vehicles are CAVs. This study also assumes that spacing between vehicles before a cut-in is less than two times the critical spacing ($2l$) and that a cut-in vehicle inserts itself in the middle of spacing available; see Figure 5.1. Therefore, a cut-in vehicle would result in spacings (ahead and behind) less than the critical spacing and instigate a speed disturbance for the vehicle(s) upstream. This study aims to minimize the disturbance via systematic parameter setting of lower k and higher b, as will be described in detail shortly.

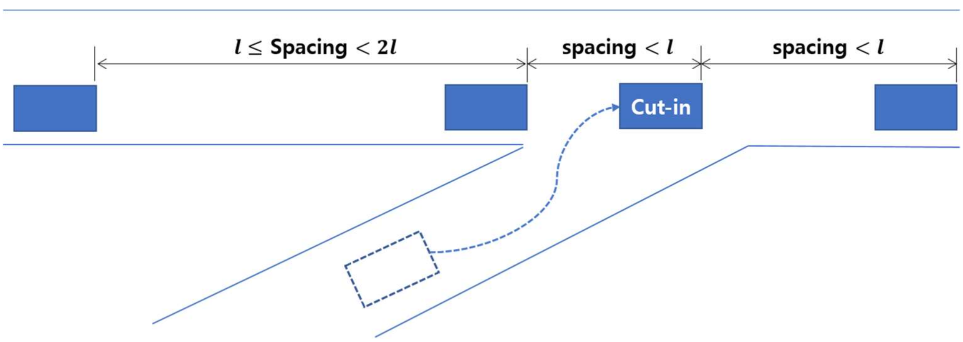


FIGURE 5.1 Hypothetical example of cut-in movement

5.1 Objective of CAV Control: Near and Over Capacity

Cut-in vehicles near merge areas can create voids (spacing greater than l) ahead (Laval and Daganzo, 2006), which can lead to inefficient use of capacity, known as "capacity drop" (Leclercq et al., 2011). A void can occur, for example, when the insertion speed is lower than the mainline speed and the vehicle has a finite acceleration rate; see Figure 5.2. It can also occur if the spacing of a cut-in vehicle is less than *l* at insertion, and the vehicle decelerates excessively (over compensation) while trying to reach the critical spacing. Insertions in the above examples also trigger speed disturbances (Mauch and Cassidy, 2002; Ahn and Cassidy, 2007; Zheng et al., 2011), which could propagate upstream in the platoon. Therefore, this study aims to control cut-in CAVs to prevent voids by minimizing the time to reach the platoon speed and CAVs upstream to minimize speed disturbances.

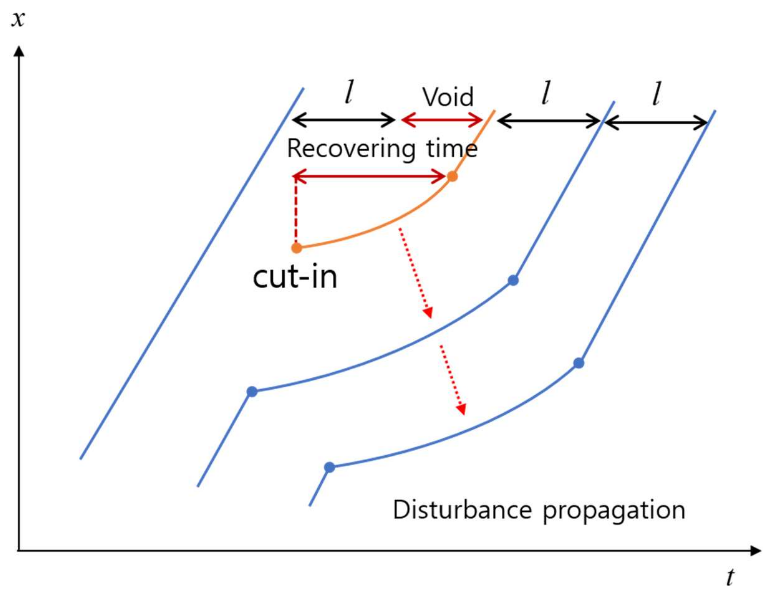


FIGURE 5.2 Occurring void resulted from a cut-in vehicle

5.2 Control Concept of Cut-in Movement

To achieve this objective, this study sets a lower spring constant, *k*, for the cut-in vehicle and the following vehicle such that they maintain shorter spacings than *l*. Under this control, the recovery time for a cut-in vehicle would be much less, particularly if the insertion speed is close to the platoon speed. Furthermore, we set a higher damping coefficient, *b*, (over-damping) such that a cut-in vehicle would quickly accelerate to the platoon speed fast if the insertion speed is lower vehicles would match their leaders' speed more quickly. Thus, by setting lower k and higher b, platoons can accommodate cut-in vehicles while maintaining stable flow, which would increase capacity as Figure 5.3.

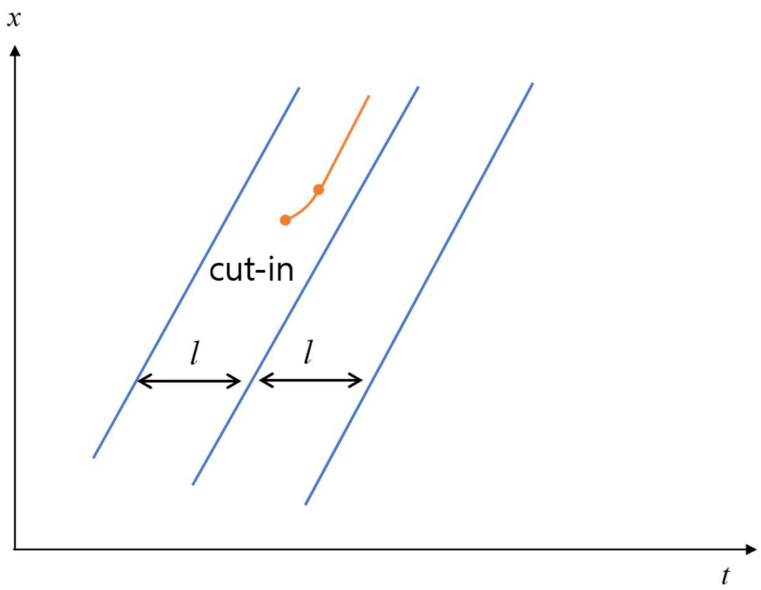


FIGURE 5.3 Control concept of cut-in movement

5.3 Relationship between Parameters and Traffic Condition

This study sets k upon insertion, k_{in}, to be proportional to spacing (S_n) as in Equation (19):

$$k_{in,n} = \left(\frac{S_n}{\alpha}\right)^{\beta} * k_0 \tag{19}$$

where k_0 represents the spring constant prior to an insertion, and α and β represent scaling constants. The setting of k_0 in uncongested traffic is provided in our previous chapter. k_0 is determined by three relationships for different traffic condition in Equation (14, 15, 16). Coefficients, e_1 and e_2, are decided to have the same value of k_0 at the capacity. Each shape of those relationship can be like Figure 5.4 as an example. In light traffic, low k_0 is calculated from cubic relationship for free flow. Near capacity, to maximize efficiency, high $k_0$is set from maximum relation. In intermediate traffic, k_0 of quadratic relationship is for balancing between freedom and efficiency. In this study, when flow is over capacity due to merging, the value of k_0 at capacity is used.

Cubic relationship for light traffic: $k_0 = e_1 * flow^3$, (20)

Quadratic relationship for intermediate traffic: $k_0 = e_2 * flow^2$, (21)

Maximum relationship for near capacity: $k_0 = \frac{1}{\Delta x} ma_{max}$. (22)

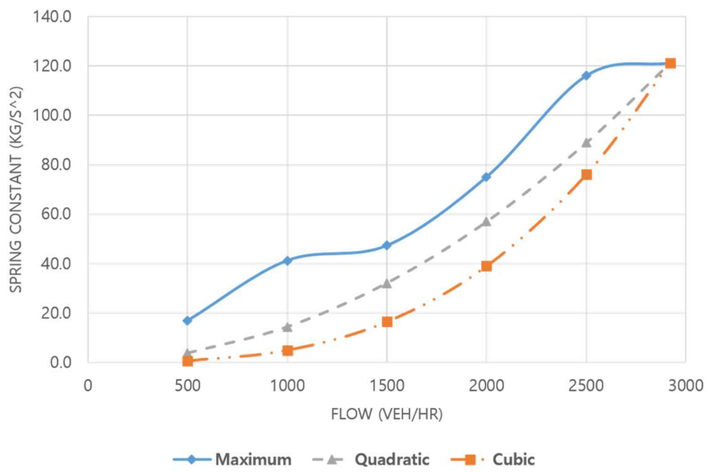
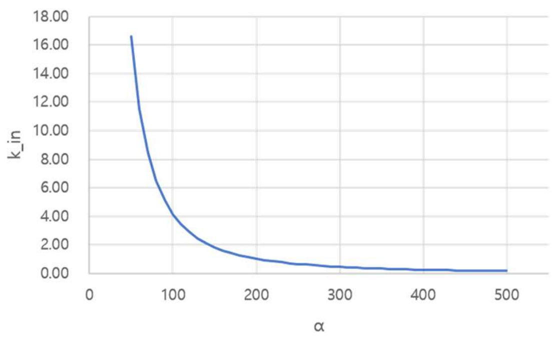


FIGURE 5.4 Three relationships of k_0

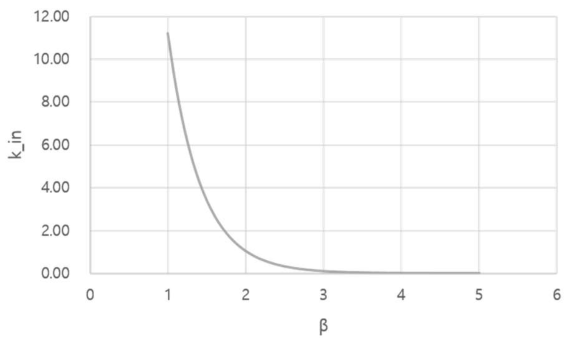
Note that k_{in} is determined for each vehicle, including the cut-in vehicle, based on the respective spacing. In Equation (19), parameter α is used to make the coefficient of k_0, $\frac{S_n}{\alpha}$, a fraction by setting α > spacing. Thus, this study can decrease k_0 by increasing α for given β. Parameter β is used to decrease the coefficient of k_0 more dramatically by setting β > 0.

This study further investigates how k_{in} and thus spacing change with respect to the parameters, α and β. For the investigation, the situation that a vehicle cuts in the middle of spacing between the vehicles in a platoon that travels as capacity with the same speed (S_n=18.5 *m*) is assumed. As illustrated in Figure 5.5(a), k_{in} decreases exponentially with α for various values of β. When α > 150, k_{in} decreases marginally. The relationship with β also shows a similar trend, as expected since the coefficient of k_0 is the βth power of $\frac{S_n}{\alpha}$; see Figure 5.5(b). When β > 2, k_{in} decreases marginally. This study further calculates the force and acceleration using Equation (3), and based on those values, this study computes the rate of spacing increase per *sec*; see Figure 5.5(c) and 5.5(d) for the results. This study assumes that when the rate of spacing increase is less than 0.01 *m/s*, a vehicle essentially keeps its spacing. Thus, α and β are set to be 250 and 2, respectively, such that the rate is less than 0.01 *m/s*.

(a)



(b)



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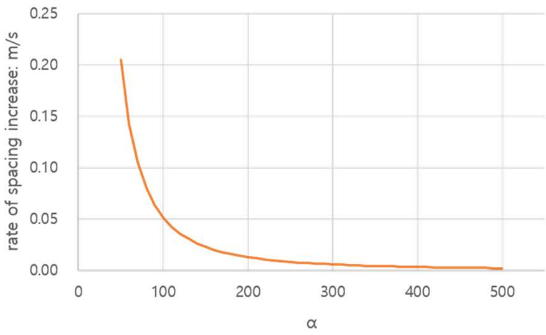

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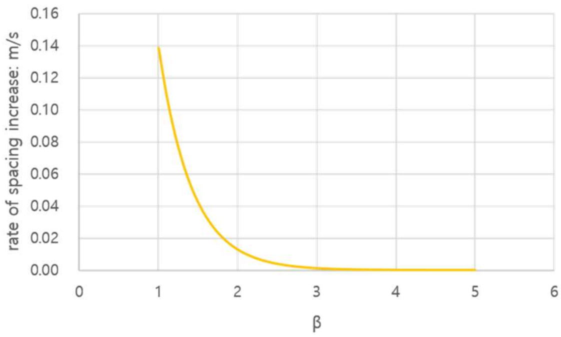


FIGURE 5.5 Sensitivity analysis of k_{in} (a) k_{in} versus α; (b) k_{in} versus β; (c) spacing increase versus α; (d) spacing increase versus β

This study also sets the damping coefficient upon insertion, b_{in}, to be proportional to the speed difference between the cut-in vehicle and its follower in the target lane at the time of insertion:

$$b_{in} = \left(\gamma * \left(v_p - v_{in}\right) + \delta\right) * b_{crit} , \tag{23}$$

where v_{in} and v_p represent the speeds of the cut-in vehicle and its follower, respectively, and γ and δ represent scaling constants for the coefficient of b_{crit}. This study assumes here that $v_p \geq v_{in}$. To achieve over-damping, the scaling constants should be set as $\gamma > 0$ and $\delta > 1$. With this setting, the platoon, including the cut-in vehicle, would move safely as one solid body with nearly constant spacing that is smaller than the critical spacing even at dramatic speed change. After $k_{in,n}$ and b_{in} are applied, the spacing of the cut-in vehicle and the vehicle behind the cut-in vehicle increase to critical spacing very slowly. This study can discontinue this control with cut-in, and transition to the CAV control for stable traffic state as our previous chapter when either of these three conditions is satisfied: i) the spacing comes to critical spacing as time goes on, ii) the cut-in vehicle leaves the platoon so that critical spacing is recovered, iii) the vehicle in front of or behind the cut-in vehicle leaves the platoon so that the cut-in vehicle or the vehicle behind the cut-in can recover critical spacing. These three conditions do not make disturbance to get back critical spacing, and the smooth transition is possible.

This study also performs a parameter analysis for b_{in} and the rate of spacing change with respect to γ and δ. In this analysis, the relative speed is set at 5 *m/s* and b_{crit} at 1500 *kg/s*. As suggested by Equation (23), b_{in} has linear relationships with δ and γ. These linear relationships are illustrated in Figure 5.6(a) for various parameter values. To set proper γ and δ, the minimum value of b_{in} is suggested. After b_{in} is applied, spacing should not change more than minimum gap to prevent a collision as safety issue even though an unexpected event happens. As an example of an unexpected event, when the leader abruptly brakes for 5 *sec* from the desired speed (30 *m/s*), the following cut-in vehicle should vary its spacing less than 2 *m* (minimum gap) by setting b_{in}. This study sets the spacing between the leader and following vehicle at 7 *m* and, k_{in} is calculated by inserting 7 *m* as spacing. As b_{in} increase, the spacing variation decreases exponentially (Figure 5.6(b)). After b_{in} is 11,500 *kg/s*, the spacing variation is under 2 *m*, so the minimum b_{in} should be 11,500 *kg/s*. Even the relative speed is zero, to attain the minimum b_{in}, δ is set at 7.67. Also, this study sets γ as 0.2 to let the cut-in vehicle reach the same speed as the vehicle in the platoon and to improve stability in terms of the speed variation.

To sum up, when a vehicle cuts in between vehicles in a platoon so that spacing of the cut-in vehicle and the vehicle behind the cut-in vehicle is less than critical spacing, this study lets these vehicles keep their short spacing with low k (increasing spacing is neglectable) and the cut-in vehicle follow the speed of the platoon with higher b. In doing so, propagation of disturbance from the cut-in vehicle is minimized and capacity is improved. At the same time, the platoon including the cut-in vehicle moves safely and stably even though the cut-in vehicle and the vehicle behind the cut-in vehicle have shorter spacing than critical spacing since it is possible to nearly fix their spacing in any situation by setting high b.

(a) (b)

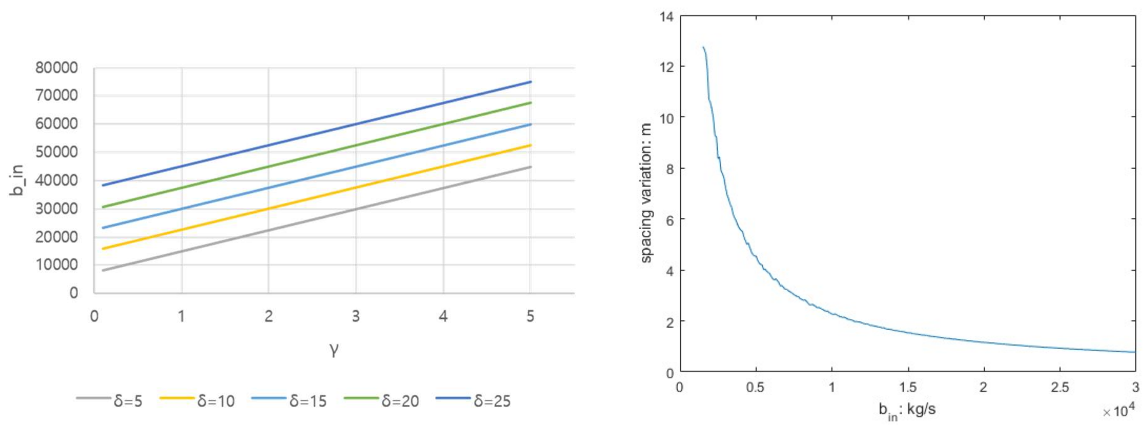


FIGURE 5.6 Sensitivity analysis for b_{in} (a) b_{in} versus γ and δ; (b) spacing variation versus b_{in}

5.4 Simulation

5.4.1 Parameter Setting

In this simulation, specifications of 2016 Chevrolet Malibu 2.0T are used for the performance of CAVs (Car and Driver, 2016). For this vehicle, m is 1,500 kg; the vehicle length is 5 m; and a_{max} and b_{max} are calculated as 4.43 m/s^2 and 9.42 m/s^2, respectively. S_o is 7 m as this study assume that the minimum gap is 2 m. When the desired speed is 30 m/s, the maximum value of c equals to 221.5 kg/s, and this study use this value for the simulation. To calculate the maximum value of k, this study uses the 85th percentile spacing for Δx based on the Pearson type III distribution, which has been shown to represent the distribution of real traffic well (May, 1990). Maximum, quadratic and cubic relationships between k and flow are used for k_0 as in our previous chapter. For b, τ is set conservatively at 1 *sec* since CACC vehicles are able to achieve time gaps of 0.5-1 *sec* (Shladover et al., 2010; Nowakovski et al., 2010; Nowakowski et al., 2011). Finally, as previously described, this study assumed α, β, γ and δ are 250, 2, 0.2, 7.67, respectively.

5.4.2 Simulation Set-up

This study assumes nine vehicles in a platoon and one cut-in vehicle between the first and second vehicles at 200 *sec*. For a significant impact of cut-in movement, this study assume that the platoon moves with the critical spacing of 37 *m* and the desired speed of 30 *m/s*, and after the cut-in, the cut-in vehicle has 25 *m* of spacing with the first vehicle, and the follower has 12 *m* of spacing. Two types of insertions are considered: (i) insertion from another mainline lane and (ii) insertion due to merging from an on-ramp. This study assumes that the cut-in vehicle travels at the same speed as the platoon for case (i) (v_{in} = 30 m/s) and at the lower speed of v_{in} = 25 *m/s* for case (ii). This study applies k_{in} and b_{in} only for the cut-in vehicle and the second vehicle (the immediate follower). For performance, this study compute (1) the average speed and spacing changes of all vehicles for the simulation duration (600 *sec*) to measure the magnitude of disturbance, (2) the time to recover the desired speed, (3) the number of vehicles that the disturbance from an insertion propagates, and (4) flow to measure the overall platoon efficiency. For (2) and (3), this study set the tolerance level at 1 *m/s* for speed and 0.01 *m* for the rate of spacing variation as previously defined.

This study considers four scenarios: (i) basic control with v_{in} = 30 *m/s*, (ii) proposed control with v_{in} = 30 *m/s*, (iii) basic control with v_{in} = 25 *m/s*, and (iv) proposed control with v_{in} = 25 *m/s*. The basic control refers to the one by previous chapter without the consideration of cut-in vehicles. The values of k and b parameters used for each scenario are presented in Table 5.1.

For both scenarios of basic control, the maximum k value (121.3 kg/s^2) and critical damping (b_{crit}=1,500 kg/s) are used to maximize efficiency. For the control scenarios, k_{in} and b_{in} are calculated from Equation (19) and (23) for each vehicle based on its spacing and $v_p - v_{in}$, respectively. This study further set b_{in} at the minimum value (11,500 *kg/s*) for control scenario 1 and at 13,000 *kg/s* for control scenario 2, as established by the parameter analysis in the previous section.

TABLE 5.1 Value of the parameters for each scenario

Parameter	Basic control (v_{in} = 30 *m/s* or 25 *m/s*)			Control scenario 1 (v_{in} = 30 m/s)			Control scenario 2 (v_{in} = 25 m/s)		
	Cut-in vehicle	2nd vehicle	Rest	Cut-in vehicle	2nd vehicle	Rest	Cut-in vehicle	2nd vehicle	Rest
k (kg/s^2)	121.3	121.3	121.3	1.21	0.28	121.3	1.21	0.28	121.3
b (*kg/s*)	1,500	1,500	1,500	11,500	11,500	1,500	13,000	13,000	1,500

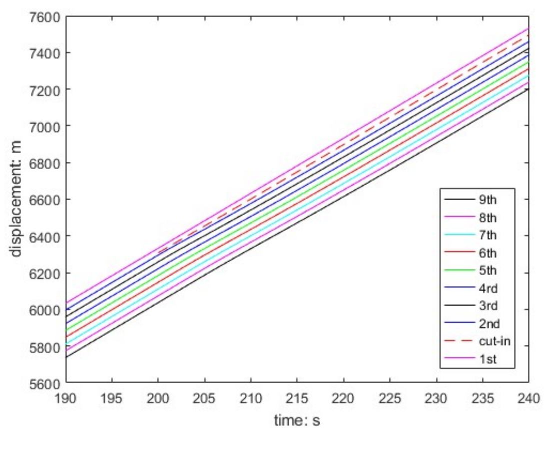
5.4.3 Simulation Result

Table 5.2 presents the simulation result. In both cases of v_{in}, the average speed and spacing changes decrease considerably with the proposed control, suggesting smaller disturbances. As a result, vehicles recover the desired speed nearly instantly. Comparing Figure 5.7 (a) and (b) with (c) and (d), after the control, all vehicles maintain their spacing, and there is no deceleration to reach the critical spacing. Due to no speed decrease, recovery time also reduces to 0 sec. The disturbance that occurs form the cut-in vehicle propagates to the last vehicle of the platoon when there is no control, so this study counts 9 vehicles including the cut-in vehicle as the disturbance size. However, after the control mechanism is applied, the disturbance size is zero. Flow of the platoon is 2,919 *veh/hr* for no control since all vehicle keep critical spacing with the desired speed as capacity, whereas it grows to 3,275 *veh/hr* for control because the cut-in vehicle and 2nd vehicle has shorter spacing than critical spacing with the desired speed. As shown in Table 5.2 and Figure 5.8, the performance of the control for merging from the on-ramp to mainline is similar to the previous case. Average speed and spacing change, recovery time, and disturbance size of control decrease dramatically comparing with those of no control. Also, this study can confirm capacity extension when the platoon is control for the cut-in movement in terms of increase of flow of the platoon.

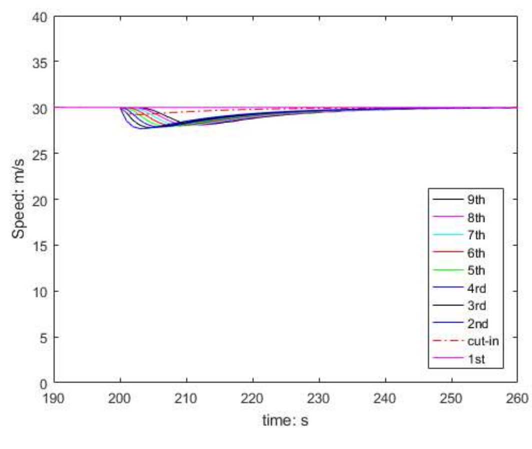
TABLE 5.2 Simulation result

Case	**No control**		**Control**	
	v_{in} = 30 *m/s*	v_{in} = 25 *m/s*	v_{in} = 30 *m/s*	v_{in} = 25 *m/s*
Average speed change (*m/s*)	1.018	1.468	0.003	0.358
Average spacing change (*m*)	5.691	5.968	0.084	0.252
Recovery time (*sec*)	23	24	0	1
Disturbance size (*veh*)	> 9	> 9	0	0
Flow of the platoon (*veh/hr*)	2,919	2,919	3,275	3,270

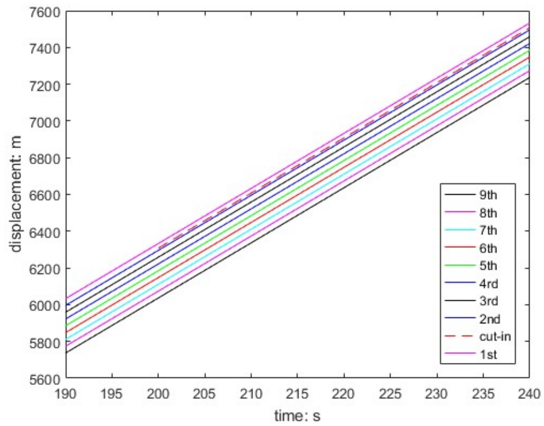
(a)



(b)



(c)



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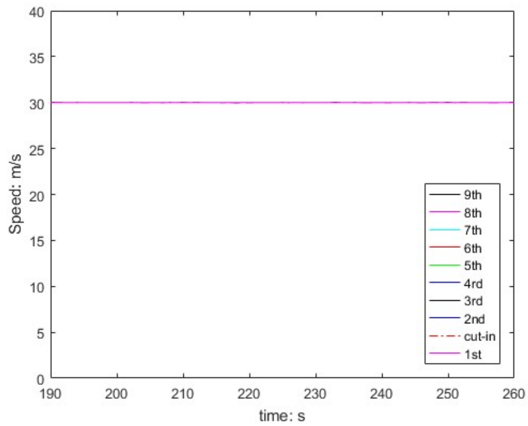
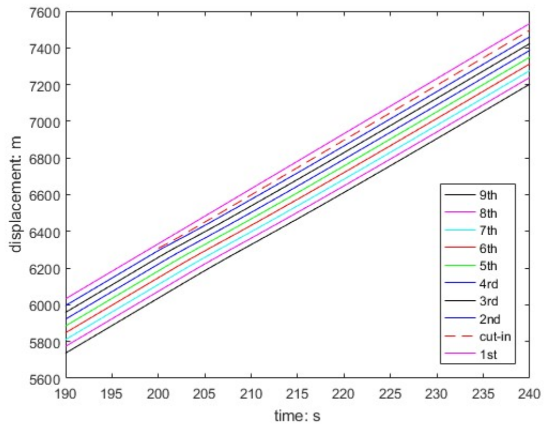
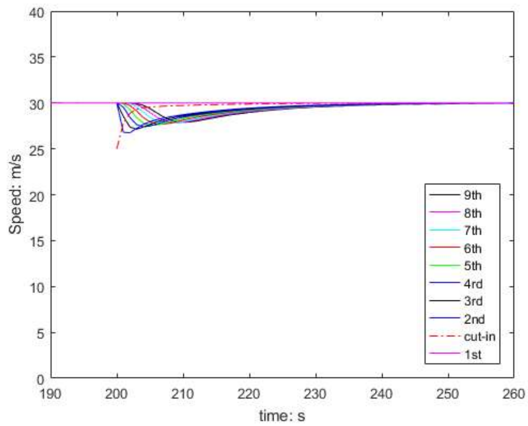


FIGURE 5.7 Trajectories and speed profiles of the case of lane change in mainline (a) Trajectory of no control; (b) Speed profile of no control; (c) Trajectory of control; (d) Speed profile of control

(a)



(b)



(c) (d)

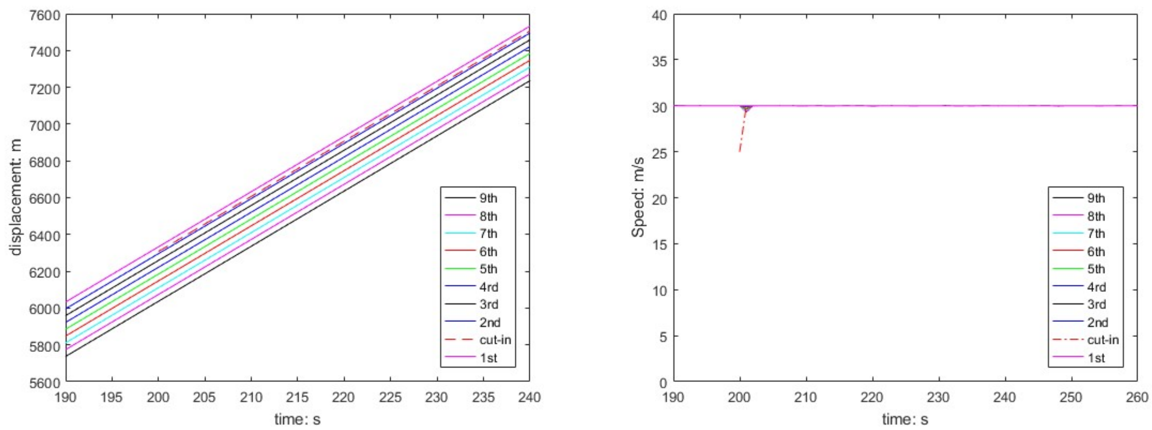
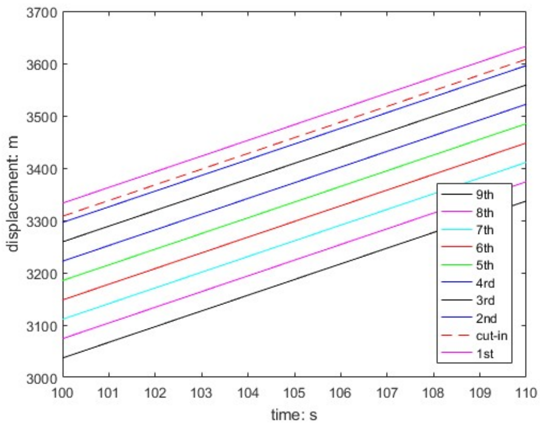


FIGURE 5.8 Trajectories and speed profiles of the case of merging form on-ramp to mainline (a) Trajectory of no control; (b) Speed profile of no control; (c) Trajectory of control; (d) Speed profile of control

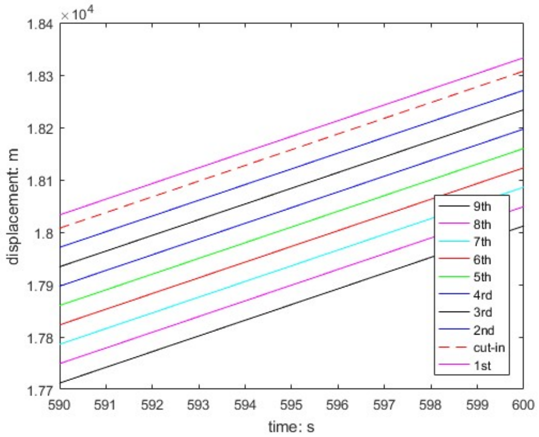
5.5 Spacing Control for Cut-in Vehicles

One of the consequences of the proposed control is that the controlled CAVs keep spacings that are smaller than the critical spacing, thereby 'absorbing' all the impact by an insertion. However, readjustment of spacing would be necessary for a variety of reasons, such as to accept more vehicles to join the platoon, to redistribute spacings more evenly within the platoon as more insertions and desertions occur, and simply to recover spacing that is more desirable to the driver. This can be achieved in two ways. One is to set the minimum value for k_{in} (while maintaining over-damping) that corresponds to some spacing greater than the standstill spacing that the driver desires and/or that would guarantee convergence to the critical spacing within some specified time period. Another way is to dynamically change the k value while maintaining over-damping: k can be increased after some specified period following an insertion. An example is presented in Figure 5.9. In this example, k_{in} = 0.28 kg/s^2 and b = 11,500 kg/s for the second vehicle (the one immediately behind the cut-in vehicle) when an insertion happens at 100 s. With this parameter setting, the vehicle maintains very short spacing with a very low rate of spacing recovery (0.0007 m/s), as shown in Figure 5.9(a). After 200 *sec*, this study changes the parameter setting to $k = 121.3\ kg/s^2$ and $b = 11{,}500\ kg/s$, such that the vehicle spacing increases by 0.06 *m/s*. With this setting, the vehicle nearly recovers its critical spacing (36.62 *m*) at around 600 *s*; see Figure 5.9(b). During this transition, the speeds of the second vehicle and all the followers are reduced slightly as shown in Figure 5.9(c). Notably, the speed reduction is much less severe compared to the basic control (see Figure 5.7(b)).

(a)



(b)



(c)

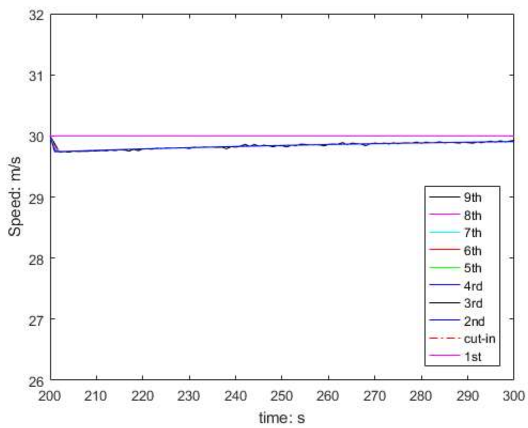


FIGURE 5.9 Spacing increment for cut-in (a) trajectory at the start; (b) trajectory of attaining spacing for cut-in; (c) speed profile

6. OPTIMAL COMBINATION OF CAVS

In this chapter, three classes of vehicles are considered for heterogeneous CAVs. From the specification of each vehicle in the market such as weight, maximum acceleration, and response time, this study calculates acceleration to cluster in SMD system, and using this value, measures the time that all vehicles cluster and form a platoon. After clustering, capacity of the platoon is estimated. This study also presents an order of heterogeneous CAVs to maximize capacity.

6.1 Specification of Heterogeneous CAVs

To find out the capability of heterogeneous CAVs in SMD system, this study borrows the specification of vehicles on the market. For a Passenger Car (PC), 2016 Chevrolet Malibu 2.0T is selected since it is popular and general PC in Unite State. For heavy duty vehicle, this study considers loaded semi-trailer (class 8 and 9 (Hallenbeck et al., 2014)). This study thinks mini-van as the middle class between the PC and semi-trailer, and use the specification of Ford Transit Connect. In Table 6.1, maximum acceleration is calculated by the time that vehicle arrive 60 *mph* from zero *mph*. In case of maximum deceleration, braking distance from 70 *mph* to zero *mph* is used. As see Table 6.1 (a), response time of the PC is set as 1 *sec* because 0.5-1 *sec* is proper response time for CACC vehicles (Shladover et al., 2010; Nowakovski et al., 2010; Nowakowski et al., 2011), but when the PC is behind the semi-trailer, this study uses 2.5 *sec* (Chen et al., 2016) because the wide and high semi-trailer block sight of the PC. In this case, it is possible to set shorter response time for the PC following the semi-trailer in terms CAVs but to make the passengers feel comfortable in the vehicle, longer response time is needed. Considering acceleration and deceleration of the semi-trailer, 2 *sec* is set for the response time of the semi-trailer (Chen et al., 2016). This study assumes the response time of mini-van is the middle value between that of the PC and semi-trailer and mini-van and semi-trailer have the same response time regardless of the type of vehicle in front. As the length of the vehicle types, the minimum gap is set at 2 *m* for the PC and mini-van, and 3 *m* for the semi-trailer. In this case, the gap is the distance between vehicle not included the vehicle length. This study can measure the gap from rear bumper of the leading one and front bumper of the following one. Differently, the spacing is the distance between vehicle included the vehicle length, which is measured from front bumper to front bumper or from rear bumper to rear bumper of two vehicles.

TABLE 6.1 Specification of vehicles

(a) Passenger Car: 2016 Chevrolet Malibu 2.0T (Chen at al., 2016; Car and Driver, 2016)

Case	Value
Weight	1,500 *kg*
Length	5 *m*
Maximum acceleration	4.43 m/s^2
Maximum deceleration	9.42 m/s^2
Response time	1 *sec* / 2.5 *sec* (behind semi-trailer)
Minimum gap	2 *m*

(b) Mini-van: 2017 Ford Transit Connect (Car and Driver, 2017)

Case	Value
Weight	1,800 *kg*
Length	4.8 *m*
Maximum acceleration	2.26 m/s^2
Maximum deceleration	9.02 m/s^2
Response time	1.5 *sec*
Minimum gap	2 *m*

(c) Semi-trailer

Case	Value
Weight	19,432 *kg* (Garrott et al., 2011)
Length	15 *m* (Jassberger, 2011)
Maximum acceleration	0.68 m/s^2 (Yang et al., 2016)
Maximum deceleration	5.97 m/s^2 (Garrott et al., 2011)
Response time	2 *sec* (Chen et al, 2016)
Minimum gap	3 *m*

6.2 Analytic Method of Heterogeneous CAVs

In this section, based on the specification of heterogeneous CAVs, clustering time and capacity are estimated by analytic method. Due to their different capability of acceleration and response time, acceleration to reach equilibrium state that all vehicles have critical damping and the desired speed so travel as capacity could be varied by composition of CAVs. Also, Capacity of a platoon will be changed by the order and ratio of each CAV

6.2.1 Clustering time

Clustering time is the time that a platoon reaches equilibrium state. In our study, since the speed and spacing of CAVs converge on the desired speed (30 *m/s*) and their critical spacing, the platoon moves as capacity after clustering time. To estimate clustering time, this study analyzes acceleration of Equation (1, 3) that describe force to achieve the desired speed and critical spacing (=capacity).

$$a = \frac{c}{m}(v_d - \dot{x}) = \gamma(v_d - \dot{x}), \tag{24}$$

$$a = \frac{k}{m}\Delta x + \frac{b}{m}\Delta \dot{x} = \alpha\Delta x + \beta\Delta \dot{x} \tag{25}$$

Equation (24) represents acceleration of the leader of the platoon until it reaches the desired speed, and acceleration of the followers to attain critical spacing and the same speed as the CAV ahead is described in Equation (25). Therefore, each parameter, α, β, γ plays an important role in how fast the platoon reaches equilibrium state and moves as capacity.

In Table 6.2, relative values of α, β,and γ to PC are calculated by using values of Table 6.1 and Equation (6, 10, 13), when this study assume that maximum values of c and k are used. As a result, the mini-van and semi-trailer have lower α, β, γ than the PC. In detail, α and γ are proportional to the maximum acceleration of each type of vehicles as Equation (26, 27) so that the PC has the biggest α and γ, and semi-trailer has the smallest α and γ. In the range of the response time for these three vehicle types, damping coefficient of critical damping (b_{crit}) is decided by $\frac{m}{\tau}$, and hence β is reciprocal relation with the response time as Equation (28). Therefore, it has the same order as α and γ.

$$\gamma = \frac{c}{m_1} = \frac{1}{m_1} * min\left(\frac{m_1 a_{max}}{v_d}, \frac{m_1 d_{max}}{\dot{x}_1}\right) = \frac{1}{m_1} * \frac{m_1 a_{max}}{v_d} = \frac{a_{max}}{v_d}, \tag{26}$$

since $\frac{m_1 a_{max}}{v_d} < \frac{m_1 d_{max}}{\dot{x}_1}$

$$\alpha = \frac{k}{m_n} = \frac{1}{m_n} * \frac{1}{\Delta x} m_n a_{max} = \frac{a_{max}}{\Delta x} \tag{27}$$

$$\beta = \frac{b_{crit}}{m_n} = \frac{1}{m_n} * max\left(\frac{m_n}{\tau}, \sqrt{k m_n}\right) = \frac{1}{m_n} * \frac{m_n}{\tau} = \frac{1}{\tau}, \tag{28}$$

since $\frac{m_n}{\tau} > \sqrt{k m_n}$

TABLE 6.2 Acceleration analysis for heterogeneous CAVs

Parameter	Passenger car	Mini-van	Semi-trailer
Weight	w	1.5 w	10 w
Max. acceleration	a	0.5 a	0.25a
Max. deceleration	d	0.8 d	0.5 d
Response time	τ (or 2.5 τ)	1.5 τ	2 τ
Spring constant	k	0.75k	4 k
Damping coefficient	b	b	5 b
α	α	0.5 α	0.25 α
β	β (or 0.4 β)	0.67 β	0.5 β
γ	γ	0.5 γ	0.25 γ

In case of the leader of the platoon, the time to reach the desired speed is listed as the PC, mini-van, and semi-trailer in the order from the fastest due to the difference value of γ. In case of the followers, also the PC, mini-van, and semi-trailer is the order of clustering time as same as the sequence of α and β.

To check the relationship between the parameters and clustering time, this study set simulated cases. First of all, this study measures the time of the leader from 0 *m/s* to the desired speed (30 *m/s*) to know how γ works for these three classes of vehicles as the effect of maximum acceleration. As Figure 6.1 (a), if maximum acceleration increase, the time exponentially decrease. When maximum acceleration is 0.68 m/s^2 (semi-trailer), it takes around 400 *sec* to attain the desired speed. Start decreasing, it is a little bit under 200 *sec* at 2.25 m/s^2 (mini-van). If it is 4.43 m/s^2 as PC, it reaches the desired speed in 100 *sec*. For the followers, α which make CAVs approach critical spacing (37 *m*) is affected by maximum acceleration, so this study set that two consecutive CAVs have the same speed (30 *m/s*) and 50 *m* spacing. In other words, by setting the same speed between two vehicles, the effect of β is minimized, and this study can find out how α which is proportional to the maximum acceleration is operated in SMD system to attain critical spacing. As a result of clustering time (Figure 6.1 (b)), maximum acceleration and clustering time have the exponentially reciprocal relation. When it has the maximum acceleration of the semi-trailer (0.68 m/s^2), clustering is near 120 *sec*. In case of mini-van (2.26 m/s^2), it takes 50 *sec* to cluster. Having the highest maximum acceleration among three vehicle types (4.43 m/s^2), it is around 30 *sec*. Secondly, the response time has an effect on β that let CAVs follow the leading one and help the platoon have the same speed (the desired speed, 30 m/s) finally. To know the response time works for β, this study makes the situation as: i) the leader starts reaching the desired speed from 15 m/s, ii) the second vehicle follows with critical spacing from 0 *m/s*. In this case, since the second vehicle start from behind critical spacing, the effect of α is minimized so that this study can understand more directly how the second vehicle follow the speed of the first vehicle as the effect of β which is related to the response time. As shown in Figure 6.1 (c), as the response time increase, clustering time increase gradually until 1 *sec* of the response time and after that, rise steeply. When the response time is 1 sec (PC), clustering time is a little bit less than 20 *sec*. Beginning increasing rapidly, it is over 22 *sec* at the response time of mini-van (1.5 *sec*). If it is 2 *sec* as the response time of the semi-trailer, clustering time is around 25 *sec*. When the response time increase to 2.5 sec (PC behind the semi-trailer), it takes near 28 *sec* to cluster. To sum up, a vehicle that has lower performance (low acceleration) and longer response time takes longer time to reach the equilibrium state (longer clustering time). If there are more lower performance vehicles and PC behind semi-trailer in a platoon, clustering time would be longer.

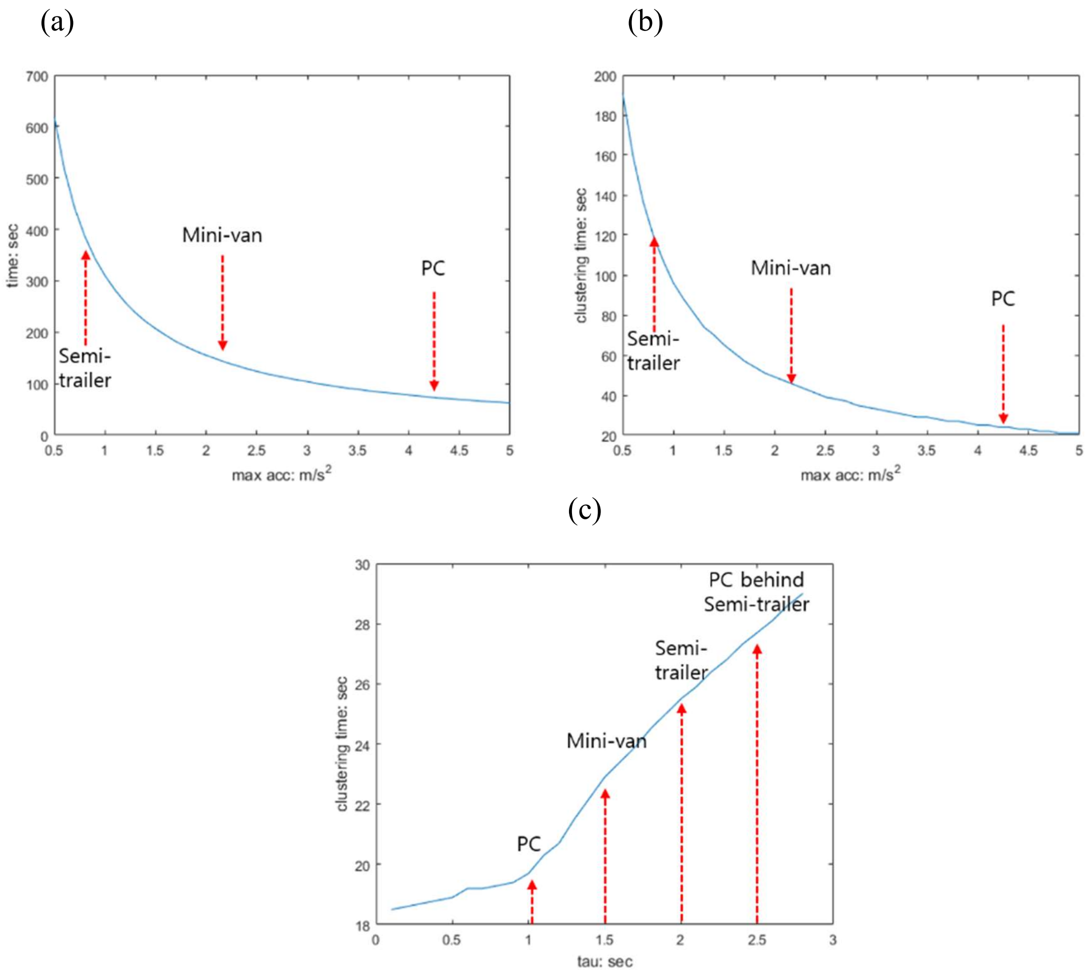


FIGURE 6.1 The effect of a_{max} and τ (a) the time that reach v_d vs. a_{max}; (b) Clustering time vs. a_{max}; (c) Clustering time vs. τ

6.2.2 Capacity

In Equation (29), the Critical spacing is the main factor that decides capacity. In the formulation of critical spacing (Equation (4)) as the denominator, considering speed is fixed for the desired speed at capacity, the response time has the biggest effect on critical spacing and capacity. If CAVs in a platoon has short response time, the capacity of the platoon is high.

$$capacity = \frac{\sum_1^n v_d}{\sum_1^n (S_o+\tau \cdot v_d)_i} \quad (i=1,2,3\ldots n) \tag{29}$$

Table 6.3 present comparison of parameters that affect capacity. Due to the longest minimum gap, vehicle length, and response time, this study can estimate that semi-trailer has the largest critical spacing at capacity. Except the PC behind semi-trailer, the critical spacing of the passenger it the shortest, and that of the mini-van would be the next. Real values of the parameters are applied, and then critical spacing and capacity are calculated when a platoon consists of a single vehicle type. In case of PC, critical spacing is 37 *m* and capacity is 2,918 v*eh/hr*. The platoon of the mini-van has *52m* of critical spacing and 2,077 *veh/hr* of capacity. The semi-trailers need 78 m for critical spacing, and 1,385 *veh/hr* can pass as capacity. When the PC is behind the semi-trailer, critical spacing is 82m, and if all PC has this spacing, capacity is 1,317 *veh/hr*. As a result, when there are more lower performance vehicles (mini-van and semi-trailer) and the PC behind the semi-trailer in the platoon, the capacity decreases as compared with the platoon of PCs.

TABLE 6.3 Parameters related to capacity

Parameter	Passenger car	Mini-van	Semi-trailer
Minimum gap	g	g	1.5 g
Vehicle length	h	h	3 h
Response time	τ or 2.5 τ	1.5 τ	2 τ
Critical spacing at capacity	$(g+h)+\tau \cdot v_d$ or $(g+h)+2.5\tau \cdot v_d$	$(g+h)+1.5\tau \cdot v_d$	$(1.5g+3h)+2\tau \cdot v_d$

6.3 Optimal Sequence of Heterogeneous CAVs

As mentioned before, this study can expect three factors that have an influence on efficiency of a platoon. There are (i) the vehicle type of the leader, (ii) the number of PC behind the semi-trailer, and (iii) the number of lower performance CAVs (mini-van and semi-trailer). To find out the best sequence of vehicles in terms of efficiency, several simulations are carried out in terms of the first and second factor (i.e., the vehicle type of the leader and the number of PC behind the semi-trailer). This study assumes that three types of CAVs travel on multi-lane highway and join the mainline from the on-ramps as Figure 6.2. An order of a platoon could be decided by how types of CAVs are mixed from the mainline and on-ramp, and also changeable through lane-changing and passing on multi lanes. This study analyzes the clustering time and capacity of platoons of the different vehicle sequence. From here, MV and ST denote mini-van and semi-trailer. Considering a combination with 3 CAVs, six combinations are possible with three types of CAVs as Table 6.4 except the case of three PC when all types of CAVs are included once, and these combinations are repeated in a platoon. Clustering time is the time that a platoon start moving with critical spacing and the desired speed so that the flow of the platoon is capacity. To know how fast the platoon with the different combination of CAVs reach critical spacing and the desired speed, the platoon start moving from a stop to the desired speed, and each CAV has 5 m more spacing than its critical spacing. In this platoon, this study set Δx at 100 m by assuming that it is intermediate flow state to calculate k from Equation (13). As this study expect, when PC is the leader of the platoon, clustering time is the shortest (case 5 and 6) since it has the highest maximum acceleration so reach the desired speed the fastest. If the leader is the same, the platoon that has PC behind ST presents longer clustering time and lower capacity due to its lower β and longer critical spacing from its larger response time. In case 6, because the order is repeated, after ST, PC follows it so that this platoon include PC behind ST. As a result, in aspect of clustering time and capacity, case 5 (PC-ST-MV) is the best order.

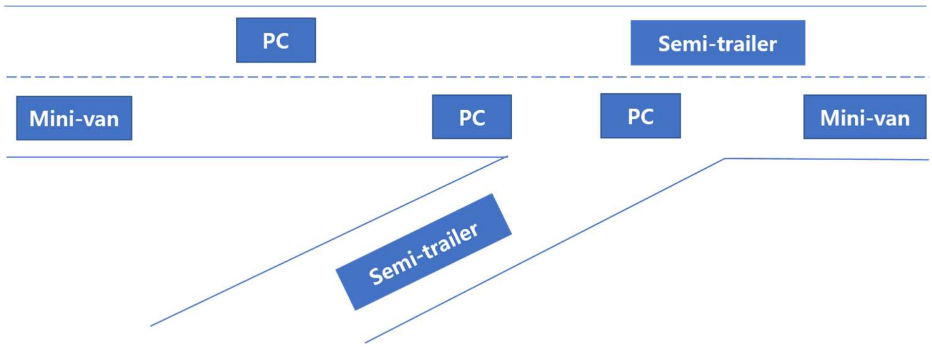


FIGURE 6.2 Merging area for heterogeneous CAVs

TABLE 6.4 Clustering time and capacity of the different orders of the platoon

Case	**Order**	**Clustering time (*sec*)**	**Capacity (*veh/hr*)**
Base	PC-PC-PC	25	2919
1	ST-PC-MV	194	1529
2	ST-MV-PC	169	1941
3	MV-PC-ST	49	1941
4	MV-ST-PC	62	1529
5	PC-ST-MV	27	1941
6	PC-MV-ST	30	1529

To find out the effect of the number of lower performance CAVs, this study analyzes clustering time and capacity by changing the ratio of MV and ST in case 5. If the ratio of the vehicle is 10, the platoon consists of only the vehicle (100%). In order for at least one PC to be included in the platoon as the leader. each ratio of MV and ST is set from 0 to 4. As the ratio of MV and ST increases, clustering time also rises (Figure 6.3(a)). When the ratio of ST increases clustering time grows faster than when the ratio of MV increases because ST has lower α and β than MV. On the other hand, capacity of the platoon decreases as the ratio of MV and ST increases (Figure 6.3(b)). The reduction of capacity by growth of ST ratio is larger than that of capacity by growth of MV ratio due to longer critical spacing of ST. From these simulation, this study confirms that the three factors (the vehicle type of the leader, the number of PC behind the semi-trailer, and the ratio of lower performance CAVs) have a negative impact on the platoon in terms of clustering time and capacity.

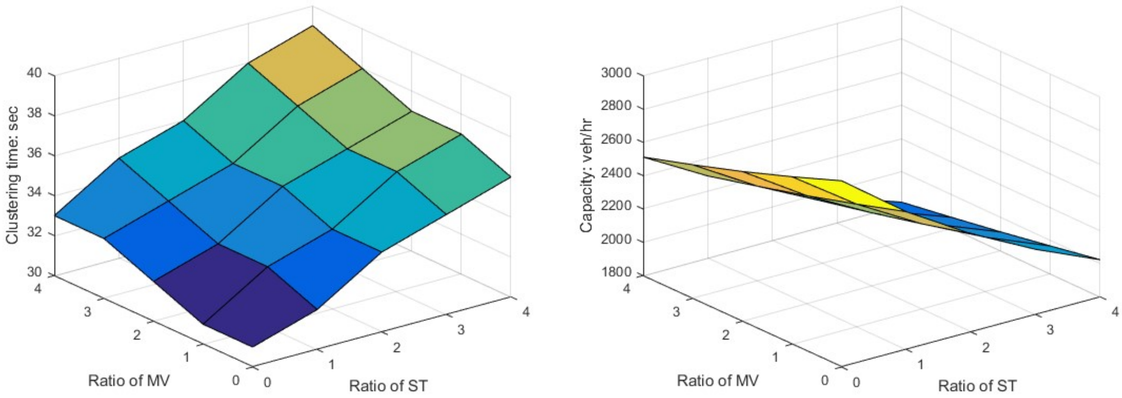


FIGURE 6.3 (a) variation of clustering time; (b) variation of capacity

7. CONTROL CAVS IN MIXED TRAFFIC

This section explains how traffic flow could be change due to the existence of CAVs for free flow and unstable flow. First, this study compares the characteristic of CAVs and manual vehicles by analyzing car-following equations of a CAV and manual vehicle. Through this comparison, how platoons of CAVs and manual vehicles would be formed is presented in light traffic. When the traffic flow can be unstable by cut-in movement, this study shows that different movement of CAVs has an impact on mixed traffic of CAVs and manual vehicles.

7.1 Characteristics of CAVs and Manual Vehicles

As equation (30) and (31) which are derived from equation (1) and (3), the leader of a CAV platoon accelerates until it achieves the desired speed, and the followers accelerate to reach both critical spacing and speed of a vehicle ahead. At equilibrium state, All CAVs in the platoon have the desired speed and critical spacing. Critical spacing is decided by the speed of a vehicle as similar to Newell's model, but the follower can travel with higher speed than the desired speed to attain critical spacing.

$$a_1 = \frac{c}{m_1}(v_d - \dot{x}_1) \,, \tag{30}$$

$$a_n = \frac{k_n}{m_n}(x_{n-1} - x_n - l) + \frac{b_n}{m_n}(\dot{x}_{n-1} - \dot{x}_n) = \frac{k_n}{m_n}\Delta x_n + \frac{b_n}{m_n}\dot{\Delta x}_n \tag{31}$$

Each parameter is set based on the specification of 2016 Chevrolet Malibu 2.0T. (Table 7.1). For setting c and k of a CAV, this study used maximum acceleration and deceleration which are calculated from the accelerating time from 0 to 97 km/h (60 mph) and braking distance from 113 km/h (70 mph). The reason why this study uses these maximum abilities of the vehicle for a CAV is to improve efficiency by setting high c and k which mean that CAVs can reach the desired speed and critical spacing (=equilibrium state) quickly when damping type is critical damping. For critical spacing, l, minimum gap is set as 2 m, and 1 sec is used for response time for CAVs since 0.6-1.1 sec is acceptable for CACC vehicles (Shladover et al., 2010; Nowakovski et al., 2010; Nowakowski et al., 2011). Lastly, the desired speed is assumed to be 30 m/s for both a CAV and manual vehicle.

TABLE 7.1 Specification of 2016 Chevrolet Malibu 2.0T (Car and Driver, 2016)

Specification	**Value**
Weight	1,500 kg
Length	5 m
Accelerating time from zero mph to 60 mph	6.1 sec
Decelerating distance from 70 mph to zero mph	51 m
Maximum acceleration	4.43 m/s^2
Maximum deceleration	9.42 m/s^2

In case of manual vehicles, when they have larger spacing than critical spacing and less speed than the desired speed, they accelerate to reach the desired speed or critical spacing. Once reaching the desired speed, they stop accelerating and maintain the desired speed even though there is larger spacing than critical spacing. If spacing is less than critical spacing due to cut-in vehicles, they reduce their speed to achieve critical spacing as the relation between spacing and speed in Newell's model (Figure 7.1). This study can present the acceleration behavior of manual vehicle as equation (32).

$$a_n = \min\left(\frac{k_n}{m_n}(x_{n-1} - x_n - l),\ \frac{c}{m_1}(v_d - \dot{x}_1)\right) \tag{32}$$

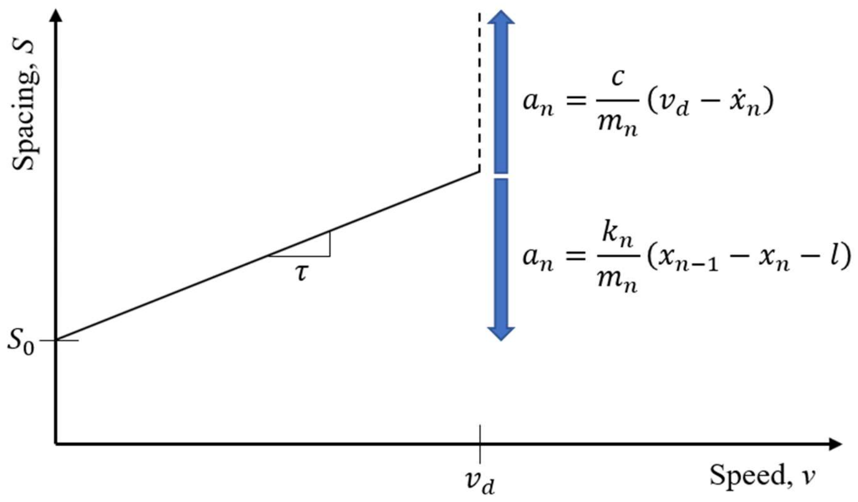


FIGURE 7.1 Relationship between spacing and speed in Newell's model

In case of a manual vehicle, desired values for a driver are used. For example, c and k values are calculated by the desired acceleration and deceleration which is from studies (Gipps, 1981; Treiber et al., 2000; Punzo and Simonelli, 2005; Ranjitkar et al., 2005; Kesting and Treiber, 2008; Hoogendoorn and Hoogendoorn, 2010; Yang et al., 2013) that calibrated car-following models (i.e., Gipps' model and IDM). They suggested 0.7-3.3 m/s^2 for desired acceleration and –1.0 - 4.5 m/s^2 for desired deceleration. Therefore, this study set the desired acceleration and deceleration of a manual vehicle as 1.7 m/s^2 and -3.0 m/s^2, respectively. In addition, 1.6 sec is used for the response time as 1.5-2 sec is a reasonable range of the response time of a manual vehicle (Ahn et al., 2004). Other values such as weight, vehicle length, minimum gap and desired speed are shared with CAVs

Using equation (9) and (10), this study compares the acceleration of a manual vehicle and CAV (Figure 7.2). Basically, if the spacing is larger and speed is slower, acceleration of a vehicle is higher. For all cases, a CAV shows higher acceleration, since critical spacing that a vehicle wants to maintain is shorter due to shorter its response time. When the spacing is between 40 *m* and 50 *m*, a manual vehicle has shorter spacing than critical spacing so that it would decelerate and show much lower acceleration than CAV. When there is larger spacing (70-90 *m*) between vehicles than critical spacing, acceleration of a manual vehicle does not increase because it speeds up to reach the desired speed regardless of its large spacing, while the acceleration of a CAV rises as spacing increases. Moreover, if speed is close to the desired speed (~30 *m/s*), a manual vehicle speeds up slightly since it is reluctant to travel at above the desired speed, but a CAV accelerates to reach critical spacing with traveling at over the desired speed.

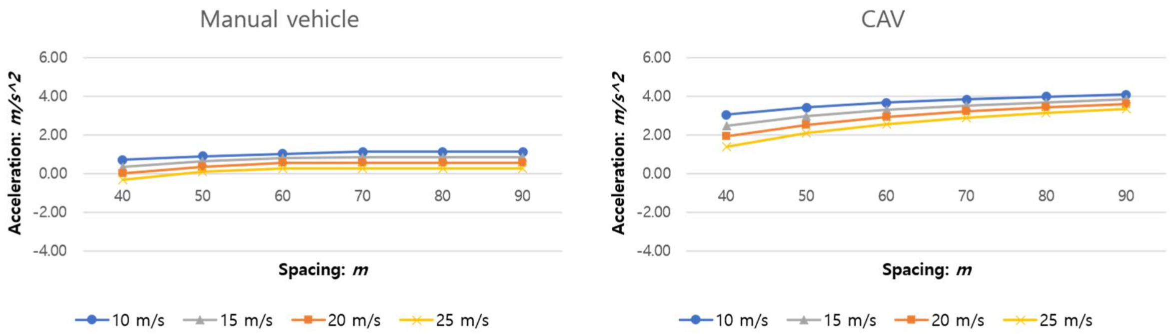


FIGURE 7.2 Comparison of acceleration between a manual vehicle and CAV (a) Manual vehicle; (b) CAV

7.2 Impact of CAVs on Mixed traffic

7.2.1 Light Traffic

This study assumes consecutive merging area as Figure 7.3. After vehicles join traffic of mainline from on-ramp1, the traffic flow of mainline is still stable, but it is enough saturated to occur oscillation when more vehicles merge through on-ramp2. To understand clearly, this study assume traffic distribution after on-ramp1 is uniform and insertion speed of on-ramp1 is 30 m/s which is the identical speed of vehicles on mainline so the vehicles of on-ramp1 can join smoothly the traffic without perturbation. For analysis, this study captures 11 vehicles that have 100m spacing and decide the sequence of manual vehicles and CAVs as penetration rate of each vehicle by using Bernoulli trials. 100%, 50%, 30% are considered as proportion of manual vehicles (proportion of CAVs: 0%, 50%, 70%, respectively) and the sequences for each proportion are presented in Table 7.2.

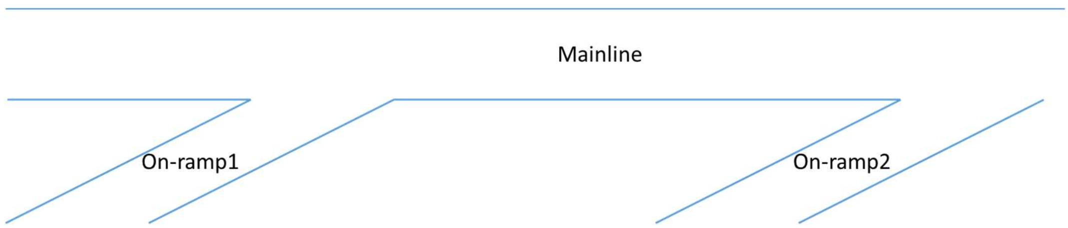


FIGURE 7.3 Merging areas

TABLE 7.2 Sequence of vehicles (manual vehicle=Man)
(a) Proportion of manual vehicles: 50%

Order	1	2	3	4	5	6	7	8	9	10	11
Veh	Man	CAV	Man	Man	CAV	Man	CAV	CAV	CAV	Man	CAV

(b) Proportion of manual vehicles: 30%

Order	1	2	3	4	5	6	7	8	9	10	11
Veh	Man	CAV	Man	CAV	CAV	CAV	Man	CAV	CAV	CAV	Man

Since manual vehicles do not exceed desired speed to reach critical spacing, but CAVs do, this study can expect that a platoon is divided into several small platoons that have a leader of the manual vehicle as the same number as manual vehicles in mixed traffic as Figure 7.4. Therefore, there are large spacing when the manual vehicle is behind CAV and as more CAVs are in front of a manual vehicle, spacing would be larger. Table 7.3 also presents this effect of

CAVs on mixed traffic. Considering cut-in vehicles from on-ramp2, it needs 110 m (double critical spacing (55 m)) to join the traffic without oscillation when the response time of a manual vehicle is 1.6 sec. When the proportion of a manual vehicle is 100 %, there is no chance to cut-in without an impact. However, as the proportion of a manual vehicle decrease to 50% and 30%, the number of the cut-in vehicle that can join the traffic without an impact increase to 4 and 5 vehicles.

TABLE 7.3 Re-distribution of a platoon with mixed traffic

Prop. of man (%)	Spacing (m)										Cut-in without an impact (# of veh)
	1	2	3	4	5	6	7	8	9	10	
100	100	100	100	100	100	100	100	100	100	100	0
50	37	163	100	37	163	37	37	37	289	37	4
30	37	163	37	37	37	289	37	37	37	289	5

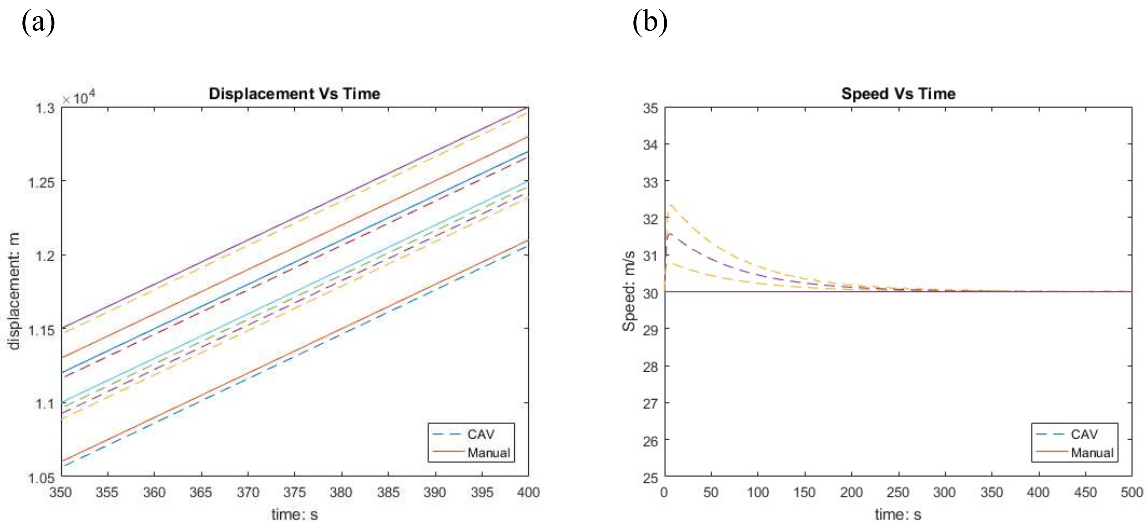


FIGURE 7.4 Platooning procedure in mixed traffic (50% proportion of Manual vehicle) (a) trajectory; (b) speed profile

7.2.2 Heavy Traffic

Traffic flow between on-ramp1 and on-ramp2 is saturated so that when vehicles cut in from on-ramp2, traffic on mainline could be unstable. Due to the cut-in vehicle, other vehicles in a platoon should be reduced and recover their speed to have critical spacing. In this situation, the behavior of CAVs has an impact on mixed traffic. Due to the lower acceleration of manual vehicles to the equilibrium state, spacing increase when a manual vehicle follows a CAV after oscillation. Therefore, if a manual vehicle follows CAV with critical spacing, spacing would be larger than critical spacing and a void which is additional spacing larger than critical spacing would occur after this pair reduces and recover their speed due to a cut-in vehicle. For example, as seen Figure 7.5, there is a platoon consist of three vehicles. A CAV follows a leader of the platoon and a manual vehicle travels behind the CAV. Each vehicle has their critical spacing. At 100 *sec*, one CAV joins the platoon at 12 *m* in front of the CAV. The three vehicles behind the leader, including the cut-in CAV, have to reduce their speed to reach their critical spacing and accelerate again to have the desired speed. In this procedure, the manual vehicle cannot follow the leading CAV simultaneously due to low acceleration rate of the manual vehicle to reach the equilibrium state. Therefore, the spacing of it increase from 55 *m* to 91 *m* and 36 *m* of the void appears.

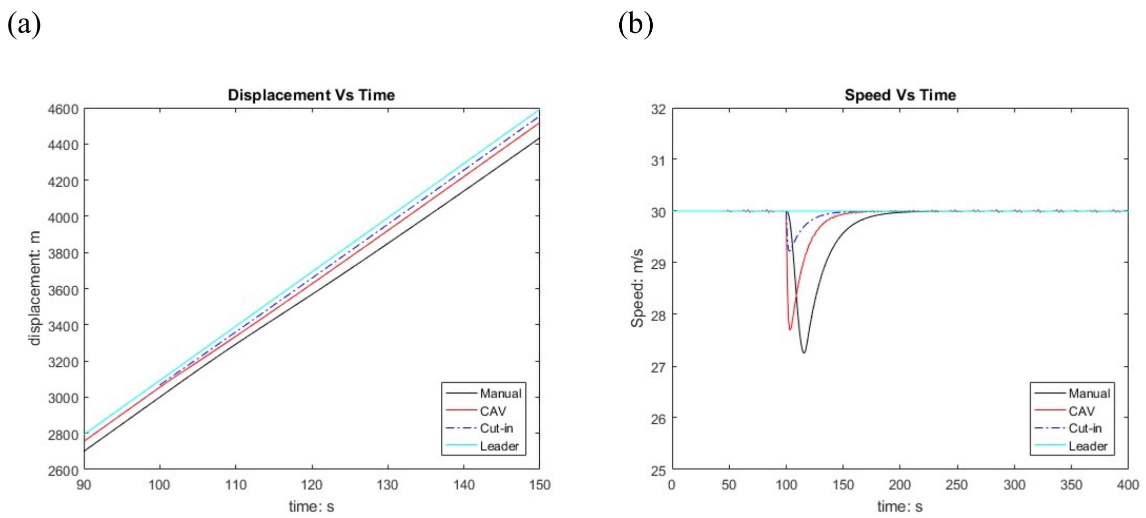


FIGURE 7.5 Increase of spacing due to the cut-in movement
(a) trajectory; (b) speed profile

7.3 Control CAVs for Absorbing the Impact.

In this section, this study develops a control method to prevent the negative impact of the cut-in movement on a manual vehicle. To this end, this study finds out that the cut-in movement actually has an impact on a manual vehicle. An equation that identifies how much spacing is insufficient is created. Based on this shortage spacing, this study presents that how CAVs in front of a manual vehicle should be controlled to absorb the impact.

7.3.1 Identifying the impact of the cut-in movement on a manual vehicle

$$Compressed\ spacing = (x_{cut\ in-1} - x_{cut\ in} - l_{cut\ in}) + (x_{cut\ in} - x_{cut\ in+1} - l_{cut\ in+1}) \quad (33)$$

$$Acceptable\ spacing = (x_{cut\ in+1} - x_{\ cut\ in+2} - l_{cut\ in+2}) + \cdots + (x_{cut\ in-n} - x_{\ man} - l_{man}) \quad (34)$$

$$Compressed\ spacing + Acceptable\ spacing = Shortage\ spacing < 0\ , \quad (35)$$

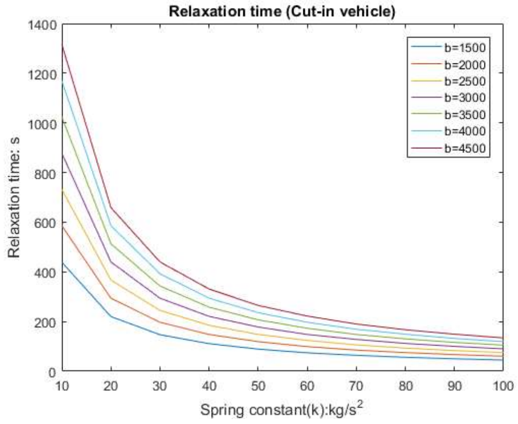
Equation (33) expresses compressed spacing (CS) that is the sum of a difference between current spacing and critical spacing of a cut-in vehicle and a CAV behind the cut-in vehicle just after the cut-in vehicle joins a platoon. It is a negative value since they have shorter spacing than their critical spacing. Equation (34) means acceptable spacing (AS) that is the sum of a difference between current spacing and critical spacing from between two vehicles from the cut-in vehicle and the manual vehicle, which is expected as equal to or larger than 0. As seen equation (35), if the shortage spacing (SS) which is the sum of the compressed spacing and acceptable spacing is negative, there is an impact on a manual vehicle, and it is possible to create a void. If the cut-in vehicle is a CAV, vehicles from cut-in vehicle to the CAV in front of the manual vehicle should absorb the impact which can be expressed as the negative value of equation (35) within acceptable spacing. When the cut-in vehicle is a manual vehicle, vehicles behind the cut-in vehicle excluding the manual vehicle should absorb the impact. Finally, this study divides the impact with those vehicles within acceptable spacing to occur flow loss of the manual vehicle.

7.3.2 Control method for absorbing the impact on a manual vehicle

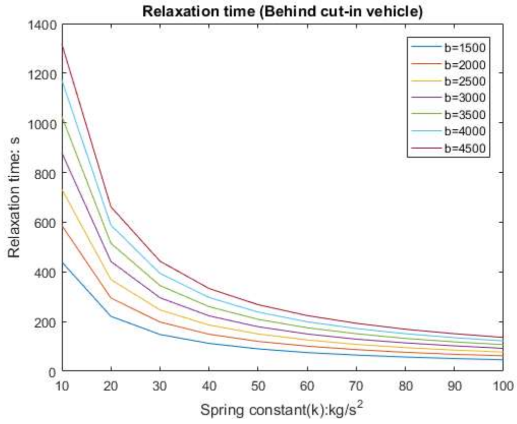
The basic method for absorbing the impact of the cut-in movement is setting low k and high b. Low k makes CAVs react insensitively to spacing variation so that they could maintain their shorter spacing than critical spacing. High b means that a CAV try strongly to keep the same speed as the speed of leading vehicle excessively. Therefore, speed variation of a cut-in CAV could be minimized since the leading vehicle of the cut-in CAV cruises at the desired speed. Propagation of this perturbation also could be reduced. In traffic consist of manual vehicles, they maintain shorter spacing than critical spacing during a short period (≈ 20 *sec*) (Leclercq et al., 2007; Zheng et al., 2013). As a result, this study extends this period to prevent abrupt speed disturbance and propagation of it. This period can be decided by expected cut-in movement such as next merging area (e.g., on-ramps and junctions). From now, this study calls this period as ‘relaxation time, T.' In this section, this study present how k and b are set properly as relaxation time and the number of CAVs between the cut-in CAV and manual vehicle.

This study assumes a platoon of 9 CAVs and one manual vehicle placed at the end of the platoon. Each vehicle has their critical spacing and a cut-in vehicle joins the platoon at the middle between the leader and the 2nd vehicle of the platoon. In doing so, the cut-in vehicle and the vehicle behind it feel the similar impact since they have the same spacing. Based on the value of k and b, how relaxation time (*sec*) and the increase of spacing (*m/s*) are changed is presented in Figure 7.6. Furthermore, this study shows how many CAVs absorb the impact and the change of void of the manual vehicle. As Figure 7.6 (a, b), as k increase and b decrease, relaxation time decline dramatically. In case of the increase of spacing, it shows opposite relationship in the same condition. The increase of spacing rises gradually when k increase and b decrease. Comparing Figure 7.6 (a) and (b), (c) and (d), they have the similar result between the cut-in CAV and the CAV behind it because of their same spacing. There are 8 CAVs from the cut-in CAV to the manual vehicle so that if 8 CAVs are affected by the impact, it is delivered to the manual vehicle. When the speed variation of the vehicle is over 1 m/s, this study assume that the vehicle is affected. The lower the k value and the higher the b value, the more the number of affected CAVs (Figure 7.6 (e)). Therefore, the impact that is delivered to the manual vehicle also increases so that the void also rises (Figure 7.6 (f)).

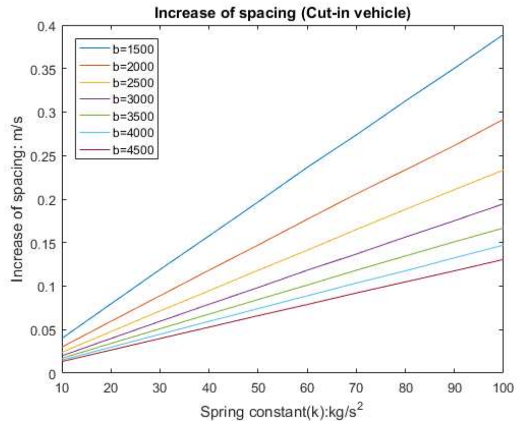
(a)


Relaxation time (Cut-in vehicle)
Relaxation time: s
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

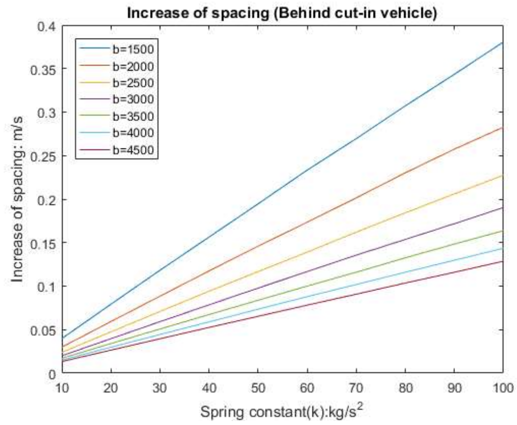
(b)


Relaxation time (Behind cut-in vehicle)
Relaxation time: s
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

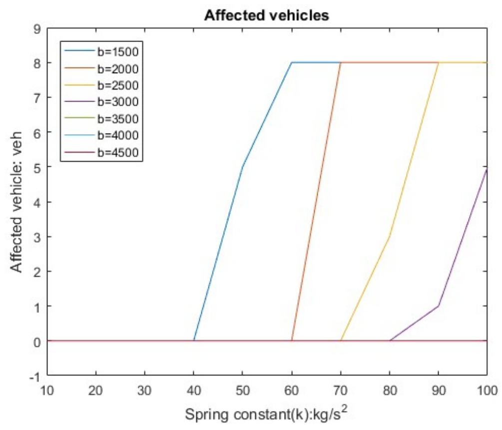
(c)


Increase of spacing (Cut-in vehicle)
Increase of spacing: m/s
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

(d)


Increase of spacing (Behind cut-in vehicle)
Increase of spacing: m/s
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

(e)


Affected vehicles
Affected vehicle: veh
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

(f)

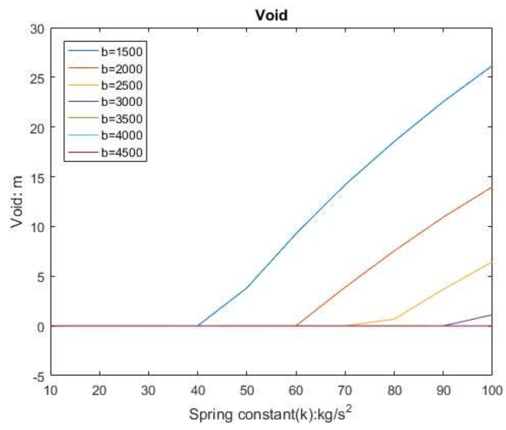

Void
Void: m
Spring constant(k):kg/s^2
b=1500
b=2000
b=2500
b=3000
b=3500
b=4000
b=4500

FIGURE 7.6 Simulation result (a) relaxation time of the cut-in CAV; (b) relaxation time of the CAV behind the cut-in CAV; (c) increase of spacing of the cut-in CAV; (d) increase of spacing of the CAV behind the cut-in CAV; (e) Affected vehicle; (f) void of the manual vehicle.

Setting low k and high b can guarantee less the affect vehicles and void but cause long relaxation time. This study need to relevant k and b as the position of an on-ramp and the number of CAVs that can absorb the impact. For example, assuming a platoon travels with the desired speed (30 *m/s*), this study need 150 *sec* of relaxation time that all CAV recover critical spacing when the next on-ramp appears in 4.5 *km*. Besides, there are 3 CAVs which can take the impact including the cut-in CAV. k and b could be set as 40 and 1500, or 60 and 2000, or 90 and 2500 to prevent void of the manual vehicle. If the possible relaxation time and absorbing CAVs increase, the available range of k and b could be wider. In this simulation, all vehicle in the platoon has their critical spacing (acceptable spacing=0). If there is more acceptable spacing so less shortage spacing, the reasonable range of k and b could be much wider.

When the cut-in vehicle is a manual vehicle, the cut-in manual vehicle reduces speed to increase spacing and recovers the desired speed. In this procedure, the void occurs since the leading CAV keep traveling with the desired speed. In doing so, shortage spacing is huge so that a lot of absorbing CAVs and long relaxation time should be needed to prevent delivering the impact to the manual vehicle in the platoon. This means that proportion of CAV in mixed traffic must be high and the distance between on-ramps should be extremely far. As this condition is hard to be satisfied, the cut-in manual vehicle has the impact on the manual vehicle in the platoon and the void occurs inevitably.

8. CONCLUSION AND FUTURE WORK

8.1 Conclusion

This study developed a strategy for platoon formation and evolution of CAVs within free-flow regimes. The proposed strategy was based on swarm intelligence that describes bird flocking, fish schooling, etc. in natural and artificial systems. In this concept, CAVs behave according to some rules to move together as a platoon without collisions. This concept was modeled as a Spring-Mass-Damper (SMD) system: CAV platoon formation and evolution are controlled by the spring constant and damping coefficient. Valid domains of these control parameters were derived based on physical vehicle properties, such as mass and bounded acceleration/deceleration, for realistic control and string stability.

This study conducted simulations to observe how platoons form and evolve over time at different flow levels. The result showed that vehicles started to make small platoons with nearby vehicles, and the platoons merged until one combined platoon was formed, which is a realistic representation of CAV platooning process. This study also examined via simulations the effects of various relationships (maximum, quadratic, cubic) between the spring constant and traffic flow, and damping conditions (critical- and over-damping) to obtain insight into desirable control parameter setting. The result suggested that this study can achieve the most efficient platooning (i.e., fastest clustering) by the *maximum* relationship between the spring constant and flow, and critical-damping. However, a *cubic* relationship, coupled with over-damping, was deemed more desirable in low flow states to allow more freedom for vehicles to cut in and out.

For unstable traffic condition, this study presented a strategy for CAVs to minimize the impact of vehicle cut-ins, building on the SMD-based developed in chapter 5. Based on the characteristics of model parameters, k and b, and their effects on vehicle movement, formulations to systematically set k and b upon a vehicle cut-in are developed. Specifically, a low k value is suggested for the cut-in vehicle and its immediate follower while maintaining over-damping to maintain short spacing, thereby minimizing the speed disturbance and preventing it from propagating through the platoon. This study performed simulation to evaluate the control method, which showed that the speed and spacing variation, and recovery time (to reach the desired speed) diminished significantly with the proposed control. Additionally, this study offered ways to smoothly recover spacing to accommodate further cut-ins.

By using SMD system, this study described how to control heterogeneous CAVs. From specification of different types of vehicles such as maximum acceleration and the response time, Clustering time that the platoon reach equilibrium state and capacity were estimated for heterogeneous CAVs. Based on these results, this study presented the best order of vehicles in the platoon to maximize capacity. The platoon of heterogeneous CAVs had to minimize not only the number of low performance vehicles but also the PC behind the semi-trailer. When the platoon was organized as the order, variation of clustering time and capacity were estimated by various ratio of each CAV.

Furthermore, this study estimated the impact of CAVs in mixed traffic of manual vehicles and CAVs due to their different characteristics. acceleration of CAVs to achieve equilibrium state is higher than that of manual vehicles because of shorter response time of CAV, and the parameters of CAVs were set based on maximum acceleration to improve efficiency instead of the desired acceleration unlike the parameters of manual vehicles. Therefore, when perturbation was delivered to a manual vehicle in a platoon from downstream, it could not recover its spacing and a void occurred. To prevent this phenomenon, this study developed a control method for absorbing the perturbation by set low k and high b with considering traffic condition and the distance between on-ramps.

In conclusion, CAV control strategies by using SMD system was suggested for all traffic state. In stable traffic state, how CAVs form and evolve without cut-in movement from light traffic to capacity was showed. In unstable traffic, this study described the procedure of CAV platooning was done to minimize the impact of the cut-in vehicle and improve capacity by setting low k and high b. In terms of composition of vehicles, heterogenous CAVs and mixed traffic were considered. Based on their capability, the best control method is presented for maximizing efficiency.

8.2 Future Work

This study was concerned with longitudinal control. To be complete, lateral control to accommodate cut-ins and cut-outs (i.e., lane changes) is desired in the future. Furthermore, for more comprehensive control, platoon control with vehicle cut-out movements should also be considered. The control method with cut-in applies to transient conditions, and a more systematic way to resume normal control should be investigated in the future, which will depend on traffic operational and geometric characteristics (e.g., merge, diverge, and weave sections). Research in these directions are ongoing.

This study developed a theoretical framework for CAV control to proactively minimize the impact of cut-in maneuvers assuming perfect conditions for CAV infrastructure, communication, and sensing. Field testing using sensor-equipped vehicles is desired in the future to calibrate and validate the proposed model with real data. For real-world implementation, several pragmatic issues should be considered. For example, short spacing under the proposed control may raise safety concerns in the event of system failure due, for example, to communication failure, sensor malfunction, etc. Thus, backup control should be considered for safety assurance. Furthermore, our model was developed for central control in a fully connected and automated environment with vehicle to infrastructure (V2I) communication. Specifically, this study assumed that CAVs can be controlled through a traffic management center that monitors traffic conditions in a target area and determines proper control. This type of central control system would require more sophisticated infrastructure and advanced communication and computing capabilities with negligible delays. Therefore, a distributed control scheme is desirable that requires less communication and computational capabilities albeit with reduced benefits.

For mixed traffic of CAVs and manual vehicle, this study assumed that those two vehicles had the same desired speed. However, since human drivers have different behavior in terms of the desired speed, a flexible range of the desired speed for manual vehicle would be need. Moreover, this study set a certain value of the desired acceleration for a manual vehicle. Also in this case, a reasonable range of the desired acceleration should be considered, and this study needs a sensitivity analysis to know how an impact on manual vehicle (i.e. void) varies according to the range of the desired acceleration of the manual vehicle.

As a way of extending this study in terms of vehicle composition, more types of vehicles can be considered. For example, it is possible that analyze several types of CAVs and manual vehicles such as a platoon mixed CAVs of PCs, mini-vans, and semi-trailers with manual vehicles of PCs and semi-trailers, and so on. Finally, the strategies of chapter 4 and 5 could apply to heterogeneous CAVs include manual vehicles.

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