

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Coordination and Analysis of Connected and Autonomous Vehicles in
Freeway On-Ramp Merging Areas

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Merging Areas

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Abstract

Freeway on-ramps are typical bottlenecks in the freeway network, where the merging maneuvers of ramp vehicles impose frequent disturbances on the traffic flow and cause negative impacts on traffic safety and efficiency. The emerging Connected and Autonomous Vehicles (CAVs) hold the potential for regulating the behaviors of each individual vehicle and are expected to substantially improve the traffic operation at freeway on-ramps. The aim of this research is to explore the possibilities of optimally facilitating freeway on-ramp merging operation through the coordination of CAVs, and to discuss the impacts of CAVs on the traffic performance at on-ramp merging.

In view of the existing research efforts and gaps in the field of CAV on-ramp merging operation, a novel CAV merging coordination strategy is proposed by creating large gaps on the main road and directing the ramp vehicles into the created gaps in the form of platoon. The combination of gap creation and platoon merging jointly facilitates the mainline and ramp traffic and targets at the optimal performance at the traffic flow level. The coordination consists of three components: (1) mainline vehicles proactively decelerate to create large merging gaps; (2) ramp vehicles form platoons before entering the main road; (3) the gaps created on the main road and the platoons formed on the ramp are coordinated with each other in terms of size, speed, and arrival time. The coordination is analytically formulated as an optimization problem, incorporating the macroscopic and microscopic traffic flow models. The model uses traffic state parameters as inputs and determines the optimal coordination plan adaptive to real-time traffic conditions.

The impacts of CAV coordination strategies on traffic efficiency are investigated through illustrative case studies conducted on microscopic traffic simulation platforms. The results show substantial improvements in merging efficiency, throughput, and traffic flow stability. In addition, the safety benefits of CAVs in the absence of specially designed cooperation strategies are investigated to reveal the CAV's ability to eliminate critical human factors in the ramp merging process.

Keywords: Freeway on-ramp merging, Connected and autonomous vehicles, Coordinative merging strategy, Operational efficiency, Safety impacts, Microscopic traffic simulation

Preface

The journey towards a PhD degree is never a piece of cake. I am grateful to the people along the way with whom I shared memorable moments over the past four years.

The greatest thanks go to my supervisors, Xiaobo Qu and Ivana Tasic. I came to Chalmers as a fledgling student with little idea of what research is like. It was under their invaluable guidance and support that I grew into the researcher I am today. I would like to thank Xiaobo for sharing his valuable expertise and experience in work, as well as his generous support for my long path development. He is a true mentor from whom I not only learned knowledge but also deepened my thinking as a researcher in general. I want to thank Ivana for being a supervisor and a friend. I can always recall how she made me welcome in the beginning and gave me continuous care, encouragement, and freedom in research in the following years. I would also like to thank Lars Rosen for leading me into the world of risk analysis and being a considerate manager and examiner especially during Covid, and the teachers and tutors at Chalmers who introduced me new knowledge and made me feel the joy of learning as a PhD student. I am thankful to the colleagues at Chalmers (special thanks to Kun Gao and Quanjiang Yu) for the insightful discussions and close collaborations, and colleagues at Volvo AB for their support during my internship there.

I came to Gothenburg in 2018 without knowing anyone. It is a great pleasure to have met many interesting friends over the past years. We accompany and help each other in lives far away from home. It is the warm and enjoyable times we spent together that make Gothenburg a lovely place to stay. A unique part in my heart is reserved for my closest friends. Even though we are apart all over the world, I know they are the ones I can always complain to, make fun of, and share with them the greatest and hardest moments in life. This thesis is dedicated to my family in China who passed on me the initial motivation towards a PhD journey. My parents are the best parents I could ask for. They shape me into who I am and give me unconditional love, understanding, and support for whatever decisions I make in life.

In the end, I would like to thank the Area of Advance Transport at Chalmers University of Technology for financially supporting this dissertation research.

Summary

This dissertation is a compilation thesis and consists of two parts: introductory chapters and appended papers. The introductory chapters present an extended summary of the research and put the relevant papers into contexts. Research details are further explained in the appended papers in Appendix A – E.

The work contained in this dissertation leads to the following papers:

- **Paper I**
Zhu, J., Easa, S.M., & Gao, K. (2022). Merging control strategies of connected and autonomous vehicles at freeway on-ramps: A comprehensive review. *Journal of Intelligent and Connected Vehicles* ahead-of-print (ahead-of-print).
- **Paper II**
Zhu, J., Tasic, I., & Qu, X. (2021). Improving freeway merging efficiency via flow-Level coordination of connected and autonomous vehicles. Retrieved from <https://doi.org/10.48550/arXiv.2108.01875>. Submitted to *IEEE Transactions on Intelligent Transportation Systems*.
- **Paper III**
Zhu, J., Tasic, I., & Qu, X. (2022). Flow-level coordination of connected and autonomous vehicles in multilane freeway ramp merging areas. *Multimodal Transportation* 1(1): 100005.
- **Paper IV**
Zhu, J., Gao, K., & Qu, X. (2022). Bi-level ramp merging coordination in congested mixed traffic conditions with human-driven and connected autonomous vehicles. Manuscript to be submitted.
- **Paper V**
Zhu, J., & Tasic, I. (2021). Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles. *Accident Analysis & Prevention*, 152, 105966.

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Nomenclature

| | |
|--------|--|
| ATM | Active traffic management |
| BASt | German Federal Highway Research Institute |
| CAV | Connected and autonomous vehicle |
| CMH | Conflicting merging headway |
| CoMC | Coordinative merging control strategy |
| CV | Connected vehicle |
| EM | End of merging |
| HDV | Human-driven vehicle |
| HEV | Hybrid electric vehicle |
| M-CoMC | Coordinative merging control strategy in mixed traffic |
| MFV | Mainline following vehicle |
| MP | Merging point |
| MPC | Model predictive control |
| NGSIM | Next generation simulation program |
| NHTSA | US National Highway Traffic Safety Administration |
| PET | Post encroachment time |
| RMV | Ramp merging vehicle |
| SAE | Society of Automotive Engineers |
| SC | Speed-change position |
| SUMO | Simulation of urban mobility |
| TraCI | Traffic control interface |
| TTC | Time to collision |
| VDA | German Association of the Automotive Industry (Verband der Automobilindustrie) |
| V2I | Vehicle to infrastructure communication |
| V2V | Vehicle to vehicle communication |
| V2X | Vehicle to everything communication |
| WP | Waiting position |

Chapter 1

Introduction

1.1 Background and motivation

On-ramp merging areas are typical bottlenecks in the freeway network, where the lane-changing maneuvers of the ramp merging vehicles impose frequent disturbances on the mainline traffic flow (Son et al., 2004, Han et al., 2018), causing reduced traffic stability and efficiency (Daganzo et al., 1999), triggering traffic breakdown and capacity drop (Cassidy et al., 1999, Srivastava et al., 2013), and resulting in a high risk of critical conflicts between the mainline and ramp vehicles (Wang, 1994, Yang et al., 2011, Mergia et al., 2013).

Traditional approaches to mitigate these negative effects at freeway on-ramp merging focus on the improvement of infrastructure and regulation design (Fukutome et al., 1960, Hunter et al., 2001) and Active Traffic Management (ATM) strategies, such as ramp metering, variable speed limit, and hard-shoulder running (Mirshahi et al., 2007). These approaches usually regulate the macroscopic traffic state parameters (e.g., flow rate and speed) based on the estimated real-time traffic conditions. With the adaptivity to traffic conditions, the ATM measures are shown to have positive effects on the merging operation at freeway on-ramps (Hegyi et al., 2005, Haj-Salem et al., 2014, Li et al., 2014, Schmidt-Dumont et al., 2015). However, the effects are somewhat limited because these approaches can only manage traffic at an aggregated level without interfering with the motions of individual vehicles and manipulating the microscopic interactions between vehicles. As a result, the traditional ATM measures usually only postpone the occurrence of congestions, rather than facilitate the overall traffic performance at on-ramp merging (Scarinci et al., 2014).

The emerging Connected and Autonomous Vehicles (CAVs) hold the potential for regulating vehicle behaviors at the individual level and are highly expected to bring substantial improvements in the freeway on-ramp merging operation. With the communication technology, the vehicles are able to exchange detailed information with the roadway infrastructures, the traffic management center, and the other road users, so as to determine the individual driving plan based on a more comprehensive understanding of the road and traffic conditions (Papadimitratos et al., 2009). Further, the self-driving technology allows the vehicles to control the engine and the steering system autonomously, so that the determined driving plan can be followed in a stable and timely manner, free of errors and delays related to the Human-Driven Vehicles (HDVs) (NHTSA, 2018). Note that the communication capability and the autonomous driving capability do not necessarily rely on each other, that is, a vehicle can be only “connected” or “autonomous” instead of being “connected and autonomous”; however, a combination of the two capabilities will enable a full use of their benefits and lead to an enhanced operational performance (Talebpour et al., 2016). Thus, this dissertation considers both the communication and autonomous driving capabilities of CAVs.

With the advanced communication and autonomous driving capabilities, CAVs are expected to bring substantial improvements in various aspects of the freeway on-ramp merging operation. A major finding is that CAVs can improve the merging efficiency and throughput and alleviate congestions at the on-ramp bottlenecks by reducing the headway between vehicles and enabling stable platoon driving (Krause et al., 2017, Liu et al., 2018, Xiao et al., 2018, Bian et al., 2019, Guo et al., 2020b, Ma et al., 2020, Cao et al., 2021). In addition, the launch of CAVs is expected to reduce the number and severity of vehicle conflicts and prevent traffic accidents by eliminating the critical human factors, especially at high market penetration rates (Park et al., 2012, Jeong et al., 2017, Papadoulis et al., 2019, Mullakkal-Babu et al., 2020). Moreover, CAVs are capable of smoothing the vehicles' speed and acceleration/deceleration trajectories, leading to improved passenger comfort and reduced energy consumptions and emissions (Rios-Torres et al., 2016, Rios-Torres et al., 2018, Qin et al., 2019, Xu et al., 2021). It is worth noting that the existing studies on the CAV impacts at on-ramp merging mainly focus on the operational efficiency and energy consumption, whereas the impacts on merging safety are only discussed to a limited extent.

Further, the emerging CAV technology enables sophisticated motion planning of individual vehicles, opening up new opportunities for cooperation/coordination at on-ramp merging. Specifically, the motions of multiple CAVs can be jointly planned to achieve a common merging goal, such as avoiding collisions and reducing the collective delay. A detailed review on the cooperative/coordinative on-ramp merging strategies leveraging CAVs is provided in Section 2.3. In summary, the existing strategies share the common objective of improved ramp merging operation, while presenting differences in many aspects, for example, the required vehicle technologies (connected, autonomous, or connected and autonomous), the required level of automation (driver-assisted, partially automated, or fully automated), the penetration of "vehicle intelligence" (full CAVs or a mix of CAVs and HDVs), the network layout (single lane or multi-lane freeway), the direction of control (longitudinal, lateral, or both), the method of control (optimal control, feedback control, or others), and the type of control (centralized or decentralized). Nevertheless, most of the existing studies mainly focus on the lower-level cooperation between individual vehicles (e.g., trajectory design), whereas the possibilities of upper-level coordination between traffic flows are barely discussed in the existing literature.

1.2 Research objectives and structure

The objectives of this dissertation are (1) to explore the possibility of improving freeway on-ramp merging operation through the coordination between CAVs, with a focus on the improvements at the traffic-flow level, and (2) to investigate the potential impacts of CAVs on the overall traffic performance in the on-ramp bottlenecks. Specifically, this study is committed to carrying out the following tasks, as illustrated in Figure 1.1:

- **Task 1:** The existing research efforts related to the key points of CAV on-ramp merging shall be reviewed in detail, with a focus on the latest trends and developments

in this field (*Task 1.1*). Based on the review, the main research gaps shall be identified (*Task 1.2*).

- **Task 2:** In view of the identified research gaps, a novel merging coordination strategy leveraging CAVs shall be developed to facilitate the overall merging operation at freeway on-ramps. The strategy shall focus on the coordination between the two streams of traffic flow (instead of individual vehicles) for merging benefits in the overall efficiency and stability of the traffic flow. The strategy shall be first tested in a basic context of single lane freeway and full CAV penetration rate, while being ready for extensions in the more complex contexts (*Task 2.1*). On this basis, the CAV merging coordination strategy shall be extended to multi-lane freeway configurations, where free lane-changes between the mainline lanes would affect the merging opportunities of on-ramp vehicles and shall be therefore taken into consideration in the coordination (*Task 2.2*). Further, the CAV merging coordination strategy shall be extended to mixed traffic conditions where CAVs and HDVs coexist. In such a context, the presence of HDVs would introduce various uncertainties in the traffic operation and shall be addressed in the coordination (*Task 2.3*).
- **Task 3:** The impacts of CAVs on freeway on-ramp merging operation shall be investigated in terms of the operational efficiency and merging safety. The efficiency benefits of the developed coordination strategies shall be demonstrated in detail through well-designed case studies (*Task 3.1*). In addition, the safety impacts of CAVs in the absence of specially designed cooperation strategies shall be investigated in order to highlight the CAV's role in eliminating critical human factors at ramp merging (*Task 3.2*).

In this dissertation, the following assumptions about CAVs are applied:

- All CAVs are at the highly automated level corresponding to SAE automation level 4 or higher (SAE, 2016). The vehicles are capable of longitudinal and lateral driving tasks without any expectations of human assistance.
- The CAVs are capable of instantaneous communication with the control center, the infrastructures, and other road users.

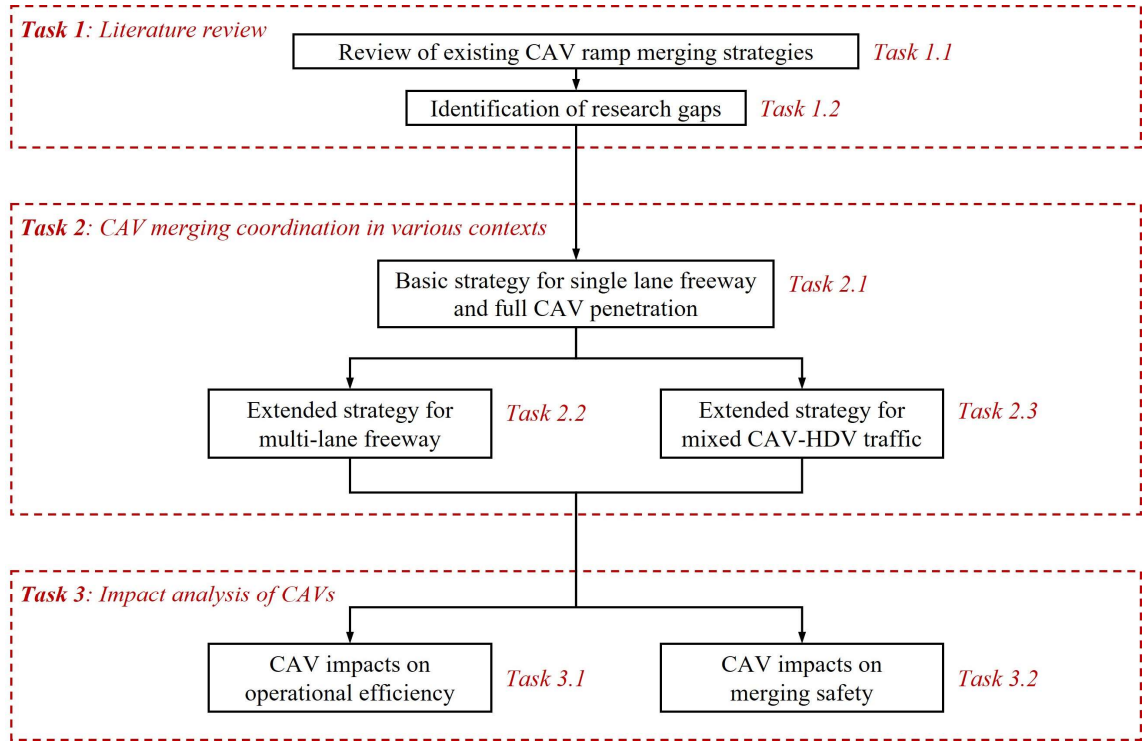


Figure 1.1 Structure of the dissertation

1.3 Contributions and Limitations

This section summarizes the main contributions and limitations of the work contained in this dissertation. The contributions lie in the following aspects:

- The review of CAV ramp merging strategies puts a focus on the latest trends and developments in the research field, such as strategies for mixed CAV-HDV traffic conditions and multi-lane freeways. These are barely covered in the previous review efforts. (Task 1)
- The developed merging coordination strategy controls the two streams of traffic (instead of individual vehicles) for the flow-level efficiency gains. The formulation of the strategy incorporates macroscopic traffic flow models, allowing for an explicit consideration of the transition of traffic state and the traffic flow stability. (Task 2)
- The developed merging coordination strategy innovatively combines the ideas of proactive gap creation on the main road and vehicle platooning on the ramp. It is expected that the consolidation of the two ideas would result in enhanced coordination benefits than applying them separately. (Task 2)
- The coordination strategy is formulated under an optimization framework with the traffic state parameters as model inputs. This allows the strategy to produce optimal control schemes adaptive to the real-time traffic conditions. (Task 2)
- The extended strategy for multi-lane freeway takes into consideration the free lane-changing maneuvers on the main road and mechanisms to protect the created gaps from being occupied by the mainline vehicles in the inner lanes. (Task 2)

- The extended strategy for mixed traffic takes into account the uncontrollability of HDVs and adopts the idea of influencing the HDV behaviors through the actions of surrounding CAVs. The developed strategy is able to accommodate the uncertainties related to HDVs' arrival and driving patterns. (Task 2)
- The existing studies on CAV safety usually assume the presence of collision avoidance measures based on the communication capability of CAVs, so the reported safety impacts are more related to the cooperation between CAVs rather than the elimination of human delays and errors. The safety analysis in this dissertation investigates CAV impacts in the absence of cooperation measures to highlight the CAV's role in eliminating critical human factors in the merging process. (Task 3)
- The safety investigation introduces an approach specially designed for the ramp merging operation, including a novel conflict index and a merging conflict model. The new index makes a significant complement to the existing surrogate safety measures. (Task 3)

This dissertation has some limitations in terms of the research scope and method:

- The operation of CAVs is an interdisciplinary topic that combines knowledge from transportation engineering, mechanical engineering, communication engineering, etc. This study focuses on the transportation aspects, such as the interaction between vehicles and the operation of traffic flow, whereas the lower-level vehicle dynamics (e.g., control of throttle, brake, and steering systems) and vehicular communication (e.g., signal transmission) are assumed to be available and not discussed in detail in this dissertation.
- Due to the lack of the empirical data on CAVs, especially at the full automation level, this dissertation makes assumptions on the capabilities and operating methods of CAVs. For example, it is assumed that the CAVs are capable of all dimensional driving tasks and instantaneous communication with the infrastructure and the other road users.
- The impact investigations in this dissertation are mainly carried out through simulation studies instead of field tests.

1.4 Outline

The following chapters of this dissertation are structured as below:

- **Chapter 2** provides a thorough review on the key points of the research background, including traffic operation at freeway on-ramp merging, state-of-the-art CAV technologies, and existing on-ramp merging strategies leveraging CAVs. Based on the review, main research gaps in the field of CAV ramp merging coordination are identified.
- **Chapter 3** presents the basic merging strategy for the context of single lane freeway and full CAV penetration rate, including a detailed description of the coordination strategy, its analytical formulation in the basic context, and an illustrative case study that demonstrates the coordination benefits.

- **Chapter 4** presents the extended merging strategy for multi-lane freeways, including the integrated lane-change rules between mainstream lanes, related discussions, and a case study of multi-lane freeway.
- **Chapter 5** presents the extended merging strategy for mixed CAV-HDV traffic conditions, including extensions in response to the presence of HDVs, analytical formulation of the extended coordination, and a case study of mixed traffic.
- **Chapter 6** investigates the safety impacts of CAVs at on-ramp merging with a focus on the CAV's role in eliminating critical human factors. This chapter introduces the safety investigation methods for ramp merging and discusses the safety impacts of CAVs under different penetration rates.
- **Chapter 7** concludes the dissertation with discussions and recommendations for future research.

Chapter 2

CAV on-ramp merging - a literature review

This chapter is based on the work contained in the following paper in Appendix A:

- **Paper I.** Zhu, J., Easa, S.M., & Gao, K. (2022). Merging control strategies of connected and autonomous vehicles at freeway on-ramps: A comprehensive review. *Journal of Intelligent and Connected Vehicles* ahead-of-print (ahead-of-print).

In this chapter, key points related to the CAV ramp merging problem are reviewed, including the critical nature of traffic operation in on-ramp bottlenecks, the emerging vehicle communication and autonomous driving technologies, and the existing cooperative and coordinative ramp merging strategies leveraging CAVs. Section 2.1 discusses freeway on-ramp merging operation, Section 2.2 introduces the CAV technologies, and Section 2.3 summarizes CAV ramp merging strategies.

2.1 Freeway on-ramp merging operation

In this section, we review the critical nature of traffic operation in the freeway on-ramp merging areas and the traditional approaches that aim at facilitating the on-ramp merging operation. The emerging cooperation/coordination strategies leveraging CAVs are reviewed in section 2.3.

Observations from numerous empirical studies (Cassidy et al., 1999, Daganzo et al., 1999, Bertini et al., 2004, Srivastava et al., 2013) have shown that the on-ramp bottlenecks are a major source for traffic congestions, and the average rate vehicles discharge from an active on-ramp bottleneck is usually lower than the flow rate measured before the onset of the congestion (known as the phenomena of capacity drop). The critical nature of the traffic operation in the on-ramp merging areas is related to the inherent conflict between the needs of the mainline and ramp vehicles. The mainline vehicles intend to maintain efficient driving on the freeway, whereas the ramp vehicles attempt to cut into the mainline traffic stream. Han et al. (2018) point out that the insertion of a merging vehicle can instigate a disturbance on the mainline traffic flow, because the immediate follower on the main road may have to reduce its speed to gain desirable space from the merging vehicle. This disturbance triggered by a merging maneuver may dissipate if the following vehicles are spaced far enough apart, as the large spaces between vehicles act as buffers for the speed disturbance. However, when the traffic flow is high, and the vehicles are closely spaced, the disturbance may propagate along the main road and grow with the successive disturbances triggered at merging, eventually leading to traffic breakdowns. This analysis is in line with the findings of Elefteriadou et al. (1995), Evans et al. (2001), and Son et al. (2004), where the authors also state that the breakdown probability is associated with the intensities of the mainline traffic and the ramp merging behaviors. In addition, the on-ramp

merging areas are also high-risk areas for motor vehicle crashes and conflicts (Wang, 1994). The safety concerns are raised by many factors related to the traffic, roadway geometric, and driving patterns in the freeway ramp merging areas, such as the high speed on the freeway, the large speed difference between the mainline and ramp traffic flows, the blind spots introduced by the separation of the freeway and the on-ramp, and the intensive workload of drivers who must conduct complex information processing and vehicle control tasks at merging (Ahammed et al., 2008, Mergia et al., 2013, Wang et al., 2019).

Various approaches that attempted to facilitate on-ramp merging operation and mitigate the negative consequences in traffic efficiency and safety have been proposed. Initial efforts targeted at the joint improvements of the infrastructure and traffic regulation design. For example, the researchers analyzed the features of different ramp geometries and combined the selection of the mainline and ramp design speeds with the design of the infrastructure layout (Fukutome et al., 1960, Harwood et al., 1993, Hunter et al., 2001). Later on, active traffic management (ATM) approaches, which refer to the ability to dynamically manage traffic based on the estimation of real-time traffic states (Mirshahi et al., 2007), were introduced into research and practice. A primary ATM approach for the on-ramp merging operation is the ramp metering system, where a traffic light is installed on the ramp to regulate the inflow of vehicles from the ramp based on the traffic conditions on the main road. The most widely deployed strategies include ALINEA (a local strategy), SWARM (a system-wide strategy), HERO (a heuristic approach) and their variations (Papageorgiou et al., 1991, Paesani et al., 1997, Papageorgiou et al., 1997, Ahn et al., 2007, Papamichail et al., 2010a, Papamichail et al., 2010b). A detailed review on ramp metering is available in Papageorgiou et al. (2002) and Shaaban et al. (2016). Other widely discussed ATM techniques include variable speed limits/signs, mainline metering, and hard-shoulder running. Variable speed limits harmonize traffic in the bottlenecks by adaptively regulating the speed of vehicles upstream of the merging point (Carlson et al., 2011, Chen et al., 2014). Mainline metering, similar to ramp metering, uses traffic signals to limit the number of vehicles arriving at the on-ramp bottlenecks from the main road (Haboian, 1995, Jin et al., 2017). Hard shoulder running opens the shoulder lane in the cases of high traffic volume to increase road capacity. The shoulder lane can thus act as a “release” for vehicles accumulated in the bottleneck areas (Geistefeldt, 2012). Strategies combining multiple ATM techniques, for example, applying ramp metering for ramp control and variable speed limits and/or hard shoulder running for mainline control, have also been discussed in the literature (Hegyi et al., 2005, Haj-Salem et al., 2014, Li et al., 2014, Schmidt-Dumont et al., 2015).

2.2 Connected and autonomous vehicles

CAV technologies incorporate the vehicle communication technology, i.e., Connected Vehicle (CV), and the autonomous driving technology, i.e., autonomous vehicle (AV). The vehicle communication system, also called vehicle-to-everything (V2X) system, uses dedicated short-range radio communications or cellular network to transfer driving-related information between a vehicle and any entities that may affect the operation of this vehicle (Papadimitratos et al., 2009). Depending on the object of communication, the V2X system can be further

classified as vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) communication, vehicle-to-pedestrian (V2P) communication, etc. (ETSI, 2009). The vehicular communication technology facilitates the real-time negotiation between vehicles, traffic management entities, and other road users, enabling a number of advanced applications for improved roadway safety and efficiency, for example, collision warning, driving navigation, cooperative lane changing and platooning, cooperative operation at intersections and merging locations (Papadimitratos et al., 2009, NHTSA, 2014). Communicative vehicles equipped with V2X systems have been ready with many leading automobile manufacturers, such as Volvo, Toyota, and General Motors.

The autonomous driving technology refers to the vehicle driving automation systems that perform part or all of the dynamic driving tasks, such as the throttle, brake, and steering control, on a sustained basis (SAE, 2016). As the autonomous driving systems, compared to the human drivers, are less prone to delays and errors in the processes of recognition, decision-making, and performance, the AV technology is expected to bring substantial improvements in traffic safety and efficiency. Depending on the role distribution between the human drivers and the driving automation systems, several key traffic authorities, such as the Society of Automotive Engineers (SAE), the US National Highway Traffic Safety Administration (NHTSA), the German Association of the Automotive Industry (VDA), and the German Federal Highway Research Institute (BAST), have defined the degree of automation. The SAE (2016) system define six automation levels between “no automation” to “full automation” (Table 2.1). The definitions from the other authorities are very similar to the SAE classification, with only minor differences in the nomenclature and the range of automation. Although the high-level driving automation has not been ready for large scale application on the public roads, various advanced driver assistance systems (ADAS) have been introduced into the market, such as adaptive cruise control, lane change assistance, and automatic parking.

Table 2.1 SAE (2016) classification of driving automation level

| Level | Name | Narrative Definition |
|-------|--------------------------------|---|
| 0 | No Driving Automation | The driver performs the entire dynamic driving tasks, even with enhanced driver assistance systems. |
| 1 | Driver Assistance | The driving automation system executes either the lateral or the longitudinal vehicle motion control subtasks (but not both simultaneously) with the expectation that the driver performs the remainder of the dynamic driving tasks. |
| 2 | Partial Driving Automation | The driving automation system executes both the lateral and longitudinal vehicle motion control subtasks with the expectation that the driver completes the subtasks of object detection, event response, and supervision of the driving automation system. |
| 3 | Conditional Driving Automation | The driving automation system executes the entire dynamic driving task with the expectation that the driver is receptive and will respond appropriately to the requests to intervene and the performance-relevant system failures. |
| 4 | High Driving Automation | The driving automation system executes the entire dynamic driving tasks and fallback without any expectation that the driver will respond to a request to intervene. |
| 5 | Full Driving Automation | The sustained and unconditional (i.e., not driving mode-specific) performance by an ADS of the entire dynamic driving task and fallback without any expectation that a user will respond to a request to intervene. |

Note that the CV and AV capabilities do not necessarily coexist in a vehicle. For example, a connected (but not autonomous) vehicle can still acquire communication-based information and pass the information to the human driver through an on-board driver advisory system to assist in decision-making and driving. On the other hand, an autonomous (but not connected) vehicle can perform dynamic driving tasks based on the information provided by the on-board sensors. Nevertheless, the combination of vehicle communication and driving automation can make a full use of the benefits of each other and lead to an enhanced vehicle operational performance.

2.3 CAV ramp merging strategies

In this section, the ramp merging strategies leveraging CAVs are reviewed in accordance with Zhu et al. (2022a), with a focus on the latest trends and developments in the research field. Based on the application contexts, the reviewed works are divided into three categories: basic strategies for single lane freeway with a full CAV penetration, strategies for mixed CAV-HDV traffic conditions, and strategies for multi-lane freeways. Note that, not all the reviewed strategies assume the same level of CAV capabilities. For example, some strategies require CV with on-board driver advisory systems, and some apply to AV with high-resolution sensors. However, these strategies are essentially the same as the strategies requiring full CAV capabilities. For example, the strategies requiring only CVs are usually achieved by assuming that the human drivers will strictly follow the recommendations from the advisory system (i.e., by assuming that the human drivers will perform the same level of motion control as AVs), so such strategies can be directly transferred to CAV operation for even better performance. In

this sense, the required vehicle capabilities are not clearly distinguished in this review, while the information is available in Table 2.2.

2.3.1 Strategies for basic contexts

In this category, we consider the application context of single lane freeways with a full CAV penetration rate. Strategies in this category focus on the formulation of the CAV ramp merging problem based on the advanced communication and autonomous driving capabilities enabled by CAVs, while ignoring the free lane-changes on the main road and the presence of HDVs. Depending on the level of control, the existing strategies are divided into two groups: operational control and tactical control. The operational control determines the lower-level actions of vehicles, such as the step-by-step acceleration and deceleration, and the tactical control addresses the upper-level decisions, such as the choice of merging sequence and merging gap.

At the lower level, A number of studies are committed to improving CAV merging trajectories under an optimization framework. The established models target at different objectives favoring traffic efficiency, merging safety, energy use, and/or passenger comfort, while being subject to vehicle dynamics, safety requirements, and technical constraints. For example, Cao et al. (2015) describe the states and actions of a ramp merging vehicle and its mainline competitor in a two-dimensional coordinate system and design their optimal paths and optimal merging point by minimizing a penalty combined of acceleration, speed deviation, and inter-vehicle distance. Zhou et al. (2019a) solve the merging trajectories of a competing pair of ramp and mainline vehicles as two optimal trajectory planning problems that relate to each other. The optimization models target at a minimal acceleration cost with explicit bounds on vehicle dynamics and safety distance. Later, the scope of control is extended from a single pair of vehicles to a series of vehicles in the communication range. By assuming the existence of a pre-determined merging sequence, the trajectories of relevant vehicles can be joint planned. For example, Ntousakis et al. (2016), Rios-Torres et al. (2017), and Sonbolestan et al. (2021) minimize the overall acceleration and/or jerk efforts in favor of energy use and passenger comfort. The models can be readily solved with Hamiltonian analysis. Similarly focusing on the energy efficiency, Xu et al. (2021) shed light on Hybrid Electric Vehicles (HEVs) and establish an optimization model with minimized travel time and energy cost to decide the speed trajectory and torque distribution of an automated HEV. In the centralized control branch, Letter et al. (2017) and Xie et al. (2017) apply optimization methods to increase the mean/total speed of all vehicles in the merging area, while constraining each vehicle's trajectories on the motions of the surrounding vehicles for safety considerations. Further, there exist various non-optimization approaches for the lower-level decisions at CAV ramp merging. In Ward et al. (2017), a set of candidate trajectories is generated for a ramp merging vehicle, from which the optimal trajectory is chosen based on a cost function incorporating merging progress, comfort, and risk. Several studies adopt the concept of "virtual vehicle/ virtual platooning", namely mapping the mainline and ramp vehicles to each other's lane to transfer the merging problem into a virtual car-following problem (Milanés et al., 2010, Wang et al., 2013, Chen et al., 2021b, Hu et al., 2021, Liao et al., 2021). Fukuyama (2020)

employs a two-level dynamic game approach to interpret the interactions between a competing pair of mainline and ramp vehicles. Under this approach, each vehicle makes trajectory decisions to maximize its own driving utility, while considering the potential actions/responses of the competing vehicle.

At the upper level, the optimal choice of a merging sequence is discussed in recent literature. Xu et al. (2019b) employ a generic algorithm to solve the choice of a merging sequence. The algorithm encodes the merging sequences in a binary representation and evaluates candidate sequences through a fitness function combining the travel time of mainline vehicles and the number of ramp vehicles allowed to merge. Xu et al. (2019a) first group vehicles with small inter-vehicle distance and then determine the optimal merging sequence of groups by minimizing the total passing time and delay. Analysis shows that this method is able to find near-optimal solutions with less computation time. Pei et al. (2019) also focus on the tradeoff between computational efficiency and solution optimality. By stipulating that vehicles on the same road follow a first-in-first-out order, the strategy assigns the right of way between the two links (mainline/ramp) instead of among individual vehicles to reduce the complexity of the sequencing problem. Further, several recent studies integrate the upper-level choice of a merging sequence with the lower-level decisions on vehicle trajectories. For example, Ding et al. (2020) adjust the merging order of vehicles to reduce the switch of right of way between the main road and the on-ramp and then plan the motion of each vehicle accordingly. Jing et al. (2019) develop an optimization model for integrated merging sequence and trajectory decisions. The model objective consists of a strategy cost related to the choice of merging sequence and an action cost determined by vehicle accelerations and jerks. Alternatively, Chen et al. (2020) determine the optimal merging gap for each ramp vehicle using a second-order dynamics model that evaluates the trajectory costs to lead the ramp vehicle into different gaps. Similarly, Nishi et al. (2019) make for each ramp vehicle a joint decision on the merging gap and the trajectory to it by choosing from a set of candidate policies the one with the lowest cost based on the state value function learned from field data. The above upper-level strategies mainly focus on the local solutions focusing on the control of individual vehicles. Through an aggregated control of the two streams of traffic, improvements in the overall traffic flow performance can be achieved at on-ramp merging. An example of such an aggregated system is introduced in Scarinci et al. (2015) and Scarinci et al. (2017), where the mainline traffic is periodically compacted to create large gaps, and the ramp vehicles are released into the gaps through ramp metering signals. The validation indicates that the proposed strategy is capable of reducing the occurrence of congestions and the number of late-merging vehicles.

2.3.2 Strategies for mixed CAV-HDV traffic conditions

In this category, ramp merging strategies considering the mixed traffic flow composed of CAVs and HDVs are reviewed. The major challenge for the strategies in this category lies in the uncontrollability of HDVs which introduces various uncertainties into the traffic operation. Therefore, this review section places a focus on how the uncertainties induced by HDVs are handled in the reviewed works.

A typical problem in the mixed traffic context is to guide a CAV from the on-ramp to merge into the mainline traffic with HDVs, where the actions of HDVs should be predicted and explicitly considered in the motion plan of the CAV. To resolve this issue, Kherroubi et al. (2021) train an Artificial Neural Network (ANN)-based probabilistic classifier to predict the passing intentions of human drivers. The prediction further serves as an input of a reinforcement learning agent to determine the longitudinal acceleration of a ramp CAV. Okuda et al. (2021) develops a logistic regression model to estimate the decisions of mainline human drivers (expressed as the probability to accept a vehicle to merge in front of it), based on which a merging strategy is proposed to maximize the acceptance probability of mainline drivers by proactively adjusting the speed of the merging CAV. In these studies, only the ramp merging CAVs are controlled, and the mainline traffic serves as uncontrollable environmental inputs in the problem formulation. Other research efforts are devoted to solving the simultaneous control of the mainline and ramp vehicles. Based on their previous work (Zhou et al., 2019a), Zhou et al. (2019b) further introduce a lower bound on the cooperative speed of the mainline facilitating vehicle to restrain the speed-drops on the mainline upstream traffic. The extended strategy is tested under mixed flow conditions, and the results show the strategy's ability to reduce conflicts at ramp merging. Karimi et al. (2020) divide the merging situations into six categories depending on the combinations of CAVs and HDVs in a merging triplet (i.e., a merging vehicle and its putative leader and follower in the target lane) and develop for each category a cooperative strategy that checks the desired speed and inter-vehicle distance at a series of set-points. The above strategies for mixed traffic flow only consider the interaction between a single ramp vehicle and its direct neighbors on the main road but neglect the influence on the surrounding traffic.

To take into consideration the operation of surrounding traffic, a number of studies plan the motions of multiple vehicles in the merging area under an optimization framework. In Mu et al. (2021), a virtual platoon-based trajectory planning method is extended to the mixed traffic conditions in two steps: (1) dividing the mixed string of vehicles into blocks containing a leading CAV and several following HDVs and (2) planning the trajectories of each block as a whole. In Omidvar et al. (2020), the strategy in Letter et al. (2017) is extended for the mixed traffic flow. The extended model accounts for deviations between the predicted and actual behaviors of HDVs through a real-time correction mechanism, yet tends to oversimplify the driving pattern of HDVs. Sun et al. (2020) assume different driving rules for CAVs and HDVs in an optimization problem that integrates the choice of merging gap and the design of vehicle trajectories. Ding et al. (2019) apply their previous strategy (Ding et al., 2020) to the mixed CAV-HDV condition and discuss the impacts of CAV penetration on throughput, traffic efficiency, fuel use, and emission. Similarly, Rios-Torres et al. (2018) apply the motion planner in Rios-Torres et al. (2017) to an environment where CAV and HDV coexist to investigate how the increasing percentage of CAVs influences the energy use at on-ramp merging.

At the traffic flow level, Chen et al. (2021a) design the mechanisms of periodic gap creation and batch merging under a mixed condition to close the extra time gaps induced by the lane-changing maneuvers of on-ramp vehicles. It is demonstrated in theory that the strategy can

reduce unutilized roadway capacity and increase merging throughput, but no numerical/simulation experiment is carried out.

2.3.3 Strategies for multi-lane freeways

In this category, ramp merging strategies designed for the multi-lane freeway configuration are reviewed. With the presence of multiple lanes on the main road, the free lane-changing maneuvers between mainstream lanes may influence the merging opportunities of ramp vehicles and should be therefore taken into consideration. This review section focuses on how the free lane-changing decisions of mainline vehicles are incorporated in the merging strategies.

A prior effort to address the multi-lane merging problem is presented in Marinescu et al. (2012), where the space on a multi-lane freeway is divided into moving slots, and an algorithm is developed to map the slots to vehicles. It is stipulated that the mainline vehicles tend to move into the free slots in their front left to facilitate the usage of inner lane spaces, releasing more slots in the outermost lane for the merging of on-ramp vehicles. Following similar ideas, subsequent studies propose various solutions to release the space in the outermost lane through proactive controls of CAVs. For example, Karbalaieali et al. (2020) add the lane-change decision on a two-lane freeway to the alternative actions of mainline CAVs and choose from various combinations of alternatives the one that minimizes the total travel time of a ramp vehicle and its direct mainline competitors. Hang et al. (2021) interpret the merging process as a coalitional game involving a ramp vehicle and the mainline vehicles directly influenced by it. In the game, each vehicle decides if they would behave cooperatively (i.e., join a coalition) or independently (i.e., leave a coalition) based on their individualized orientations towards efficiency, safety, and comfort, and the lane-changing decisions and longitudinal trajectories of vehicles in each coalition are optimized for the maximal benefits of the coalition. Hu et al. (2019) extend the trajectory optimization strategy in Letter et al. (2017) for a multi-lane layout. The extended strategy sets a cooperative lane-changing zone upstream of the trajectory control zone, in which a part of mainline vehicles in the outer lane are allocated to the inner lane in order to balance the after-merging flows between mainline lanes. Liu et al. (2021) integrate a lane selection model with the trajectory planning problem to account for the unevenness between lanes. The lane selection model employs a reinforcement learning approach to output the lane choice decision of each individual vehicle base on the real time traffic flow conditions.

Moreover, recent studies shed light on the more complicated situations where CAVs and HDVs coexist in a multi-lane merging area. Gao et al. (2021) test an optimization-based trajectory planning strategy in a two-lane freeway merging area under various CAV penetration rates. Williams et al. (2021) consider the challenging situation where vehicles may freely change lanes on a multi-lane freeway and uncontrolled HDVs exist. The problem is addressed by updating the merging sequence and accounting for deviations in the measured vehicle positions in real time. Guo et al. (2020a) develop a reinforcement learning approach that takes the speed of a vehicle and its distances to the surrounding vehicles as inputs and outputs the decisions of lane-change and speed adjustment. The approach can be applied to multi-lane freeways with the presence of HDVs. A few recent studies take into account the macroscopic

traffic flow performance and propose strategies that integrate multiple control measures at on-ramp merging. For example, Tajdari et al. (2020) combine the CAV-enabled lane-changing control with the conventional ramp metering strategy, where the combined strategy decides the lane-changing flows between mainstream lanes and the ramp inflow rate to maximize the merging throughput. Pan et al. (2021) integrate ramp metering, variable speed control, and lane change control for CAVs and the corresponding recommendations to HDVs in a merging control system. The strategy explicitly considers the stability of traffic flow and the compliance rate of human drivers.

2.4 Research gaps

Based on the review of existing literature in the field of CAV ramp merging, a few research gaps are identified:

- As shown in Table 2.2, the existing strategies mainly focus on the local control of individual vehicles, whereas the traffic flow performance, such as whether the traffic remains stable and balanced with the disturbances induced by the cooperation, and whether the needs of the mainline and ramp traffics are addressed in a fair and timely manner, are either ignored or only discussed to a limited extent.
- The majority of existing strategies only applies to the basic context where all vehicles are controllable CAVs and there is only one lane on the freeway, whereas the more realistic contexts, such as mixed CAV-HDV traffic and multi-lane freeways, are discussed to a limited extent.
- The existing strategies for mixed traffic usually make simple assumptions on the driving patterns of HDVs, for example, assuming that the HDVs strictly follow certain pre-defined driving rules without errors, delays, or variances in the human driver population. These assumptions tend to underestimate the uncertainties induced by HDVs and overestimate the cooperation willingness of human drivers. Further, most existing strategies for mixed traffic conditions only regard HDVs as an uncontrolled external factor that restricts the decisions of CAVs, but the possibilities to influence the behaviors of HDVs and include them in the coordination framework for enhanced benefits are not explored.
- As the multi-lane control problem is relatively complicated, many existing strategies propose solutions in a discrete decision space (e.g., increase/decrease one step in speed, change lane or not). Moreover, the existing multi-lane solutions usually focus on the local benefits without explicitly considering consequences at the continuous traffic-flow level.
- The safety aspects of CAV ramp merging are not sufficiently discussed in the literature. Most existing studies only consider safety as a constraint in the decision model without investigating the direct safety impacts of CAVs at ramp merging. Furthermore, the reviewed studies usually assume the presence of well-designed cooperation strategy for collision avoidance, so the reported safety benefits are more related to enhanced cooperation between CAVs rather than the elimination of errors, delays and aggressive

driving factors related to the human drivers. Thus, there is a need to explore the CAV's role in eliminating critical human factors through autonomous vehicle control, namely how CAVs influence merging safety in the absence of the specially designed cooperation/coordination strategies.

This dissertation aims to expend and improve the on-going discussion on CAV on-ramp merging operation by partially filling the above-identified research gaps.

Table 2.2 Ramp merging strategies leveraging CAVs

| Strategy | Vehicle capability | Penetration | Freeway layout | Control Decision | | Primary method |
|----------------------------|--------------------|-------------|----------------|-----------------------|--------------------|--------------------|
| | | | | Upper level | Lower level | |
| Milanés et al. (2010) | CV | full | multi-lane | - | trajectory | fuzzy control |
| Wang et al. (2013) | CAV | full | one-lane | - | trajectory | virtual vehicle |
| Cao et al. (2015) | CV | full | one-lane | - | trajectory | optimization |
| Ntousakis et al. (2016) | CAV | full | one-lane | - | trajectory | optimization |
| Letter et al. (2017) | CAV | full | one-lane | - | trajectory | optimization |
| Rios-Torres et al. (2017) | CAV | full | one-lane | - | trajectory | optimization |
| Scarinci et al. (2017) | CAV | full | one-lane | periodic gap-creation | - | traffic flow model |
| Ward et al. (2017) | AV | full | one-lane | - | trajectory | optimization |
| Xie et al. (2017) | CAV | full | one-lane | - | trajectory | optimization |
| Zhou et al. (2017) | AV | mix | one-lane | - | trajectory | car-following rule |
| Rios-Torres et al. (2018) | CAV | full | one-lane | - | trajectory | optimization |
| Ding et al. (2019) | CAV | mix | one-lane | merging sequence | trajectory | optimization |
| Hu et al. (2019) | CAV | full | multi-lane | - | trajectory | optimization |
| Ito et al. (2019) | CAV | mix | one-lane | - | trajectory | optimization |
| Jing et al. (2019) | CAV | full | one-lane | merging sequence | trajectory | optimization |
| Nishi et al. (2019) | AV | full | one-lane | merging gap choice | trajectory | machine learning |
| Pei et al. (2019) | CAV | full | one-lane | merging sequence | - | optimization |
| Xu et al. (2019a) | CAV | full | one-lane | merging sequence | - | optimization |
| Xu et al. (2019b) | CAV | full | one-lane | merging sequence | trajectory | generic algorithm |
| Zhou et al. (2019a) | CAV | full | one-lane | - | trajectory | optimization |
| Zhou et al. (2019b) | CAV | full | one-lane | - | trajectory | optimization |
| Chen et al. (2020) | CAV | full | one-lane | merging gap choice | trajectory | optimization |
| Ding et al. (2020) | CAV | full | one-lane | merging sequence | trajectory | optimization |
| Fukuyama (2020) | CAV | full | one-lane | - | trajectory | game theory |
| Guo et al. (2020a) | CAV | mix | multi-lane | - | lane change, speed | machine learning |
| Karbalaieali et al. (2020) | CAV | full | multi-lane | - | lane change, speed | optimization |
| Karimi et al. (2020) | CAV | mix | one-lane | - | trajectory | optimization |
| Omidvar et al. (2020) | CAV | mix | one-lane | - | trajectory | optimization |

| | | | | | | |
|---------------------------|-----|------|------------|------------------------------------|-------------------------|--------------------|
| Sun et al. (2020) | CAV | mix | one-lane | merging gap choice | trajectory | optimization |
| Tajdari et al. (2020) | CV | mix | multi-lane | lane change flow, ramp inflow | - | feedback control |
| Chen et al. (2021a) | CAV | mix | one-lane | periodic gap-creation, batch merge | - | traffic flow model |
| Chen et al. (2021b) | CAV | full | one-lane | - | trajectory | feedback control |
| Gao et al. (2021) | CAV | mix | multi-lane | - | trajectory | optimization |
| Hang et al. (2021) | CAV | full | multi-lane | - | lane change, trajectory | game theory |
| Hu et al. (2021) | CAV | full | one-lane | - | trajectory | feedback control |
| Kherroubi et al. (2021) | CAV | mix | one-lane | - | trajectory | machine learning |
| Liao et al. (2021) | CV | full | one-lane | - | trajectory | feedback control |
| Liu et al. (2021) | CAV | full | multi-lane | - | lane change, trajectory | machine learning |
| Mu et al. (2021) | CAV | mix | one-lane | - | trajectory | optimization |
| Okuda et al. (2021) | AV | mix | one-lane | - | trajectory | optimization |
| Pan et al. (2021) | CAV | mix | multi-lane | ramp inflow | lane change, speed | optimization |
| Sonbolestan et al. (2021) | CAV | full | one-lane | - | trajectory | optimization |
| Williams et al. (2021) | CAV | mix | multi-lane | - | trajectory | car-following rule |
| Xu et al. (2021) | CAV | full | one-lane | - | trajectory | optimization |

Chapter 3

Merging coordination in basic contexts

This chapter is based on the work contained in the following paper in Appendix B:

- **Paper II.** Zhu, J., Tasic, I., & Qu, X. (2021). Improving freeway merging efficiency via flow-Level coordination of connected and autonomous vehicles. Retrieved from <https://doi.org/10.48550/arXiv.2108.01875>. Submitted to IEEE Transactions on Intelligent Transportation Systems.

In this chapter, a novel flow-level ramp merging coordination strategy leveraging the communication and autonomous driving capabilities of CAVs and its application in the basic context of single lane freeway with a full CAV penetration rate are introduced. This strategy, combining the ideas of gap creation on the main road and platoon merging on the ramp, coordinates the two streams of traffic, instead of individual vehicles, at on-ramp merging for the flow-level gains in merging efficiency and traffic flow stability. Section 3.1 introduces the developed merging coordination strategy, and Section 3.2 evaluates the efficiency of the strategy through an illustrative case study.

3.1 Coordinative merging control (CoMC) strategy

3.1.1 Problem description

The CAV merging coordination strategy, called Coordinative Merging Control (CoMC), consists of three components: (1) mainline control: mainline vehicles decelerate in advance to create large gaps on the main road; (2) ramp control: merging vehicles form platoons on the on-ramp; and (3) centralized coordination: the gaps created on the main road and the platoons formed on the ramp are coordinated by a control center in terms of size, speed, and arrival time. As shown in Figure 3.1, the coordination is carried out in the following steps:

Step 1: Upon arrival, the ramp vehicles stop at a pre-specified position on the ramp and register themselves with the control center.

Step 2: The control center counts the number of ramp vehicles arriving. When a certain number of ramp vehicles has accumulated, the control center initiates coordinative merging by appointing a mainline vehicle as the facilitating vehicle and sending instructions on where and how much this vehicle should cooperatively decelerate.

Step 3: The facilitating vehicle accepts the cooperation request and sends back a confirmation to the control center. Then, it executes the required deceleration and develop a gap from its original leader.

Step 4: Upon receiving the confirmation from the facilitating vehicle, the control center releases the vehicles waiting on the ramp as a platoon by specifying their moving trajectories.

Step 5: The ramp vehicles follow the instructions from the control center when driving towards the merging point.

Step 6: Under the centralized coordination instructions, the ramp merging platoon is able to merge into the created mainline gap at the merging point.

In order to achieve smooth and efficient merging, the mainline cooperation and the ramp platoon formation should be coordinated in terms of three requirements: (1) the created mainline gap should be large enough for the platoon to merge into (the requirement of size); (2) the platoon should reach the same speed as the mainline facilitating vehicle when arriving at the merging point (the requirement of speed); (3) the gap should be just available at the merging point when the platoon arrives there (the requirement of arrival time).

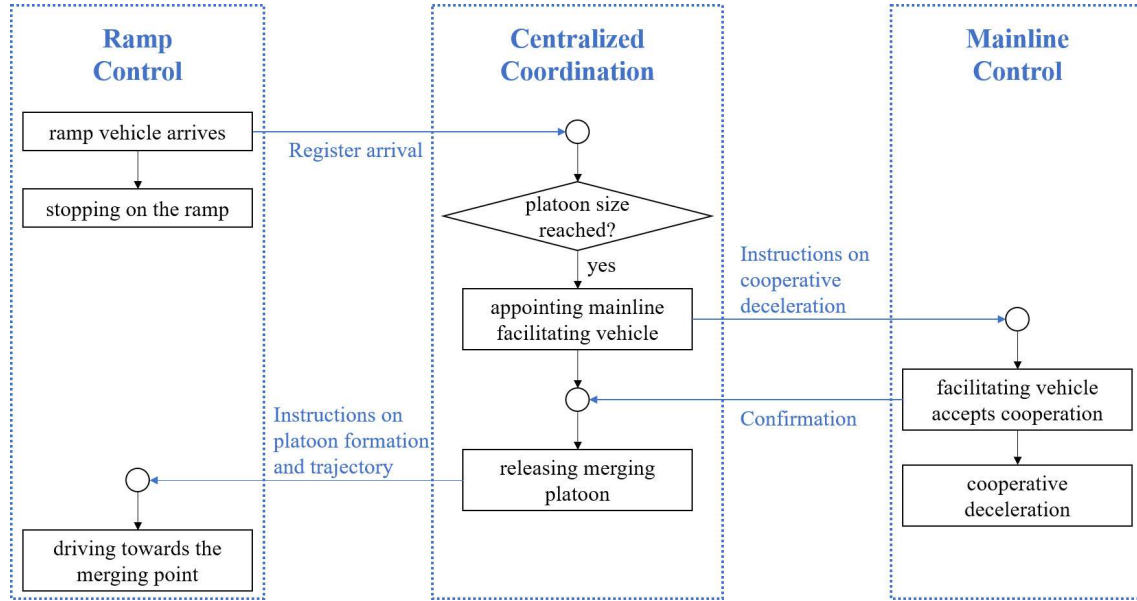


Figure 3.1 Coordinative Merging Control (CoMC) strategy

The essence of CoMC is to collect space on the main road by compacting mainline vehicles and to make full use of the collected space by grouping merging vehicles into proper platoons. This is supported by the macroscopic traffic flow theories. Assume that the mainline traffic is in an original state (state O) before the coordination takes place. When the facilitating vehicle decelerates, the vehicles following it also decelerate and accept shorter car-following distances corresponding to the reduced speed. This changes the state of the mainline traffic behind the facilitating vehicle to a denser cooperative state (state C). The transition in state compacts the mainline vehicles and increases the traffic flow rate according to the fundamental diagram, providing spaces for the merging of on-ramp vehicles. However, the transition from state O to state C also causes a shockwave spreading on the main road at a speed defined by the difference between the original and cooperative states. If the mainline cooperation is too frequent, new shockwaves will be generated before the existing ones dissipate, leading to long-lasting mainline disturbances and potentially traffic breakdowns on the main road. Therefore, the key to CoMC is to balance the efficiency of the mainline and ramp traffic and to ensure that the merging of ramp vehicles is facilitated without breaking the mainline stability. To this end, the CoMC strategy is dedicated to finding the optimal control scheme that optimizes the overall mainline and ramp efficiency by making a joint decision on the following aspects:

- Size of the ramp merging platoon (n)
- Movements of the ramp merging platoon (a)
- Position at which the facilitating vehicle decelerates (d)
- Cooperative merging speed (v_C)

3.1.2 Analytical formulation

Figure 3.2 illustrates the coordinative merging process with the following elements. The Merging Point (MP) is the position at which the main road and the ramp connect. The Waiting Position (WP) is where the ramp vehicles stop to form the merging platoon. The Speed-Changing position (SC) is where the mainline facilitating vehicle decelerate. The cooperative deceleration may affect several vehicles behind the facilitating vehicle on the main road. These vehicles are denoted as cooperative vehicles. The End of Merging (EM) is the position at which the merge influence area ends. The entire course of one gap creation and one platoon formation is defined as a coordinative merging cycle. CoMC functions through the recurrent implementation of merging cycles. In this introductory chapter, the basic framework of the formulated model is introduced, while detailed derivations are available in Zhu et al. (2021b) (Paper II in Appendix B).

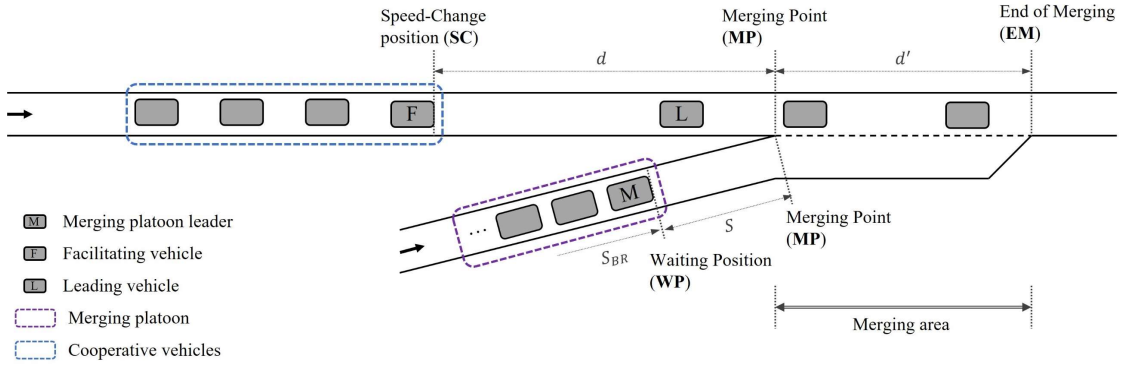


Figure 3.2 CoMC in basic context

In order to generate the optimal control scheme with respect to real-time traffic conditions, the coordination is formulated under an optimization framework using the macroscopic traffic state parameters as inputs. To facilitate the overall merging efficiency, the objective of the optimization problem is to minimize the total delay to all vehicles passing through the merging area (D), as in Eq. (3.1).

$$\min D = \left(w_m \cdot \sum_{i=1}^m D_{main}^i + w_r \cdot \sum_{j=1}^n D_{ramp}^j \right) \times r \quad (3.1)$$

where w_m and w_r are the weights of the mainline and ramp traffic, respectively, m is the number of cooperative vehicles in a merging cycle, n is number of ramp vehicles in a merging platoon, D_{main}^i is the delay to the i^{th} mainline cooperative vehicle, D_{ramp}^j is the delay to the j^{th} ramp vehicle in the platoon, and r is the frequency of merging cycles in number of times per hour.

The delay to a mainline cooperative vehicle (D_{main}^i) is defined as the difference between the theoretical minimal travel time and the actual travel time for a mainline vehicle to pass through the merging area. The theoretical travel time is defined by the length and design speed of the road. The actual travel time (t_{main}^i) is calculated based on the vehicle's interaction with the shockwave, as in Eq. (3.2):

$$t_{main}^i = \frac{d + d'}{v_c} + \left(1 - \frac{v_o}{v_c}\right) \times \frac{(i-1)\omega h_o}{v_o - \omega} \quad (3.2)$$

where d is the distance between SC and MP, and d' is the distance between MP and EM (see Figure 3.2), v_o and v_c are the traffic flow speed in the original and cooperative states, respectively, h_o is the inter-vehicle headway in the original state related to the original traffic flow rate, ω is the shockwave speed determined by the difference between the original and cooperative states.

The number of mainline cooperative vehicles (m) can be calculated as in Eq.(3.3) based on the shockwave dissipation time:

$$m = \left\lceil \frac{d + d'}{h_o} \times \left(\frac{1}{\omega} - \frac{1}{v_o}\right) \right\rceil \quad (3.3)$$

where $\lceil \cdot \rceil$ represents the nearest upper integer.

Similarly, the delay to a ramp merging vehicle (D_{ramp}^j) is defined as the difference between the theoretical travel time, given by the road length and design speed, and the actual travel time for a ramp vehicle to pass through the merging area. Depending on the moving pattern of a ramp vehicle, the actual travel time (t_{ramp}^j) consists of four parts: the time the vehicle spends braking when arriving at WP, the time the vehicle waits at WPs, the time the vehicle spends accelerating from WP to MP, and the time the vehicle spends cruising from MP to EM, namely

$$t_{ramp}^j = \frac{v_r}{b} + \frac{n-j}{\lambda} + \frac{d}{v_c} - nh_c + \frac{d'}{v_c} \quad (3.4)$$

where v_r is the initial speed of the ramp vehicle, b is the braking rate, λ is the arrival rate of ramp vehicles related to the ramp flow rate, h_c is the inter-vehicle headway in cooperative state which can be estimated as a function of v_c based on the car-following rule.

The frequency of coordinative merging cycles (r) is related to the arrival rate of ramp vehicles (λ) and the merging platoon size (n):

$$r = \frac{3600\lambda}{n} \quad (3.5)$$

To satisfy the requirements of safety, traffic stability, and vehicle dynamics, the optimization model is subject to the following constraints:

$$h_o + \frac{d}{v_c} - \frac{d}{v_o} \geq (n+1) \cdot h_c \quad (3.6)$$

$$\frac{n}{\lambda} \geq \frac{d + d'}{\omega} \quad (3.7)$$

$$v_{crit} < v_C < v_O \quad (3.8)$$

$$a \leq a_{ramp} \quad (3.9)$$

$$0 < n \leq n_{max}, n \in \mathbb{N}^+ \quad (3.10)$$

$$0 < d \leq d_{max} \quad (3.11)$$

where v_{crit} is the critical traffic speed given by the fundamental relationship of mainline traffic flow, and a_{ramp} is the maximum allowable ramp acceleration. Here, Eq.(3.6) ensures that the created mainline gap is no smaller than the space required by the merging platoon. Eq.(3.7) stipulates that a new merging cycle can be initiated only when the shockwave caused by the last cooperation has dissipated. Eq.(3.8) requires that the cooperative speed should not fall below the critical speed of the mainline traffic. Eq.(3.7) and Eq.(3.8) restrict the negative impacts of the cooperation on the mainline traffic. Eq.(3.9) limits the acceleration range on the ramp lane. Eq.(3.10) and Eq.(3.11) set limits of the platoon size and the SC position.

So far, the coordination is formulated as a constrained optimization problem with three decision variables: the merging platoon size n , the SC position of the facilitating vehicle d , and the cooperative merging speed v_C . It is usually difficult to solve such a non-linear non-convex problem. In Zhu et al. (2021b) (Paper II in Appendix B), a method is presented to analytically obtain a closely approximated solution by relaxing the integer constraint on m and transforming the objective function. In practice, a heuristic solution to a certain degree of accuracy should also be robust enough.

3.2 Case study

An illustrative case study is conducted to verify the efficiency of CoMC under various traffic volume conditions. The case study employs a microscopic simulation platform composed of the traffic simulation tool VISSIM version 11.0 and scripts compiled in Python version 3.6 and C++ version 2017. VISSIM provides the basic simulation environment, including the road network, traffic flow generation, vehicle dynamics, and raw data record. The centralized control of CoMC is compiled in Python and integrated into VISSIM through the COM interface. The cooperative behaviors of the mainline facilitating vehicle and the merging platoon leader are controlled by external driving models coded in C++ and called by the DLL interface of VISSIM when the coordination turns active.

The simulated freeway extends 2000 meters upstream and 500 meters downstream from the merging area. A 700-meter-long one-lane on-ramp connects to the freeway via a 240-meter-long acceleration lane. As the main purpose of CoMC is to promote merging under high traffic volume conditions, six scenarios at relatively high traffic volume level are considered, combining two levels of mainline flow and three levels of ramp flow, as shown in Table 3.1. The corresponding control decisions in Table 3.1 are the optimal solutions with respect to the traffic volumes and the input parameters in Table 3.2. For each demand scenario, a CoMC-controlled case is developed and compared to a baseline case where no coordination is applied. For each case, 10 simulation runs with different random seeds are carried out, and the aggregated results are reported.

Table 3.1 Study scenarios and coordination decisions (basic context)

| | 1A | 1B | 1C | 2A | 2B | 2C | |
|------------|-------|-------|-------|-------|-------|-------|-------|
| q_{main} | 1600 | 1600 | 1600 | 1800 | 1800 | 1800 | veh/h |
| q_{ramp} | 300 | 400 | 500 | 300 | 400 | 500 | veh/h |
| v_c | 96.67 | 89.80 | 83.53 | 99.61 | 88.16 | 82.25 | km/h |
| d | 624 | 794 | 1062 | 911 | 847 | 1266 | m |
| n | 4 | 7 | 12 | 5 | 8 | 15 | veh |

Table 3.2 Input parameter

| Parameter | Value | Unit |
|------------|-------|------------------|
| w_m | 1 | - |
| w_r | 1 | - |
| v_o | 120 | km/h |
| v_r | 60 | km/h |
| d' | 457.2 | m |
| v_{crit} | 75 | km/h |
| b | 2.75 | m/s ² |
| a_{ramp} | 2.75 | m/s ² |

Figure 3.3 plots five-minutes vehicles trajectories in the most critical 2C (1800, 500) scenario. As it shows, the coordination phenomena, such as the compaction of mainline traffic and the formation of merging platoons are observed in the simulation experiments as expected (see Figure 3.3b). In the baseline no-control case (Figure 3.3a), the disturbances induced by the merging vehicles accumulate and eventually trigger traffic breakdowns, whereas under CoMC (Figure 3.3b), the periodic coordination can well collect and accommodate the disturbances on the main road, leading to fluent merging operation.

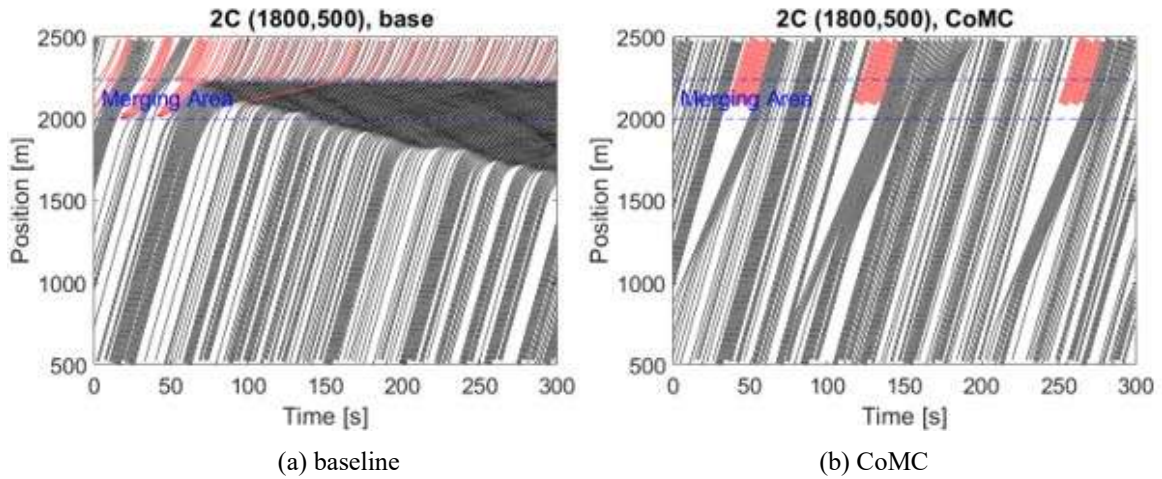


Figure 3.3 Vehicle trajectory (basic context)

Figure 3.4 presents the travel time and delay results, and Figure 3.5 shows the speed contour of the 2C (1800, 500) scenario. According to the results, CoMC may increase the ramp travel time and delay when the traffic condition is not critical (as in 1A and 1B), because the traffic operates well even without control, so it is unnecessary to pause the merging vehicles on the ramp. As the traffic volume increase (e.g., 1C, 2A, 2B, and 2C), CoMC reduces both the mainline and ramp delay to different extents. In 2A and 2B with higher mainline volume, the ramp vehicles can hardly merge in time in the baseline cases. When CoMC is applied, the ramp efficiency is substantially improved through the proactively created on-demand gaps. The most

remarkable efficiency gain is observed in the most critical scenario 2C, resulted from CoMC's ability to stabilize traffic and prevent recurrent congestions. As shown in Figure 3.5a, under high traffic volume, the intensive merging of ramp vehicles may trigger traffic breakdowns in the uncontrolled base cases, and the congestions may persist and even spread upstream along the main road. When CoMC is applied, the periodic coordination ensures both the timely merging of ramp vehicles and the recovery of mainline stability, thereby guaranteeing a fluent operation of traffic even under the high traffic volume conditions. As a result of the prevention of traffic breakdowns and capacity drop phenomena, the case study show that CoMC can increase the overall throughput of the merging area by approximately 6.6% in the critical 2C scenario.

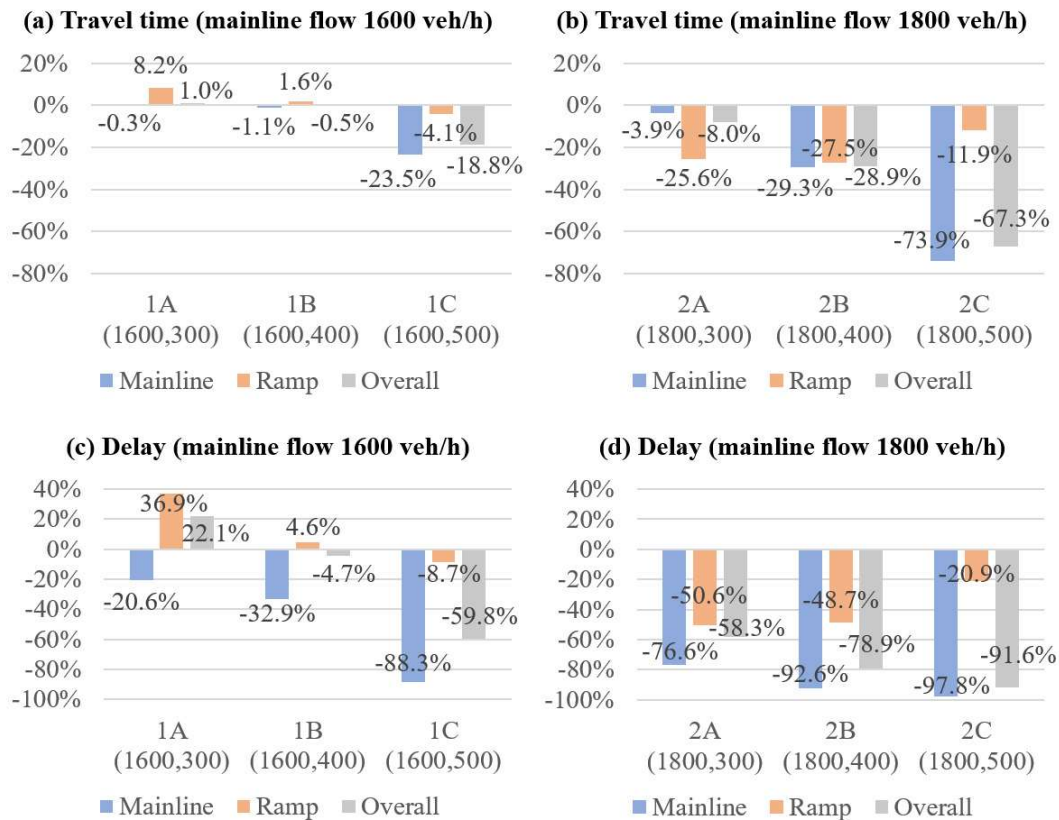


Figure 3.4 Travel time and delay (basic context)

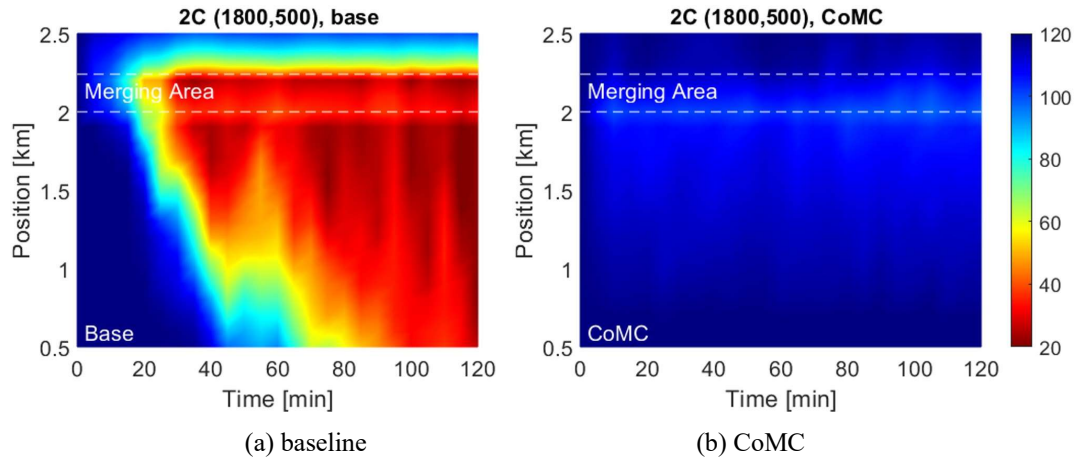


Figure 3.5 Speed contour (basic context)

As the benefits of CoMC are more remarkable with higher traffic volumes, and it may even cause extra delays to certain vehicles in the cases where external coordination is not needed, it is recommended to introduce in practice a threshold in terms of the traffic volumes, at which the CoMC strategy would be activated. The activation threshold should take into account the overall efficiency gains and the fairness between the mainline and ramp traffic, and be determined on a ‘case by case’ basis in the light of the specific conditions of a merging area. More results and discussions about the efficiency of CoMC are available in Zhu et al. (2021b) (Paper II in Appendix B).

Chapter 4

Merging coordination in multi-lane freeways

This chapter is based on the work contained in the following paper in Appendix C:

- **Paper III.** Zhu, J., Tasic, I., & Qu, X. (2022). Flow-level coordination of connected and autonomous vehicles in multilane freeway ramp merging areas. *Multimodal Transportation* 1(1): 100005

In this chapter, the flow-level CAV ramp merging coordination strategy is extended for the application in multi-lane freeway contexts. This extended strategy adopts the ideas of gap creation and platoon merging for flow-level coordination benefits, while considering the free lane-changing flow between mainstream lanes and the reservation of created gaps in the mainline outermost lane. Section 4.1 formulates the extended strategy for multi-lane freeways, and Section 4.2 evaluates the performance of the proposed strategy through a case study.

4.1 Extension of CoMC in multi-lane freeways

In a multi-lane freeway, the ramp merging traffic is coordinated with the mainline traffic in the outermost lane, whereas the traffic in the inner lanes will not directly interact with the ramp merging vehicles. In comparison with the application in a basic single lane context, two issues should be further addressed in the multi-lane contexts:

First, when applying the CoMC strategy in a multi-lane freeway, vehicles in the inner lanes may change into the gaps created in the outermost lane and occupy the space reserved for the ramp merging vehicles, if no additional control is applied. This issue can be addressed by combining CoMC with the one-sided lane-change prohibition rule. The rule allows vehicles in the outermost lane to change into the inner lanes (the facilitating vehicle should not change lanes), whereas prohibiting vehicles in the inner lanes from entering the outermost lane. The prohibition should cover the entire control segment (i.e., from SC to EM as in Figure 4.1) and be effective during the whole coordination period. This measure can prevent the created gaps from being occupied by the inner lane vehicles and at the meantime speed up the dissipation of shockwaves by allowing the outer lane vehicles to change lanes.

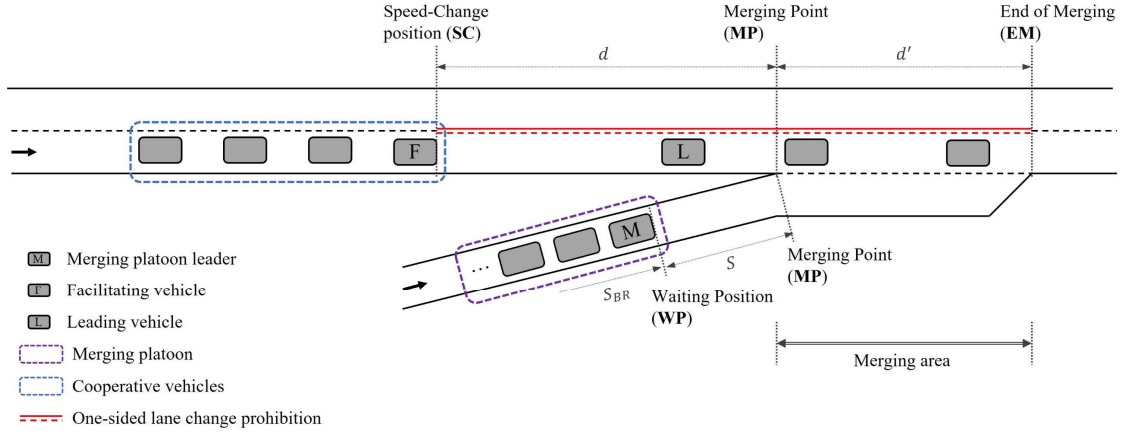


Figure 4.1 CoMC in multi-lane context

Further, under the CoMC control, when the facilitating vehicle decelerates, the vehicles following it in the outermost lane may tend to change into the inner lanes to maintain a higher speed. Therefore, the remaining traffic volume in the outermost lane should be estimated and used as the input flow rate of coordination. As shown in Figure 4.2, it is assumed that the mainline traffic volume in the upstream road segment is evenly distributed between lanes, and the number of vehicles changing into the inner lane depends on the ability of the inner lane to accommodate extra vehicles. The remaining outer-lane volume for coordination is estimated as

$$q_E = q_m - \rho \cdot (C - q_m) \quad (4.1)$$

where q_E is the effective outer-lane flow (i.e., the remaining flow after free lane-changes), q_m is the upstream mainline volume per lane, C is the theoretical capacity of the inner lane which is defined by the fundamental diagram of traffic flow, and $\rho \in [0, 1]$ captures the number of lane-changing vehicles as a fraction of the reserved inner lane capacity (i.e., $C - q_m$).

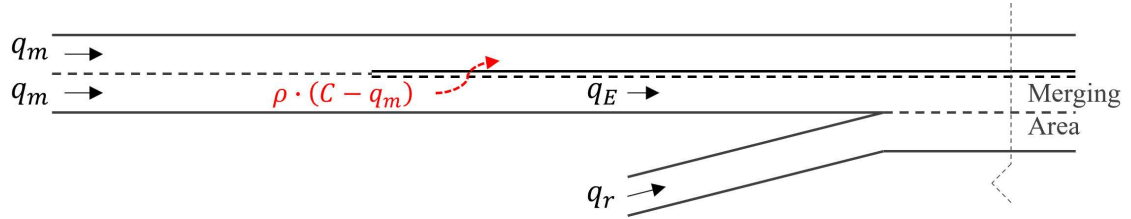


Figure 4.2 Effective outer-lane flow in multi-lane context

The parameter ρ describes the proportion of reserved inner lane capacity that is utilized by the vehicles changing from the outer lane. It determines the effective flow remaining in the outermost lane and thereby plays a crucial role in the control decisions of CoMC. Figure 4.3 shows the maximum on-ramp flow that can be accommodated by multi-lane CoMC with respect to the mainline traffic volume for the parameters in Table 3.2. As it shows, as the value of ρ increases, more inner-lane spaces are utilized to facilitate the merging of ramp vehicles, leading to an increase in the on-ramp flow. However, the large value of ρ also implies frequent changes into the inner lane, which may overload the inner lane and break the stability of the upstream traffic. Therefore, it is important to determine a reasonable ρ value to balance the merging efficiency and the mainline stability.

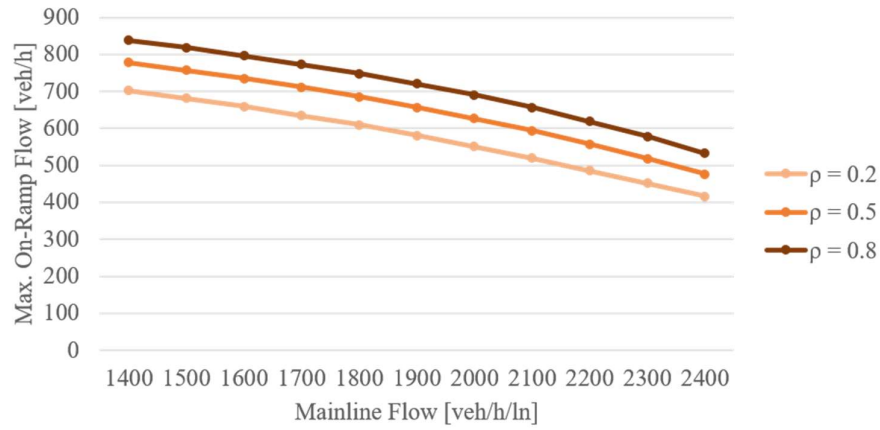


Figure 4.3 Maximum on-ramp flow with respect to mainline flow (multi-lane context)

4.2 Case study

An illustrative case study for multi-lane freeway is conducted through microscopic simulation integrating VISSIM, Python and C++ scripts, as introduced in Section 3.3. The simulated network consists of two lanes on the mainline freeway and one lane on the ramp. The freeway and on-ramp are connected to each other through a 240-meter-long parallel acceleration lane. The freeway extends 2000 meters upstream and 500 meters downstream along the main road. One-sided lane-change prohibition rule is applied in and near the merging area as introduced in Section 4.1.

The performance of CoMC is evaluated in six demand scenarios with relatively high traffic volumes, combining two levels of mainstream flow (2000 and 2200 veh/h/ln) and three levels of on-ramp flow (300, 400, and 500 veh/h). The study scenarios and the corresponding CoMC control plans, solved for the parameters in Table 3.2, are summarized in Table 4.1. For each scenario, 10 simulation runs under the centralized control of CoMC (i.e., CoMC case) and 10 without CoMC (i.e., baseline case) are carried out. Aggregated results of the CoMC and baseline cases are compared to each other in terms of travel time, delay, and vehicle speed.

Table 4.1 Study scenarios and coordination decisions (multi-lane context)

| | 1A | 1B | 1C | 2A | 2B | 2C | |
|------------|------|------|------|-------|------|------|-------|
| q_{main} | 2000 | 2000 | 2000 | 2200 | 2200 | 2200 | veh/h |
| q_{ramp} | 300 | 400 | 500 | 300 | 400 | 500 | veh/h |
| v_c | 98.5 | 92.9 | 85.4 | 100.0 | 90.1 | 81.1 | km/h |
| d | 687 | 909 | 1044 | 934 | 917 | 1137 | m |
| n | 4 | 7 | 11 | 5 | 8 | 14 | veh |

Figure 4.4 presents the travel time and delay results for the multi-lane context, and Figure 4.5 shows the speed contour of the most critical 2C (2200, 500) scenario. When comparing the multi-lane results to the basic results reported in Section 3.3, it is noted that the traffic performs better with even higher traffic volumes and is less sensitive to the increase in traffic flow, indicating that the multi-lane configuration is more resilient compared to the single lane layout. Nevertheless, the multi-lane results suggest similar findings about CoMC as revealed in the single lane results, which are

- The CoMC coordination functions as expected and improves the overall traffic efficiency of on-ramp merging. In the most critical situations, CoMC can further stabilize traffic and prevent the onset of long-lasting and wide-spreading congestions.
- The benefits of CoMC are more remarkable with higher traffic volumes compared to the lower volume conditions.

More results and discussions about the application of CoMC in the multi-lane context are available in Zhu et al. (2022b) (Paper III in Appendix C).

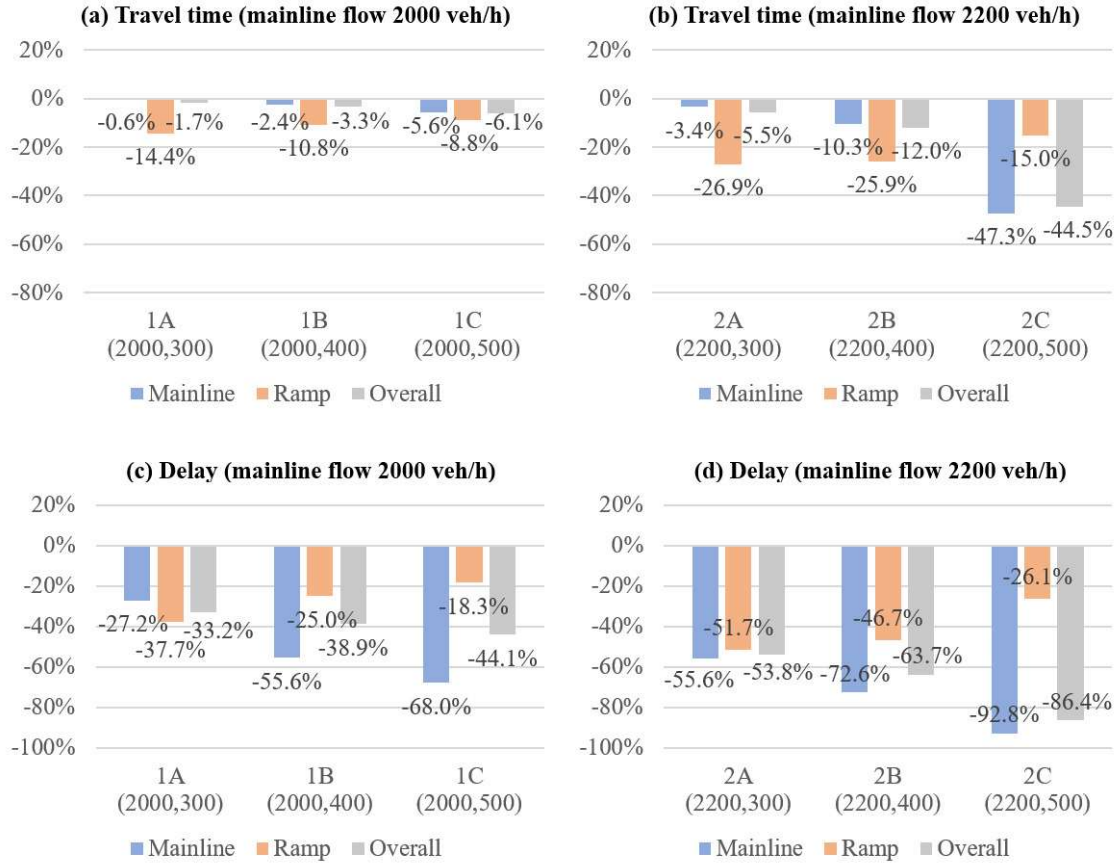


Figure 4.4 Travel time and delay (multi-lane context)

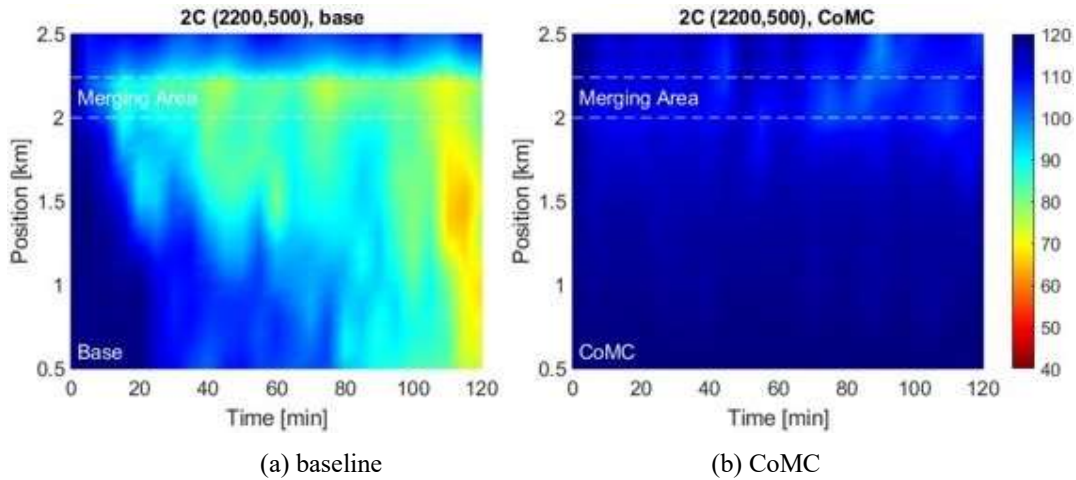


Figure 4.5 Speed contour (multi-lane context)

Chapter 5

Merging coordination in mixed traffic

This chapter is based on the work contained in the following paper in Appendix D:

- **Paper IV.** Zhu, J., Gao, K., & Qu, X. (2022). Bi-level ramp merging coordination in congested mixed traffic conditions with human-driven and connected autonomous vehicles. Manuscript to be submitted.

In this chapter, the flow-level CAV ramp merging coordination strategy is extended for the application in mixed CAV-HDV contexts. This extended strategy, called Coordinative Merging Control in Mixed traffic (M-CoMC), retains the ideas of gap creation and platoon merging for flow-level coordination benefits, while addressing uncertainties and variations related to the presence of HDVs. The strategy is tested in a simulation-based case study under different traffic volumes and CAV penetration rates. Section 5.1 introduces the strategy and its formulation, and Section 5.2 shows preliminary results of the simulation-based case study. More derivations and results are available in the appended Paper IV in Appendix D.

5.1 Extension of CoMC in mixed traffic

5.1.1 Coordinative merging control strategy in mixed traffic (M-CoMC)

In mixed traffic conditions where HDVs are present, the behaviors of HDVs cannot be directly controlled but can be influenced by the surrounding CAVs. Under the coordination of gap creation and platoon merging, only the mainline facilitating vehicle and the merging platoon leader in each merging cycle obey instructions from the control center, while the other vehicles (e.g., platoon followers, mainline vehicles following the facilitating vehicle) drive in their regular car-following manner. Therefore, as long as the facilitating vehicle and the platoon leader are CAVs, coordination can be achieved even with the presence of HDVs. The underlying idea is to use CAVs as actuators for HDVs. For example, if we ignore the possibility of free lane-changing, the deceleration or stop of a preceding CAV will force the following HDVs to decelerate or stop. In this way, the HDVs are indirectly controlled and incorporated into the coordination. Figure 5.1 illustrate such a coordination strategy for mixed traffic.

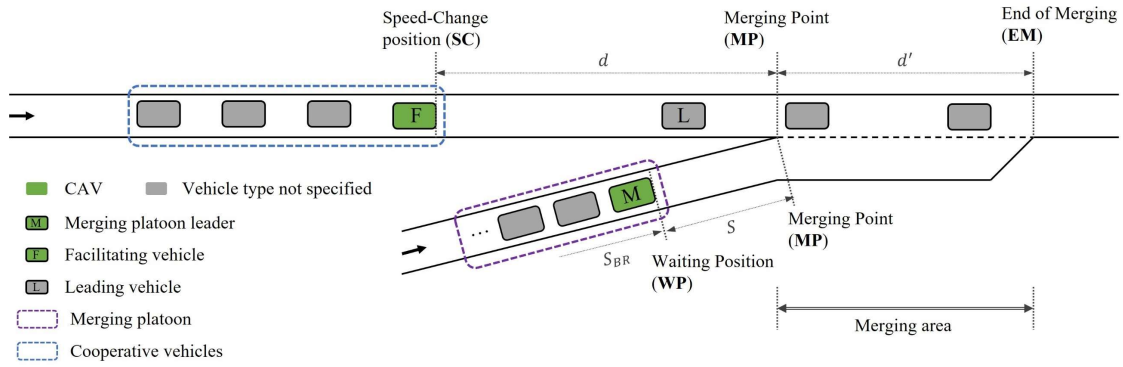
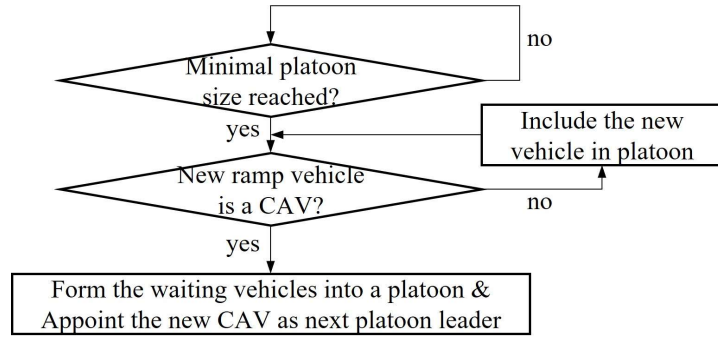


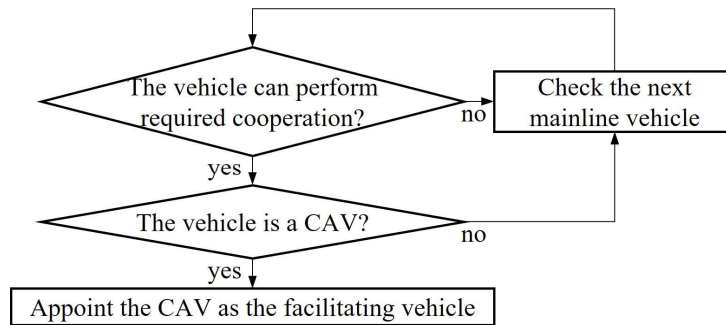
Figure 5.1 CoMC in mixed traffic context (M-CoMC)

In order to ensure that the merging platoon leader and the mainline facilitating vehicles are CAVs, two mechanisms are introduced in the M-CoMC (coordinative merging control for mixed traffic) strategy to determine the formulation of merging platoon and the appointment of facilitating vehicle:

Decision mechanism 1 (formation of merging platoon): As shown in Figure 5.2a, the formation of a merging platoon requires two conditions: (1) a sufficient number of vehicles are accumulated on the ramp, and (2) the next vehicle directly after the platoon is a CAV. The decision mechanism is triggered every time a new ramp vehicle arrives. The control center first counts the number of vehicles waiting on the ramp (excluding the new vehicle). If the minimum number is reached, the control center further checks if the new vehicle is a CAV. If yes, the waiting vehicles are grouped as a platoon, and the new CAV is appointed as the leader of the next platoon. This ensures that the first vehicle in a platoon is always a CAV.



(a) Formation of merging platoon



(b) Appointment of facilitating vehicle

Figure 5.2 Decision mechanisms in M-CoMC

Decision mechanism 2 (appointment of merging platoon): As shown in Figure 5.2b, two requirements are considered for a facilitating vehicle: (1) the vehicle is able to perform the required cooperation, that is the vehicle has not reached the required speed-change position; and (2) the vehicle is a CAV. When the coordination is initiated, the control center checks the mainline vehicles one by one (from front to back) and appoints the first vehicle that meets the above two conditions as the facilitating vehicle.

According to the decision mechanisms, the formation of merging platoon and the appointment of facilitating vehicle depend on on-going traffic operation (e.g., the arrival of CAVs/HDV, vehicle distribution) and varies across different merging cycles. To account for such variations, a bi-level coordination model is established as in Figure 5.3. The model consists of a macro-level and a micro-level. The macro-level uses traffic state parameters as inputs and employs optimization methods, combined with macroscopic traffic flow models, to determine the minimal platoon size (n_{min}) and the cooperative merging speed (v_c). The micro-level uses outputs from the macro-level and real-time traffic information as inputs and determines the speed-change position (d) and the platoon acceleration trajectory (a) in each merging cycle. Note that, as long as the macroscopic traffic state is stable, the macro-level decisions (i.e., n_{min} and v_c) remain unchanged, whereas the micro-level decisions (i.e., d and a) are updated in each cycle to account for real-time variations in traffic operation.

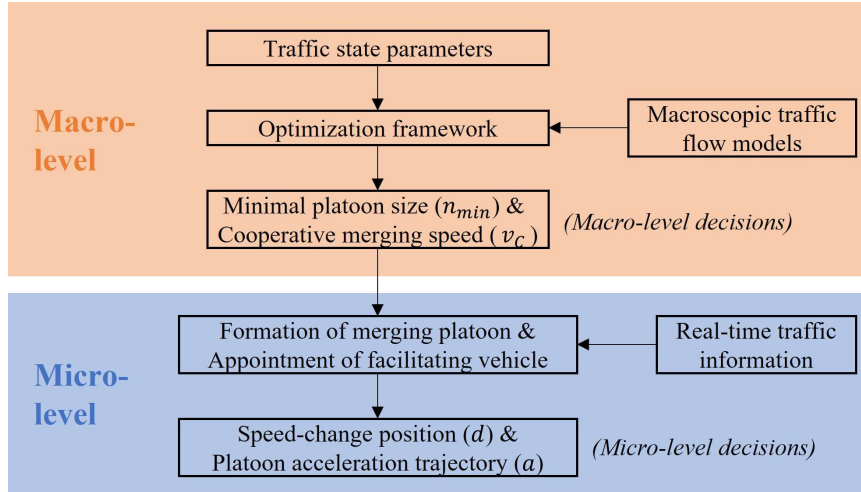


Figure 5.3 Bi-level coordination of M-CoMC

In comparison with the basic CoMC strategy in Chapter 3, the M-CoMC strategy is modified in three aspects to account for the presence of HDVs: (1) it incorporates decision mechanisms to assign the roles of facilitating vehicle and platoon leader to CAVs, (2) it considers distributions (instead of fixed values as in the basic strategy) of the merging platoon size and the SC position at the macro-level, and (3) it introduces a micro-level to address variations in real-time traffic operation.

5.1.2 Bi-level coordination model

5.1.2.1 Macro-level

The macro-level employs an optimization model to determine the minimal platoon size (n_{min}) and the cooperative speed (v_c) according to traffic state. According to decision

mechanism 1, the size of a merging platoon depends on the minimal size n_{min} and the number of HDVs consecutively arriving after n_{min} is reached. The arrival of ramp vehicles is described as an infinite Bernoulli process with constant success probability p , where a success represents the arrival of a CAV, and a failure an HDV (p equals the CAV penetration rate in the traffic flow). Therefore, the number of vehicles in a merging platoon (n) follows the shifted geometric distribution:

$$P(n) = (1 - p)^{n - n_{min}} \cdot p, \quad n \in \{n_{min}, n_{min} + 1, n_{min} + 2, \dots\} \quad (5.1)$$

The size of a merging platoon determines the size of the required merging gap and thus the SC position of facilitating vehicle. According to the requirement that the created gap is large enough to accommodate the platoon, the SC position (defined by d in Figure 5.1) is expressed as a function of n :

$$d = \frac{v_o v_c}{v_o - v_c} [(n + 1)h_c - h_o] \quad (5.2)$$

The macro-level coordination is formulated as an optimization problem that minimizes the total delay to the mainline and ramp vehicles:

$$\min D = w_m \cdot D_{main} + w_r \cdot D_{ramp} \quad (5.3)$$

where w_m and w_r are the weights of the mainline and ramp traffic, respectively; and D_{main} and D_{ramp} are the total hourly delay to the mainline and ramp vehicles, respectively.

Considering the distribution of n , the total mainline delay is

$$D_{main} = r \cdot \sum_{n=n_{min}}^{\infty} P(n) \cdot D_{main}^n = r \cdot \sum_{n=n_{min}}^{\infty} \left[P(n) \cdot \sum_{i=1}^m D_{main}^i \right] \quad (5.4)$$

where D_{main}^n is mainline delay resulted from the merging of a platoon consisting of n vehicles, r is the expected number of merging cycles per hour, D_{main}^i is the delay to the i^{th} mainline cooperative vehicle, and m is the number of cooperative vehicles in a merging cycle. D_{main}^i , m and r are derived through Eq.(3.2), Eq.(3.3), and Eq.(3.5) in Section 3.1.2.

The total mainline delay is

$$D_{ramp} = r \cdot \sum_{n=n_{min}}^{\infty} P(n) \cdot D_{ramp}^n = r \cdot \sum_{n=n_{min}}^{\infty} \left[P(n) \cdot \sum_{j=1}^n D_{ramp}^j \right] \quad (5.5)$$

where D_{ramp}^n is the ramp delay to a merging platoon of n vehicles, and D_{ramp}^j is the delay to the j^{th} ramp vehicle in platoon derived in Eq.(3.4).

Similar to the CoMC model for basic context in Section 3.1.2, the coordination model for mixed traffic is subject to constraints on traffic stability and vehicle dynamics in Eq.(3.6) – Eq.(3.11).

5.1.2.2 Micro-level

The micro-level updates the decisions on SC position (d) and platoon trajectory (a) according to real-time traffic operation in each merging cycle, such as the actual number of CAVs and HDVs in the merging platoon and the actual positions of vehicles on the main road.

According to decision mechanism 2, the micro-level appoints the facilitating vehicle in each merging cycle through an iterative process as in Figure 5.4. Under this process, mainline CAVs are checked one by one from front to back until the first CAV that satisfies Eq.(5.6) is found and appointed as the facilitating vehicle.

$$P_k \geq P_{k,min} = \max \left\{ \begin{array}{l} \frac{P_{k-1}v_C}{v_{k-1}} + [(n_{CAV}^* + 1)h_C^{CAV} + n_{HDV}^*h_C^{HDV}]v_C \\ t_{RT,min}v_C + [n_{CAV}^*h_C^{CAV} + n_{HDV}^*h_C^{HDV}]v_C \end{array} \right\} \quad (5.6)$$

Here, P_k is the position of a mainline CAV k , $P_{k,min}$ is the foremost position for vehicle k to be the facilitating vehicle, P_{k-1} and v_{k-1} are the position and speed of the vehicle in front of k on the main road, n_{CAV}^* and n_{HDV}^* are the actual number of CAVs and HDVs in the merging platoon, h_C^{CAV} and h_C^{HDV} are the car-following headways of CAVs and HDVs at speed v_C which are derived from the car-following relationship, and $t_{RT,min}$ is the minimal time needed for the platoon to arrive at the MP considering the vehicles' acceleration performance on the ramp

$$t_{RT,min} = \frac{S}{v_C} + \frac{v_C}{2a_{ramp}} \quad (5.7)$$

where S is the distance between WP and MP, and a_{ramp} is the maximum ramp acceleration.

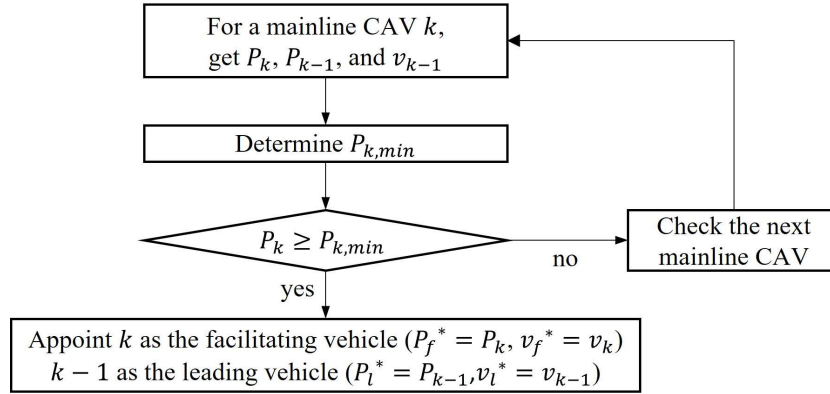


Figure 5.4 Traversal approach to appoint the facilitating vehicle

The actual speed change position of facilitating vehicle (d^*) depends on the current speed and position of the vehicle and the size of gap it creates:

$$d^* = \frac{v_f^*v_C}{v_f^* - v_C} \left(t_{RT}^* + n_{CAV}^*h_C^{CAV} + n_{HDV}^*h_C^{HDV} - \frac{P_f^*}{v_f^*} \right) \quad (5.8)$$

where P_f^* and v_f^* are the position and speed of the facilitating vehicle, and t_{RT}^* is the actual ramp travel time of the merging platoon determined by

$$t_{RT}^* = \max \left\{ \frac{P_l^*}{v_l^*} + h_C^{CAV}, t_{RT,min} \right\} \quad (5.9)$$

where P_l^* and v_l^* are the position and speed of the leading vehicle.

The acceleration trajectory of merging platoon is adapted in each merging cycle in accordance with the required ramp travel time t_{RT}^* . Here, two cases are distinguished according to the relationship between t_{RT}^* and $\frac{2S}{v_C}$, as shown in Figure 5.5. When $t_{RT}^* \leq \frac{2S}{v_C}$ (red case), the

platoon accelerates at the rate a_1^* until reaching v_c and then keeps v_c until arriving at the MP. The acceleration time (t_{a1}^*) and rate (a_1^*) are

$$t_{a1}^* = \frac{2(v_c t_{RT}^* - S)}{v_c} \quad (5.10)$$

$$a_1^* = \frac{v_c^2}{2(v_c t_{RT}^* - S)}$$

When $t_{RT}^* > \frac{2S}{v_c}$ (blue case), the platoon first waits for t_{a2}^* and then accelerates at the rate a_2^* until arriving at the MP, with

$$t_{a2}^* = t_{RT}^* - \frac{2S}{v_c} \quad (5.11)$$

$$a_2^* = \frac{v_c^2}{2S}$$

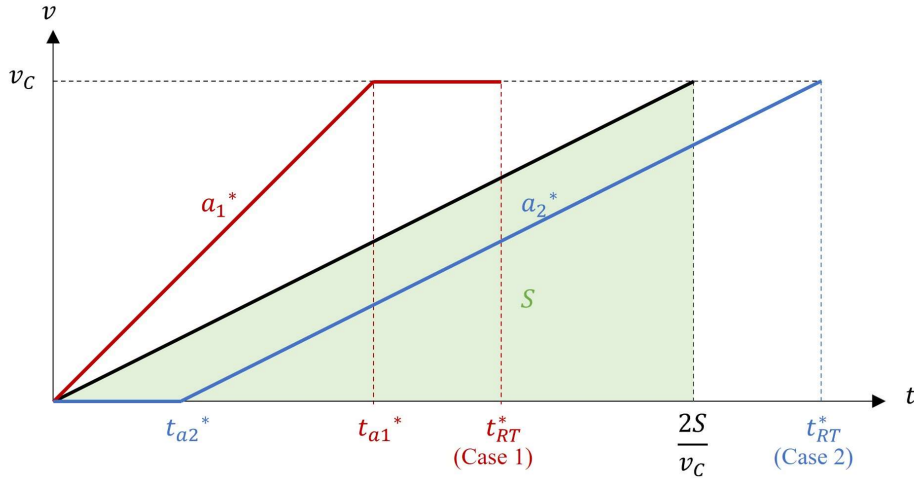


Figure 5.5 Acceleration trajectory of merging platoon leader

5.2 Case study

An illustrative case study for mixed traffic is carried out to demonstrate the benefits of the M-CoMC strategy on a traffic simulation platform integrating SUMO, MATLAB, and Python. SUMO is used to simulate traffic operation at on-ramp merging. The macro-level decisions are solved offline in MATLAB, and the micro-level coordination is carried out in Python in an online manner. The interaction between SUMO and Python is achieved through the Traffic Control Interface (TraCI), which transfers vehicle status and micro-level decisions between SUMO and Python in real-time. The car-following behaviors of mixed traffic are described by the Intelligent Driver Model (IDM), with different parameter sets for HDVs and CAVs. Notably, the actual driving dynamics of HDVs may deviate from the theoretical estimations in the micro-level model due to the heterogeneity in human driving patterns. Such deviations are accommodated by continuously updating the micro-level decisions under a Model Predictive Control (MPC) mechanism for the entire course of coordination.

The simulated road segment is composed of a 230-meter-long merging area and its upstream and downstream influence areas, including a 3000-meter-long upstream segment, an 800-meter-long downstream segment, and a 1500-meter-long on-ramp. A total of 18 scenarios are investigated, combining two levels of mainline volume (1800 and 2000 veh/h), three levels of ramp volume (500, 600, and 700 veh/h), and four levels of CAV penetration rate (0.3, 0.5, 0.7, 0.9). The study scenarios and the corresponding macro-level decisions are summarized in Table 5.1. For each study scenario, a M-CoMC case and an uncontrolled base case are carried out and compared to each other with aggregated results of multiple simulation runs.

Table 5.1 Study scenarios and macro-level coordination decisions (mixed context)

| (a) CAV penetration $p = 0.3$ | | | | | | | | |
|-------------------------------|-------|------|------|------|------|------|------|------------|
| Traffic volume | q_m | 1800 | 1800 | 1800 | 2000 | 2000 | 2000 | veh/h/lane |
| | q_r | 500 | 600 | 700 | 500 | 600 | 700 | veh/h/lane |
| M-CoMC decision | n | 6 | N/A | N/A | 15 | N/A | N/A | km/h |
| | v_c | 75.5 | | | 75.0 | | | veh |
| (b) CAV penetration $p = 0.5$ | | | | | | | | |
| Traffic volume | q_m | 1800 | 1800 | 1800 | 2000 | 2000 | 2000 | veh/h/lane |
| | q_r | 500 | 600 | 700 | 500 | 600 | 700 | veh/h/lane |
| M-CoMC decision | n | 6 | 10 | N/A | 7 | 19 | N/A | km/h |
| | v_c | 84.0 | 76.5 | | 75.2 | 75.1 | | veh |
| (c) CAV penetration $p=0.7$ | | | | | | | | |
| Traffic volume | q_m | 1800 | 1800 | 1800 | 2000 | 2000 | 2000 | veh/h/lane |
| | q_r | 500 | 600 | 700 | 500 | 600 | 700 | veh/h/lane |
| M-CoMC decision | n | 6 | 8 | 12 | 7 | 9 | 19 | km/h |
| | v_c | 88.2 | 83.3 | 75.7 | 87.1 | 75.9 | 75.0 | veh |
| (d) CAV penetration $p=0.9$ | | | | | | | | |
| Traffic volume | q_m | 1800 | 1800 | 1800 | 2000 | 2000 | 2000 | veh/h/lane |
| | q_r | 500 | 600 | 700 | 500 | 600 | 700 | veh/h/lane |
| M-CoMC decision | n | 6 | 7 | 9 | 6 | 8 | 10 | km/h |
| | v_c | 92.0 | 89.0 | 82.2 | 91.8 | 86.2 | 75.7 | veh |

* N/A: not applicable due to low CAV penetration rate

Figure 5.6 presents vehicle trajectories of the 2000-700-0.7 scenario. Travel time results and speed contours are shown in Figure 5.7 and Figure 5.8, respectively. According to the results, main findings about the efficiency of M-CoMC are summarized as below:

- M-CoMC achieves the expected coordination between the mainline and ramp traffic in mixed traffic conditions with HDVs and CAVs. The coordination smoothens vehicle trajectories and eliminates traffic oscillations and stop-and-go in the on-ramp merging areas.
- M-CoMC substantially improves the overall traffic efficiency at on-ramp merging by reducing vehicle travel times, preventing recurrent traffic congestions, and increasing merging throughputs. The degree of improvements varies in different scenarios in terms of mainline volume, ramp volume, and CAV penetration rate.

- The benefits of M-CoMC are more remarkable under high traffic volumes and high CAV penetration rate. Overall speaking, M-CoMC benefits the mainline traffic more than the ramp traffic. In a few scenarios, the ramp efficiency is even reduced under M-CoMC (see Figure 5.7b). This indicates the need to introduce in practice an activation threshold of M-CoMC in terms of the traffic volume and CAV penetration rate.

More results and analysis about the M-CoMC strategy are available in the appended Paper IV in Appendix D.

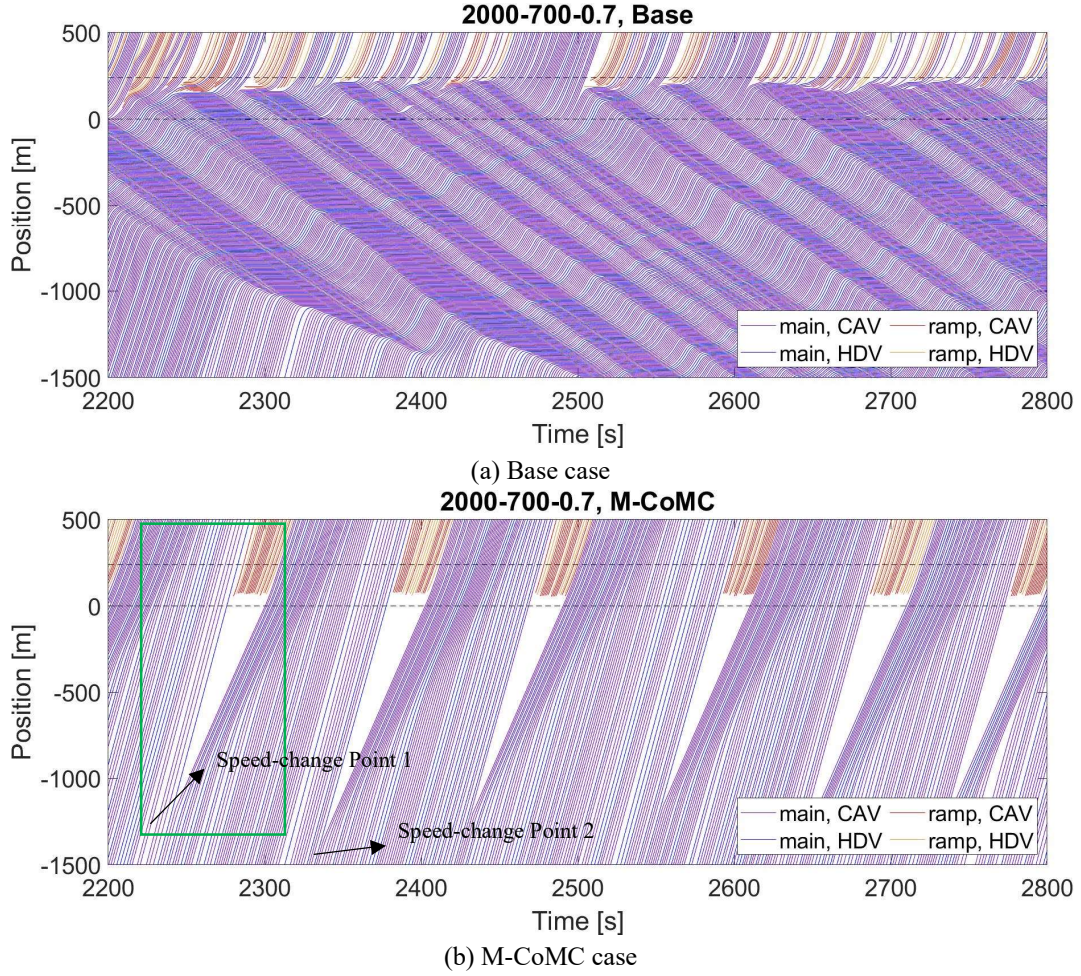
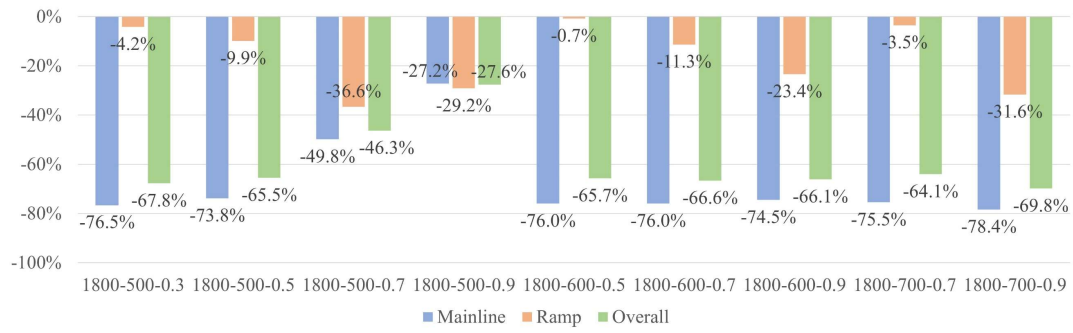
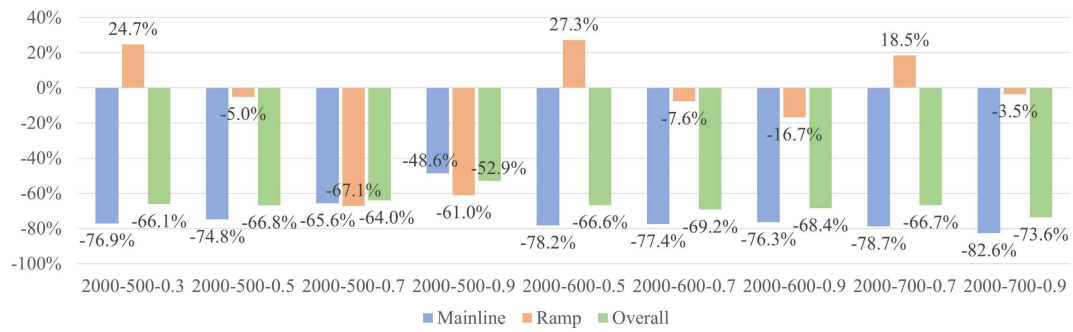


Figure 5.6 Vehicle trajectory (mixed context)

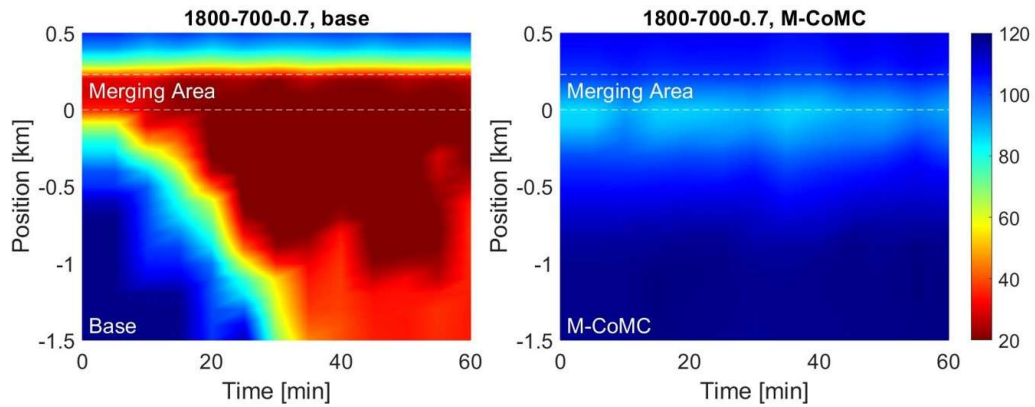


(a) 1800 veh/h mainline flow

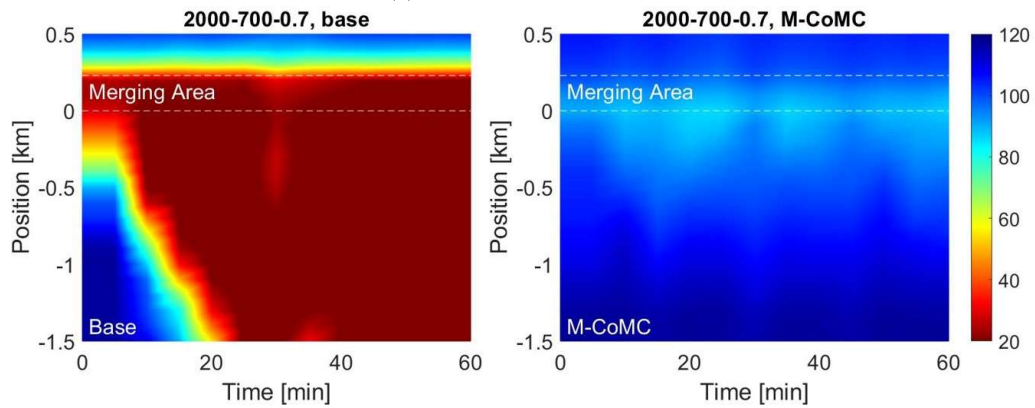


(b) 2000 veh/h mainline flow

Figure 5.7 Travel time (mixed context)



(a) 1800-700-0.7 scenario



(b) 2000-700-0.7 scenario

Figure 5.8 Speed contour (mixed context)

Chapter 6

Safety analysis of CAV ramp merging

This chapter is based on the work contained in the following paper in Appendix E:

- **Paper IV.** Zhu, J., & Tasic, I. (2021). Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles. *Accident Analysis & Prevention*, 152, 105966.

In this chapter, the safety impacts of CAVs at on-ramp merging are investigated. The investigation focuses on the ability of CAVs to eliminate critical human factors through autonomous vehicle control. Therefore, the communication capability of CAVs is partially considered in this chapter in the sense that information exchange among vehicles and infrastructures are available so that the CAVs possess more comprehensive information compared to HDVs; however, no specially designed cooperation/coordination between CAVs is considered in this chapter. Section 6.1 introduces the safety investigation methods, including a novel conflict index and a merging conflict model; Section 6.2 investigates safety impacts of CAVs through a Monte-Carlo simulation study. In this introductory chapter, an overview of the safety investigation is provided, while detailed derivations and results are available in Zhu et al. (2021a) (Paper V in Appendix E).

6.1 Safety investigation methods

6.1.1 Conflicting merging headway

Due to the limited access to CAV accident data, safety impacts of CAVs are primarily investigated through safety surrogate measures. However, the prevailing safety surrogate measures present limitations in capturing ramp merging conflicts. Specifically, the widely used measures, such as time-to-collision (TTC), post-encroachment time (PET), and their variations, are primarily developed for the rear-end conflicts at car-following and the crossing conflicts at intersections, whereas vehicle interactions at ramp merging are essentially different from the situations of car-following or intersection crossing. In view of this concern, a novel conflict index, called Conflicting Merging Headway (CMH), is proposed to serve specially for the ramp merging context. The CMH index, implicitly adopting the inherent idea of PET, is defined as the time interval between a Ramp Merging Vehicle (RMV) arriving at the merging point and the Mainline Following Vehicle (MFV) that directly follows this ramp vehicle arriving at the same position, as illustrated in Figure 6.1.

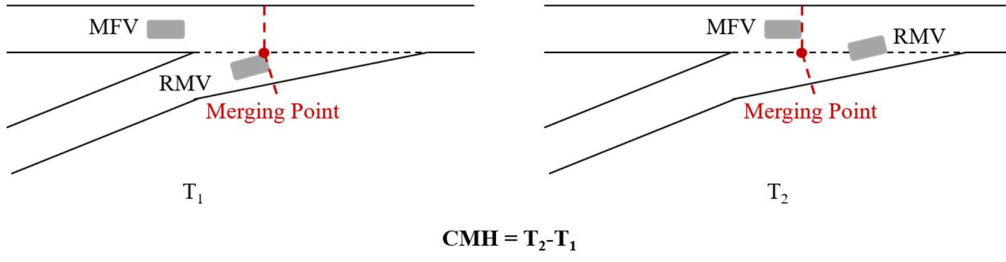


Figure 6.1 Definition of conflicting merging headway (CMH)

6.1.2 Merging conflict model

In order to estimate CMH, a merging conflict model is developed by considering the decisions, responses, and actions of vehicles in the merging process. The model describes the merging process as a sequence of three consecutive event processes:

Process 1 (RMV gap selection): This process determines which mainline gap the RMV merges into. The gap should satisfy two conditions: (1) the gap is large enough and (2) the RMV has enough time to catch up with the gap:

$$g_{target} \geq g_{acc} \quad (6.1)$$

$$t_{MFV} \geq t_{earliest} \quad (6.2)$$

Here, g_{target} is the size of the target gap, g_{acc} is the acceptable gap of the RMV, t_{MFV} is the arrival time of the MFV, $t_{earliest}$ is the earliest arrival time of the RMV, estimated as

$$t_{earliest} = \frac{S}{v_{limit}} + \frac{(v_{limit} - v_r)^2}{2a_{ramp} \cdot v_{limit}} \quad (6.3)$$

where S is the remaining ramp travel distance, v_r is the speed of the RMV, v_{limit} is the ramp speed limit, and a_{ramp} is the maximum ramp acceleration.

Process 2 (RMV merging maneuver): This process determines the exact position of RMV in the gap and the initial headway between the RMV and the MFV. Specifically, two positions are compared: (1) the desired position (t_{desire}) defined as $\frac{1}{2}g_{acc}$ from the leading vehicle and (2) the earliest achievable position defined by the earliest arrival time in Eq.(6.3); the RMV takes the latter of these two positions, namely

$$t_{RMV} = \max(t_{desire}, t_{earliest}) \quad (6.4)$$

and the initial headway (h_0) is

$$h_0 = t_{MFV} - t_{RMV} \quad (6.5)$$

Process 3 (MFV evasive action): This process determines if the MFV brakes to expand the distance to RMV, and if yes, the resulted evasive braking rate (b) and final headway (CMH). In this process, four situations are distinguished, considering the desired headway (h_d), reaction time (τ), and braking limit (b_{max}) of the MFV, as illustrated in Figure 6.2.

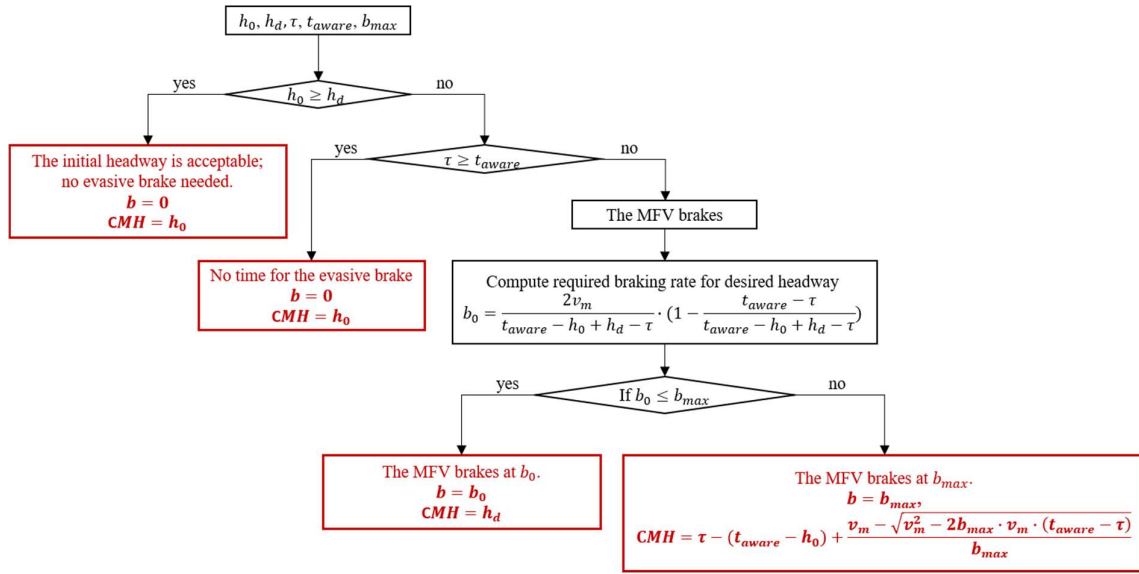


Figure 6.2 MFV evasive action process

The merging conflict model is validated on trajectory data collected under the Next Generation Simulation (NGSIM) program. Figure 6.3 compares the results estimated by the merging conflict model to the empirical results derived from data in terms of the size of accepted merging gaps and the CMH value. The good agreement between model estimations and data observations suggests the model's ability to capture the actual merging process.

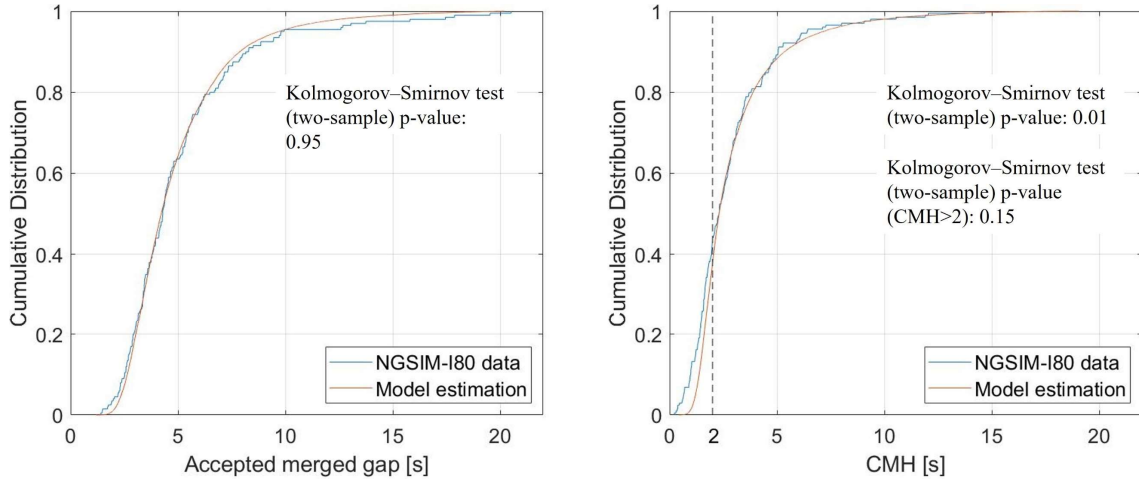


Figure 6.3 Validation of merging conflict model

6.2 Monte-Carlo simulation study

To account for uncertainties and variations in traffic conditions and road users, Monte-Carlo methods are applied in the simulation study. Specifically, probabilistic distributions (instead of deterministic values) are used as inputs of the merging conflict model. In each simulation run, we draw a random value from the input distribution of each parameter and use the drawn values to perform a deterministic computation through the merging conflict model. By repeating this process for a large-enough number of times, the outputs are aggregated to

obtain a distribution of CMH that indicates the overall merging risk and the probabilities of critical merging events, such as conflicts and near-crashes.

The Monte-Carlo simulation is carried out through MATLAB R2020a. A total of five scenarios at different CAV penetration rates (0%, 20%, 50%, 80%, 100%) are investigated:

- 100% HDV scenario (HDV100)
- 20% CAV and 80% HDV mix-scenario (CAV20)
- 50% CAV and 50% HDV mix-scenario (CAV50)
- 80% CAV and 20% HDV mix-scenario (CAV80)
- 100% CAV scenario (CAV100)

For each scenario, 50,000 simulation runs are conducted. The input distributions are reported in Table 6.1. Inputs for HDVs are calibrated on the empirical I-80 data collected under the NGSIM program, and inputs for CAVs are derived in accordance with widely recognized assumptions on CAV capabilities. Further, it is assumed that CAVs operate in different driving modes (e.g., aggressive, neutral mode, or conservative) to accommodate various preferences of CAV users. Thus, the driving mode related parameters (e.g., acceptable gap, desired headway) follow discrete distributions for CAVs.

Table 6.1 Input distributions of merging conflict model

| Model input parameter | Label | Unit | HDV | | CAV | |
|--|-------------|------------------|---------------------------|---|--------------|---|
| | | | Distribution | Parameter | Distribution | Parameter |
| Traffic & Design parameter | | | | | | |
| Mainline gap | g_i | s | Burr | $\alpha = 2.20, \mathbf{c} = 4.53, \mathbf{k} = 0.67$ | Burr | $\alpha = 2.20, \mathbf{c} = 4.53, \mathbf{k} = 0.67$ |
| On-ramp speed limit | v_{limit} | km/h | Point Value | 80 | Point Value | 80 |
| Driving behavior parameter for the RMV | | | | | | |
| Initial speed of the RMV | v_r | km/h | Normal | $\mu = 36.50, \sigma = 15.58$ | Point Value | 36.5 |
| Merging point position | S_{rd} | m | Generalized Extreme Value | $\mu = 1.78, \sigma = 1.06, \mathbf{k} = 0.89$ | Uniform | 5 - 95 |
| Acceptable gap of the RMV | g_{acc} | s | Inverse Gaussian | $\mu = 2.78, \lambda = 13.77$ | Discrete | 1.90 (30%), 2.95 (40%), 5.20 (30%) |
| Critical headway for checking alternative gaps | h_c | s | Point Value | 0.88 | Point Value | 0.88 |
| Number of alternative gaps checked | m | - | Point Value | 1 | Point Value | 3 |
| Maximum acceleration of the RMV | a_{max} | m/s ² | Point Value | 3.4 | Point Value | 3.4 |
| Driving behavior parameter for the MFV | | | | | | |
| Initial speed of the MFV | v_m | km/h | Lognormal | $\mu = 3.54, \sigma = 0.23$ | Point Value | 35.5 |
| Desired headway of the MFV | h_d | s | Generalized Extreme Value | $\mu = 1.21, \sigma = 0.38, \mathbf{k} = -0.11$ | Discrete | 1.10 (30%), 1.50 (40%), 2.15 (30%) |
| Mainline awareness time | t_{aware} | s | Uniform | 12.1 – 12.9 | - | - |
| Mainline awareness distance | S_{aware} | m | - | - | Point Value | 300 |
| Reaction time of the MFV | τ | s | Lognormal | $\mu = 0.43, \sigma = 0.37$ | Discrete | 1.0 (0.99%), infinite (0.01%) |
| Maximum deceleration of the MFV | b_{max} | m/s ² | Point Value | 3.4 | Point Value | 3.4 |

Table 6.1 shows the CMH distribution results, and Table 6.2 reports the probability of critical merging events. The results show CAV has a positive effect on ramp merging safety in terms of reducing the probability of merging conflicts and eliminating near-crash events, especially at higher penetration rates. Further, it is found that most near-crashes at merging are related to the aggressive driving patterns of human drivers, which are avoided in CAV driving.

In addition, a sensitivity analysis is conducted on the parameters related to CAV driving patterns, such as acceptable gap and desired headway. The results show that the proper operation of autonomous driving systems and the selection of appropriate acceptable gaps are crucial to CAV merging safety. More results and discussions are available in Zhu et al. (2021a) (Paper V in Appendix E).

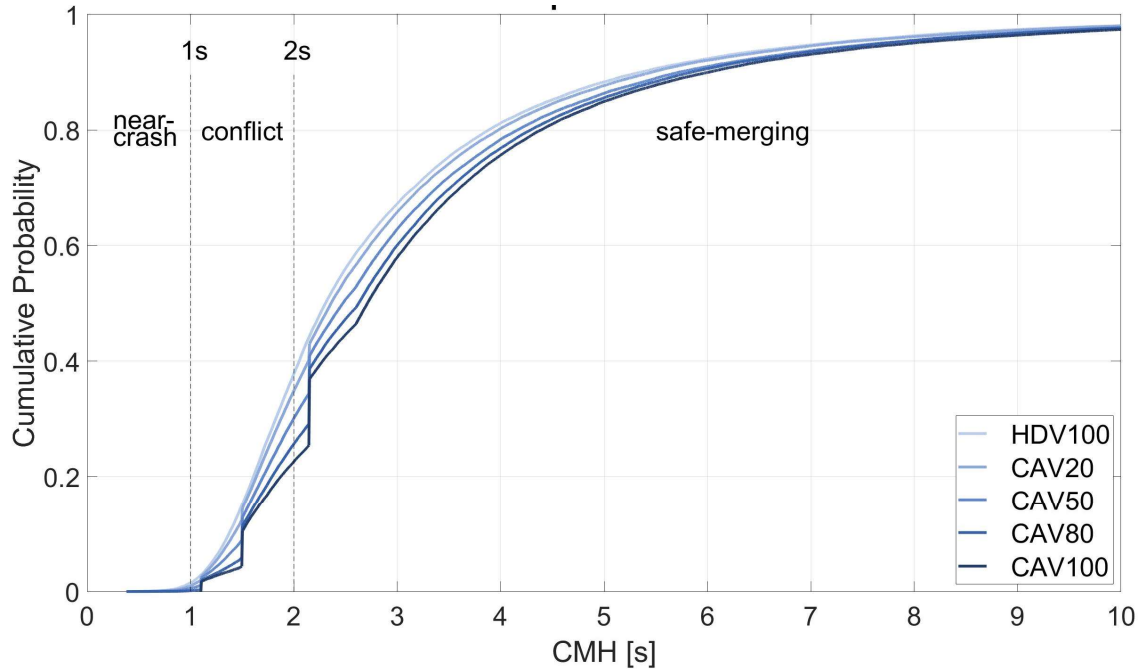


Figure 6.4 CMH distributions under incremental CAV penetration rates

Table 6.2 Probability of critical merging events

| | | HDV100 | CAV20 | CAV50 | CAV80 | CAV100 |
|--------------------------------------|------------------|--------|--------|--------|--------|--------|
| Near-crashes | $h \leq 1s$ | 1.47% | 1.02% | 0.52% | 0.15% | 0.00% |
| Conflicts | $1s < h \leq 2s$ | 38.52% | 36.05% | 32.22% | 28.78% | 26.25% |
| Total probability of critical events | | 39.99% | 37.07% | 32.75% | 28.93% | |

Chapter 7

Conclusion and Future Work

7.1 Conclusion

This dissertation discusses the possibilities to coordinate CAVs at freeway on-ramp merging and analyses the potential impacts of CAVs on ramp merging operation. Within the scope of this dissertation, key points related to the CAV ramp merging problem is thoroughly reviewed, and clear research gaps are identified. In view of the research gaps, a novel CAV coordination strategy is developed to facilitate the overall merging operation at freeway on-ramps. The strategy combines the ideas of proactive gap creation and platoon merging for flow-level gains in merging efficiency and traffic flow stability. The strategy is first tested in a basic context of single lane freeway and full CAV penetration rate and later extended to more realistic contexts of multi-lane freeways and mixed CAV-HDV traffic conditions. The benefits of CAV coordination are investigated through illustrative case studies conducted on microscopic simulation platforms. Further, the safety impacts of CAVs are assessed with a highlight on the CAV's ability to eliminate critical human factors at ramp merging. Main findings of this dissertation are summarized as below:

- Literature confirms that CAVs have the potential to substantially improve traffic operation at freeway on-ramps. The improvements are expected in many aspects, such as traffic safety, efficiency, energy use, emission, and passenger comfort. Nevertheless, a few limitations are identified in the current discussions on CAV ramp merging: (1) The existing CAV ramp merging strategies mainly focus on the local level control of individual vehicles, whereas considerations at the traffic flow level are either ignored or discussed to a limited extent. (2) The majority of CAV ramp merging strategies only applies to the basic context of single lane freeway and full CAV penetration rate, while ignoring the free lane-changes between mainstream lanes and the presence of HDVs. (3) The safety impacts of CAVs are not sufficiently discussed in the literature, especially the role of CAVs in eliminating critical human factors through autonomous vehicle control.
- In view of the first research gap, a novel CAV coordination strategy, called CoMC, is proposed to facilitate ramp merging operation at the traffic flow level. The strategy combines the ideas of proactive gap creation on the main road and platooning of ramp merging vehicles. The coordination is formulated as an optimization problem incorporating macroscopic traffic flow models. The model uses traffic state parameters as inputs and determines the optimal coordination decisions adaptive to real-time traffic conditions. The CoMC strategy is tested in a basic context of single lane freeway and full CAV penetration rate. The results show that the coordination functions as expected in continuous traffic flow, and it substantially improves the overall efficiency

of on-ramp merging, especially under high traffic volume conditions, where recurrent traffic congestion is prevented, and merging throughput increased.

- In view of the second research gap, the CoMC strategy is extended to multi-lane freeway configurations. On the basis of gap creation and platoon merging, the extended strategy integrates one-sided lane-change prohibition rules on the main road and considers free lane-changes between mainstream lanes. A case study of two-lane freeway is carried out to demonstrate the proposed multi-lane strategy. The results show that the coordination balances the traffic flow between mainstream lanes and improves the overall ramp merging efficiency and stability in multi-lane freeways.
- In view of the second research gap, the CoMC strategy is extended to mixed traffic conditions where CAVs and HDVs coexist. To accommodate uncertainties related to HDVs, the extended strategy introduces flexible decision mechanisms for the formation of merging platoon and the appointment of mainline facilitating vehicles. The decision mechanisms ensure that CAVs take the roles of platoon leader and facilitating vehicle to implement the coordination requests, and HDVs are indirectly incorporated in the coordination by obeying regular car-following rules. The extended mixed strategy is formulated as a bi-level coordination problem. The macro-level takes traffic state parameters as inputs and uses optimization methods for coordination decisions, and the micro-level adjust coordination decisions in each merging cycle in accordance with real-time traffic operation. The case study shows that the extended strategy for mixed traffic improves overall merging efficiency, stabilizes traffic operation, and increases merging throughput at freeway on-ramps, especially under high CAV penetration rates.
- In view of the third research gap, a safety investigation approach, including a new merging conflict index CMH and a merging conflict model, is developed to assess the safety impacts of CAVs at freeway on-ramps. The investigation focuses on CAV's ability to eliminate critical human factors in the merging process. Data-driven probabilistic distributions and Monte-Carlo methods are applied in the investigation to account for real-world uncertainties and variations. The results show that CAVs have the potential to reduce critical merging events by eliminating aggressive driving patterns related to human drivers, on the conditions that the autonomous driving systems function properly with reasonable settings of driving pattern parameters.

The works in this dissertation have the potential to aid to the current engineering practice in the following aspects:

- The developed CoMC strategy and its extensions, which are expected to substantially improve ramp merging operation in various contexts, are readily integrated into the traffic management practice. The implementation of CoMC does not require reconstructions of roadway infrastructures or installations of additional control devices other than those required for CAV operation. In addition, the CoMC models use macroscopic traffic state parameters as inputs, which are relatively stable over time. Therefore, when implemented in real-time, the CoMC decisions can be updated at

longer intervals (e.g., 5 or 10 minutes or even longer), requiring less computational efforts from the traffic management system.

- The CoMC strategy has the potential to influence infrastructure design in on-ramp merging areas. As one of the main purposes of CoMC is to create readily available gaps for on-ramp vehicles, most ramp vehicles merge into the main road from the front part of the acceleration lane under CoMC. Therefore, the acceleration lane can be shortened to save space in the on-ramp merging areas when CoMC is applied.
- The CMH index introduced in Chapter 7 is a significant supplement to the prevailing safety surrogate measures, as it makes up for the limitations of existing measures in capturing ramp merging conflicts. The CMH index can be applied to a variety of situations where merging safety is assessed, such as for CAVs and HDVs, for cooperative and non-cooperative merging, and for research and engineering practice.

7.2 Future Research Topics

This dissertation deepens the understanding of CAV operation in freeway on-ramp merging areas and, in the meantime, sets the foundation for follow-up works. Based on the results of this dissertation, future works can focus on refining and further extending the developed methods and reporting more analysis results:

- As indicated in Chapter 4, the multi-lane coordination strategy can be further improved by planning cooperative lane-changes between mainstream lanes. For example, the proportion of vehicles changing from the outer lane to the inner lanes, or more specifically, the exact vehicles to change lanes, can be determined according to real-time traffic conditions to facilitate the overall traffic flow performance at ramp merging. However, the coordination should ensure that the cooperative lane-changes are conducted without breaking the stability of upstream mainline traffic.
- Furthermore, there is a potential to expand the coordination to the more complex context of multi-lane freeways with mixed CAV-HDV traffic flow. In such a context, the coordination should take into account the free lane changing behaviors of HDVs. A potential solution is to integrate rules and recommendations for HDV lane-change decisions into the coordination.
- The impacts of the proposed coordination strategy shall be further investigated in terms of merging safety, energy use, and emission. As the coordination creates readily available mainline gaps for ramp merging vehicles, it is expected to reduce conflicts between the mainline and ramp traffic. Further, the coordination stabilizes traffic operation and reduces stop-and-go in the on-ramp merging area, leading to potential improvements in energy use and emission. These impacts should be measured quantitatively with a thorough discussion on the factors influencing the coordination performance.
- The developed merging conflict index, CMH, shall be further investigated. For example, the efficiency of CMH can be benchmarked with existing safety surrogate measures, such as TTC and PET, preferably with empirical data on actual crashes

observed in the field. In addition, the potential of CMH to be transferred to safety investigations in the other lane-changing cases (e.g., overtaking, merging into a platoon, and merging at lane reduction) is worth being discussed.

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