Ph.D. Dissertation of Engineering

# PID-Based Freeway Work Zone Traffic Control with Short-Term Traffic State Prediction under Mixed Traffic Flow of CAV and MV

## CAV와 MV 혼합류에서 단기 교통류 예측을 활용한 PID 기반의 고속도로 공사구간 교통제어

February of 2023


Graduate School of Engineering
Seoul National University
Civil & Environmental Engineering Major

Sunho Kim

# PID-Based Freeway Work Zone Traffic Control with Short-Term Traffic State Prediction under Mixed Traffic Flow of CAV and MV

Chungwon Lee

Submitting a Ph.D. Dissertation of Engineering

December 2022

Graduate School of Engineering
Seoul National University
Civil & Environmental Engineering Major

Sunho Kim

Confirming the Ph.D. Dissertation written by
Sunho Kim
January 2023

| | | |
|---|---|---|
| Chair | 김　동　규 | (Seal) |
| Vice Chair | 이　청　원 | (Seal) |
| Examiner | 고　승　영 | (Seal) |
| Examiner | 김　도　경 | (Seal) |
| Examiner | 김　영　호 | (Seal) |

# Abstract

During road work, lane closure is a primary reason for the reduction in road capacity. Merging of vehicles from the queue in closed work zone lane to the neighboring lane may cause congestion to worsen. This study proposes a freeway work zone traffic control to relieve congestion and improve flow efficiency in mixed flow with connected automated vehicles (CAV). To resolve the problem, a new work zone traffic control consists of Merge control and Speed control. A short-term prediction model and a Proportional-Integral-Derivative (PID) controller are applied to Merge control for work zones. The merge control determines the traffic state through the predicted density of open lanes at each segment, and can flexibly respond to the traffic situation by determining "Merge" or "No merge". When "Merge" is determined at a segment, the proper number of merging vehicles is estimated through PID control using the threshold of severely congestion as the target value. The purpose of Speed control is to provide a sufficient vehicle gap to merging vehicles through "Slow down" or "No speed limit" control depending on the predicted density of open lanes for upstream vehicles. The effect of the proposed work zone traffic control was analyzed by implementing a calibrated real world network under mixed traffic flow of CAVs and manual vehicles using a microscopic simulation tool. Simulation results show that work zone traffic control improves the merging behavior of work zone vehicles. First of all, the number of merging vehicles concentrated near the work zone has been dispersed upstream. Additionally, the ratio of vehicles with low merging speed decreased, and the density of open lanes maintained below the threshold causing severe congestion. As a result, the proposed work zone traffic control improved the operational efficiency, safety, and environmental indices of the work zone by providing the number of merging vehicles and the speed limit value suitable for the traffic situation.

**Keyword :** Work zone, Traffic control, Traffic Prediction, Connected automated vehicle, Merge control, Speed control
**Student Number :** 2015-22919

# Table of Contents

# List of Tables

# List of Figures

# Chapter 1. Introduction

## 1.1. Study Background

Road work is defined as any activity carried out on the road for maintenance and repair purposes. Most freeway road work is a lane closure type as a short−term work. A typical form of short−term road work is gradual lane closure as shown in Figure 1.1. These short−term works consist of lane closure signs and rubber cones.

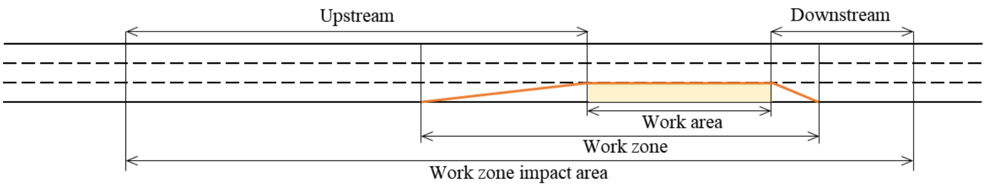



Figure 1.1 Layout of a typical freeway road work with lane closure

In short−term road work of less than one day, lane closure or shift is a primary reason that road capacity decreases. Road work also makes the section vulnerable to congestion and formation of queues especially in closed lane (Ren et al., 2020; Tympakianaki et al., 2014; Ullman et al., 2014; Radwan et al., 2011; Yang et al., 2009; Pesti et al., 2008). During the road work, traffic flow conditions can sensitively change with demands. Notably, the number of merging maneuvers concentrate on the right upstream point of the work zone and are conducted with a significantly low speed (Yang et al., 2009; Pesti et al., 2008). Some drivers in the queue also try to merge aggressively into the neighboring lane, even though they do not approach the work zone yet. These aggressive merges intensify turbulence which negatively affects traffic flow, causing to worse congestion (Tympakianaki et al., 2014; Tarko et al., 1998).

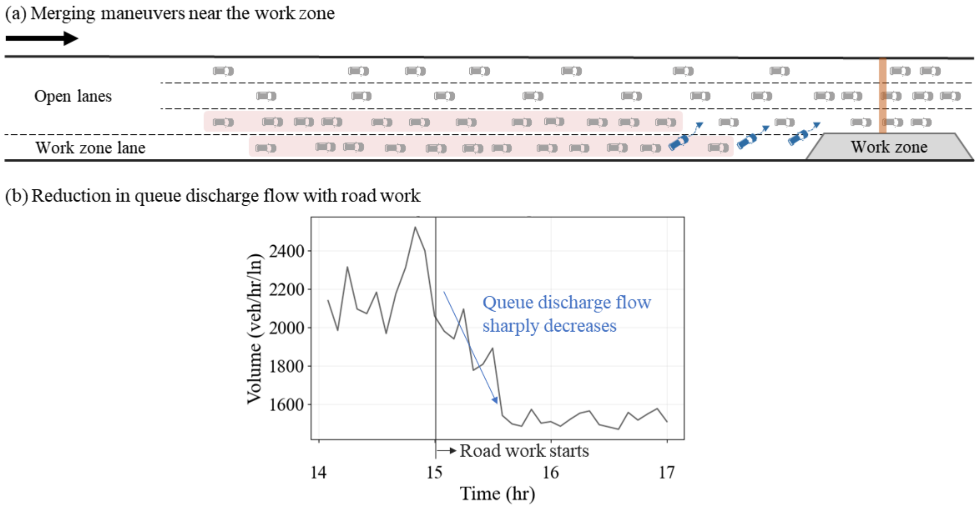



Figure 1.2 Flow characteristics at the work zone

Therefore, traffic management strategies have been proposed and operated to relieve the negative impact of merging and to improve the operational efficiency and safety of roads during the road work. The US Federal Highway Administration (FHWA) provides Smarter Work Zones program including various traffic management strategies for work zones. The manual includes real-time provision of driver information, queue warnings, incident management, merge control, and speed control.

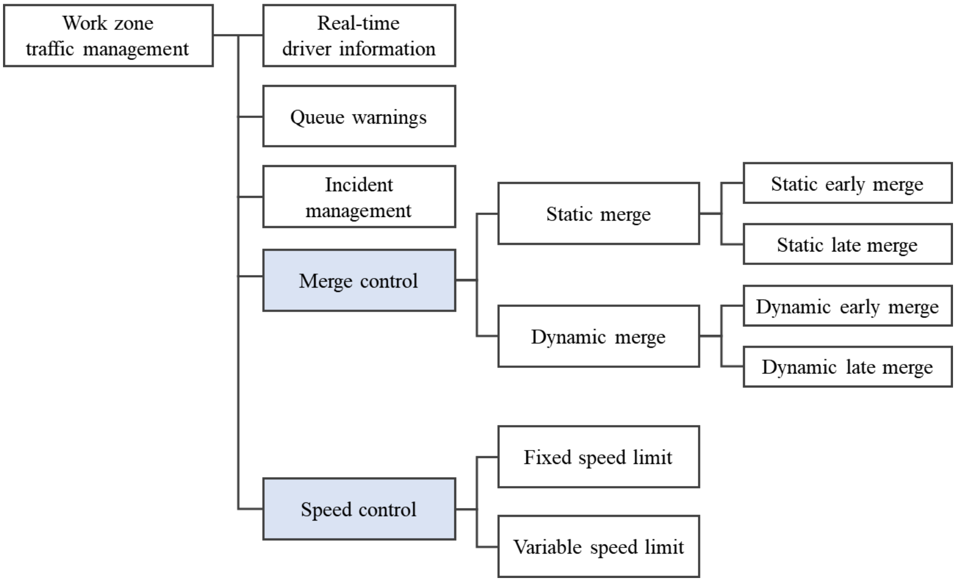


Figure 1.3 Classification of conventional work zone traffic management

Various Department of Transportation (DOTs) have operated work zone traffic management to improve traffic operational efficiency. Most existing work zone traffic management belong to two categories: merge control and speed control. Merge control displays proper merging messages at several predetermined points directing drivers to effectively use road capacity. Speed control regulates the speed of approaching vehicles in order to minimize the shockwave impacts due to lane closure.

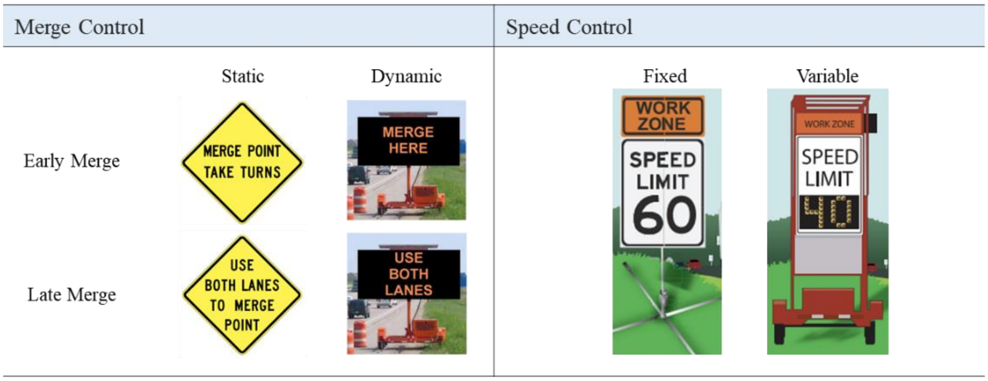



Figure 1.4 Typical road signs for merge control and speed control in work zones

Notably, merge control has been applied to relieve congestion by various DOTs such as those of Kansas, Maryland, and Indiana (Meyer et al., 2004; McCoy et al., 2001). Merge control can be classified into static merge and dynamic merge. Static merge guides merging by fixed sign at predetermined points. Road operators can operate static merge simply, but cannot respond to changes in traffic condition. Dynamic merge implements ‘on’ or ‘off’ merging signs for different work zone types and volume levels. Dynamic merge can be operated in response to demand, but requires proper threshold for each traffic condition. Especially, dynamic merge cannot determine an appropriate merging strategy for the transition period (i.e. congestion↔recovery). Merge control is also divided into early merge and late merge depending on the location of merging guidance.

The merge control recommends early merge or late merge using road work sings or merge guide signs based on the time of day and road conditions and therefore adjusts the merge point. In case of early merge, road operators provide the information of the work zone and lane changing guidance to drivers so that they can merge in advance at the upstream segment before joining the queue. Several DOTs reported that the early merge strategy can improve traffic efficiency in light traffic conditions (Yang et al., 2009; McCoy et al., 2001), although the effect varies depending on the drivers' ability and compliance (Ge and Menedez, 2013; McCoy et al., 2001). In late merge strategy case, on the other hand, road operators guide drivers in the work zone lane (i.e. closed lane) to maintain their lanes and to merge immediately before the work zone so as to fully use capacity of the work zone lane. This merge strategy is beneficial for bottleneck discharge flow rate when the road is lightly congested, since it reduces turbulence by concentrating merging maneuvers (Taavola et al., 2004; Walters et al., 2000).

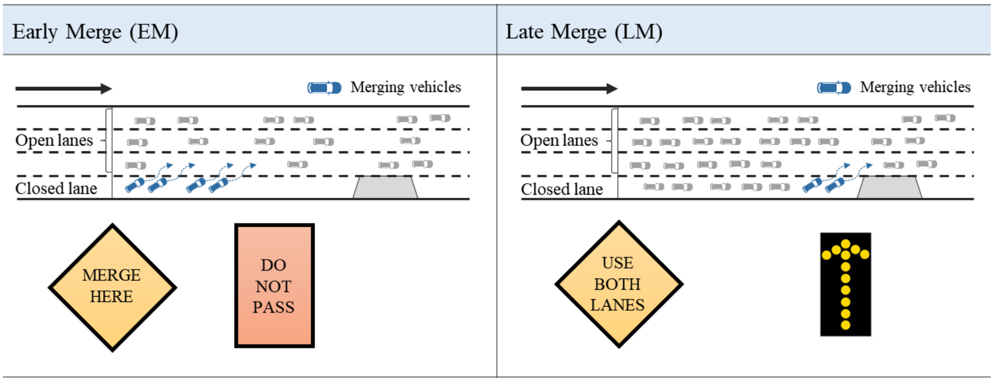


Figure 1.5 Typical road signs for early merge and late merge

Although those strategies can improve traffic performance by adjusting merge points, it is not possible to guide merges at a specific point only for the proper number of vehicles with consideration of traffic conditions. Therefore, the first issue is how to operate appropriate merge control according to the traffic situation that changes over time. Also, the second issue is how to operate merge control in the space located between the points that guide early merge and late merge.

Speed control is classified into fixed speed limit and variable speed limit based on the operation method. Fixed speed limit posts the predefined speed limits constantly. It can be operated simply, but cannot respond to varying traffic condition. Variable speed limit posts the changeable speed limits with consideration of traffic condition. It operated with responding to the downstream condition, but may occur additional bottleneck. Conventional speed controls focus on smoothing outflow of open lanes. However, since the merge of the work zone lane is a mandatory lane change, it is important to guide a smooth merge through speed control.

In connected and automated vehicles (CAVs) environment, a traffic management center can provide guidance to specifically targeted vehicles. CAVs are vehicles that can automatically perform acceleration, deceleration, and steering, and can communicate not only with surrounding vehicles but also with the management center (Shladover et al., 2014). Various studies have reported CAVs to utilize shorter gap distances than manual vehicles (MVs) and that the connectivity can improve operational performance and safety of traffic flow (Ghiasi et al., 2017; Talebpour et al., 2016; Shladover et al., 2014). Shladover et al. (2014) suggested that average time headway could be reduced from the 1.4 seconds of MVs to 0.6 seconds by receiving preceding vehicle speed information through vehicle-to-vehicle communication. In other words, CAVs can receive traffic information, and more vehicles can be accommodated per unit length compared to MVs. Therefore, the adoption of CAVs is expected to increase road capacity and prevent or relieve congestion. Due to the distinct features of CAVs, including wireless communication with infrastructure (vehicle-to-infrastructure, V2I), several studies have proposed traffic management strategies specifically for CAV environments (Ren et al., 2020; Ghiasi et al., 2017; Xie et al., 2017). Their findings suggest that at work zones, despite the unavoidable reduction in road capacity due to lane closures, reduction in operability can be effectively prevented by operating a traffic management strategy based on CAVs.

During road work, traffic flow conditions can sensitively change with demands, since road capacity is reduced; thus, the work zone management strategy should be able to respond promptly and efficiently in the event of a sudden change, such as the occurrence and worsening of congestion. When using only current traffic flow information for work zone management, it is difficult to respond immediately to sudden changes. Using a traffic state prediction model can address this limitation, allowing traffic management to effectively confront various road condition changes. Traffic state predictions aim to forecast the future flow state, either long-tem or short-term, using past and present flow data. Machine learning is effective for analyzing a large amount of information, such as the trajectory and aggregated traffic flow data generated by vehicles. One commonly used method is a neural network composed of two or more hidden layers, termed a Deep Neural Network (DNN); an extension of DNNs, the Recurrent Neural Network (RNN), is mainly used to analyze or predict time dependent sequential data (Gao et al., 2020). Cho et al. (2014) developed the Gated Recurrent Units (GRU) algorithm, which consists of a single hidden state vector that also fills the role of cell state. GRU is an appropriate method for situations where the influencing factors are complex and multiple, since some of the past state variables are selected and considered in order to increase predictive accuracy. Traffic state prediction is affected not only by past information but also by upstream and downstream traffic conditions, hence the GRU method is well-suited to improving the accuracy of traffic state prediction.

Drivers approaching the work zone try to merge from the time they recognize the work guide or merge guide signs installed as part of merge management. The number of merging vehicles is dependent on drivers' compliance; thus, adjusting the merge number is practically impossible in MVs environment. If an excessive number of merges are conducted at a specific point, severe turbulence and severely congestion may occur in open lanes flow (Tarko et al., 1998). Since the control of individual vehicles will be available using

CAVs, the merge number can be used as a control measure and should be determined not to hinder the flow in open lanes. Setting and regulating control measures in accordance with traffic management goals are important aspects of traffic management. Accordingly, estimating an optimal control value is one of the main focuses of recent traffic research. One feedback control methodology widely used in control engineering research is Proportional-Integral-Differential (PID) control, which calculates and considers the error between the current state value and the desired target value (set point). This logic has also seen use in traffic management research in recent years (Roncoli et al., 2017; Carlson et al., 2013).

## 1.2. Purpose of Research

This is the problem statement of this study organized according to the issues.

1. How to dynamically operate the controls in response to traffic conditions even in the transition period?
2. What if drivers are guided to multiple merge points and some of them merge at each point?
3. How to smooth both merging maneuvers and outflow of open lanes with speed control?
4. How to integrate merge control with speed control to improve traffic operational efficiency?

This study aims to propose a work zone traffic control consists of Merge control and Speed control. Work zone traffic control prevents heavy congestion and improves flow efficiency during road work situations in mixed flow with CAV and MV. The proposed strategy combines short-term traffic state prediction and PID-based merge number calculation. Short-term traffic state prediction forecasts the density of control segments and uses the predicted densities to determine whether to encourage or suppress merging and speed limit. PID-based merge number estimation calculates the proper number of merging vehicles for each control segment. As a case study, this study examines the proposed merge control using microsimulation on a calibrated real-world network in which road work was being conducted for various mixed traffic flow scenarios. Finally, The detailed purpose of this study.

1. Developing a short-term traffic prediction model for proactive control
2. Applying PID control for determining proper amount of merge
3. Slowing down to reserve adequate gap for merging vehicles
4. Combining Merge control and Speed control
5. Implementing the proposed control using microsimulation for a calibrated real-world network
6. Evaluating the effect of the proposed control for various mixed traffic flow scenarios

The scope of this study is dynamic early merge, dynamic late merge, and variable speed limit among work zone traffic management.

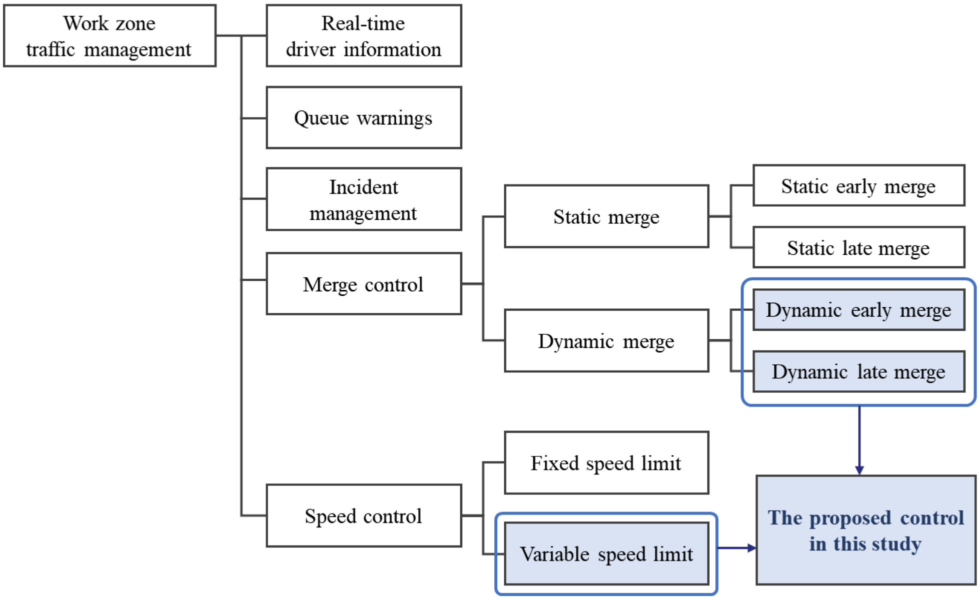



Figure 1.6 Research scope in this study

The remainder of the paper is organized as follows: Chapter 2 provides an overview of previous studies. Chapter 3 describes the density prediction using a GRU model, number estimation of merging vehicles with PID control, and speed limit control value. Chapter 4 presents the experimental design for simulation case study, Chapter 5 shows the results of the investigation into improving flow efficiency, safety, environmental index through the proposed work zone traffic control. Section 6 concludes the article.

# Chapter 2. Literature Review

## 2.1. Merge control for work zones

FHWA guides Smarter Work Zones for work zone traffic control and provides the Work Zone Intelligent Transportation Systems Implementation Guide, which lays out operational guidelines for merge control (Ullman et al., 2014). Work zone merge control includes both static and dynamic methods. Static merge control guides early or late merges in a specified time-space range regardless of traffic conditions. Such methods can be simply implemented in the real world and are effective at improving road efficiency and safety (Saha and Sisiopiku, 2020; Ge and Menedez, 2013; Pesti et al., 2008; Taavola et al., 2004; Walters et al., 2000). Saha and Sisiopiku (2020) operated static early and late merge methods according to traffic volume by time step, and investigated their effects on the improvement of average travel time. However, static merge control cannot respond sufficiently to sudden traffic demand changes, and historical work zone data is not generally available for short-term road work. Dynamic merge control (DMC) operates both early and late merge in accordance with the traffic situation, or dynamically adjusts the merge point (Yang et al., 2009; Taavola et al., 2004; McCoy et al., 2001). DMC can effectively respond to fluctuations in demand and thereby congestion and delay (Radwan et al., 2011; Yang et al., 2009; Kang et al., 2006; McCoy et al., 2001), thus it has been the mainstream focus of research in freeway work zone control in recent years. Beacher et al. (2004) compared the performance of late merge and conventional merge using simulation. Conventional and late merge systems were investigated under different traffic demand, heavy vehicle percentage, lane closure configurations. The results indicated that the use of late merge is required in the case of a 2-to-1 and 3-to-1 work zone configuration. Combining conventional merge and dynamic late merge based on the traffic conditions, a further study showed when demand level is low, the speed is relatively high and late merge may cause confusion to the drivers. Therefore, the study suggested using conventional merge in non-peak and changing into late merge during on-peak (McCoy et al., 2001). However, merge guidance through roadside signs or portable changeable message signs can only instruct drivers to merge at a fixed installation point. In addition, static merge control can be applied simply but not respond to sudden traffic demand changes. Also, Dynamic merge control can respond to traffic conditions but cannot be properly operated in transition period.

Table 2.1 Research on merge control in State−of−the−Practice

| Research | Methodology | Results |
|---|---|---|
| Beacher et al. (2004) | Static late merge | Bottleneck throughput↑ (6.6% ~ 9.9%) |
| Taavola et al. (2004) | Dynamic late merge (Threshold : Traffic volume) | Queue length↓ (35%) |
| Kang et al. (2006) | Dynamic late merge (Threshold : Occupancy) | Bottleneck throughput↑ (6.8% ~ 11%) |
| Yang et al. (2009) | Dynamic late merge with signal (Threshold : Occupancy) | Bottleneck throughput↑ (11% ~ 28%)<br>Number of stops↓ (10% ~ 57%) |
| Ge and Menendez (2013) | Static early and late merge | Bottleneck throughput↑ (5.6% ~ 6.6%)<br>Queue length↓ (35%) |
| Saha et al. (2020) | Static early and late merge | Bottleneck throughput↑ (40%) |

Traffic management in CAVs environment is one of the major research topics. Karimi et al. (2020) observed both congestion and environmental improvement with calculation of condition for specific merge numbers through Model Predictive Control under a CAV environment with 100% compliance. However, when it comes to work zones, the traffic conditions upstream, which is to say in the section where merge control is applied, may change depending on time and space. Recent DMC studies did not divide the upstream stretch into multiple segments, and hence did not consider the possibility of different situations in different upstream segments. Some studies instruct smooth merges by controlling individual CAVs; for example, Ren et al. (2020) guided smooth merging by controlling the acceleration of merging CAVs so that the lateral positions of several CAVs in open lanes and the work zone lane do not overlap. Ding et al. (2020) similarly controlled the speed of merging vehicles by calculating the distances to leading and following vehicles at the initiation of merging behavior. However, controlling each vehicle unit requires a substantial amount of calculation be conducted in a short period, and it is not realistically appropriate for work zone control without enforcement that controls each vehicle over a long distance and ignores the autonomy of individual drivers. Instead, it is realistic to improve DMC with subdivided segments and through future applicable transportation infrastructure and the latest control algorithm. Due to the nature of the work zone flow, which is sensitive to changing traffic conditions, there is a limit to appropriate merge guidance with only current information. Therefore, this study estimates an appropriate number of merging vehicles at several merge points. In addition, traffic state prediction is used to flexibly respond to changes in traffic conditions.

Table 2.2 Research on merge control in State−of−the−Art

| Research | Vehicle Type | Methodology | Results |
|---|---|---|---|
| Wei et al. (2010) | MV | Dynamic late merge with full−connectivity<br>Rule−based control (Threshold : volume) | Average travel time↓ (11%)<br>Bottleneck throughput↑ (21%) |
| Radwan et al. (2011) | MV | Dynamic merge and variable speed limit<br>Rule−based control (Threshold : speed) | Bottleneck throughput↑ (16%) |
| Yuan et al. (2019) | CAV | Signal based merge control<br>Genetic algorithm for maximizing throughput | Bottleneck throughput↑ (34% ~ 48%) |
| Ren et al. (2020) | CAV | Individual merge control with acceleration<br>Positioning for not overlap in the lateral | Average travel time↓ (70% ~ 79%)<br>Bottleneck throughput↑ (19% ~ 48%) |
| This study (2022) | CAV | Dynamic merge determining the proper amount of merge at multiple merge points<br>Short−term traffic state prediction to flexibly respond to rapid change in traffic condition | Average travel time<br>Bottleneck throughput |

## 2.2. Speed control for work zones

Speed control for work zone aims to reduce the speed difference between the work zone and upstream or to control the oncoming inflow. Many studies have conducted effect analysis in the field to review practical effects. Rather than calculating an appropriate speed limit in consideration of road efficiency, the focus is on deceleration induction considering the driver's compliance rate for the purpose of securing safety. Rule based Variable Speed Limits (VSL) are still operated in the field. Migletz et al. (1998) suggested main steps for determining the posted speed limits at work zone and investigated field evaluation in many sites. In addition, Lin et al. suggested combined VSL with merge control. The VSL can be the most effective way for maximizing the merge control effects because it can dynamically create a smooth environment for merging maneuvers by displaying the optimal speed limits based on detected traffic conditions in advance of the work zone. Kuhn et al. evaluated Texas DoT's VSL in many ways such as construction condition, weather condition, and demand condition. Pesti et al. (2008) analyzed the effect with speed advisory sign control. The study suggested reducing the average speed of vehicles approaching the work zones. Jura et al. provided a portable and dynamic system that was easy for construction personnel to use to prudently reduce speeds within an active work space and make construction work zones safer for workers and the traveling public, while limiting the need to reduce speed throughout the AWS, rather than the entire construction work zone.

Table 2.3 Research on speed control in State–of–the–Practice

| Research | Methodology | Performance Indices |
|---|---|---|
| Migletz et al. (1999) | Rule based variable speed limit (Field evaluation) | Spillbacks prevention<br>Stop–and–go reduction |
| Kwon et al. (2007) | Rule based variable speed limit (Field evaluation) | Bottleneck throughput↑ (2% ~ 7%) |
| Kuhn et al. (2015) | Rule based variable speed limit (Field evaluation) | Bottleneck throughput↑ (6%)<br>Crash severity |
| Jura et al. (2018) | Rule based variable speed limit (Field evaluation) | Average speed↑ (5%) |

Several studies are actively under way to improve speed control. Most studies limit speed to control traffic approaching bottlenecks for purposes of congestion and queue suppression. Lyles et al. (2004) implemented a VSL system on the I–96 work zones, and evaluated its impacts on traffic flow and safety. The study concluded that the average speed of motorists appeared to increase, and the travel time seemed to decrease but unlikely to be noticed by the average travelers. Both the average speed and occupancy were used as the control thresholds for displaying the set of speed limits. Yang et al. (2017) suggested multiple VSLs at the upstream part of the bottleneck section that is divided into several segments. The speed control for each segment is operated at an optimal speed, resulting in higher road efficiency than single speed control. The study predicted the traffic state and to determine the optimal speed limits to smooth speed transition. Shuming et al. (2019) developed equilibrium state–oriented discrete time sliding mode control based

VSL. The study implements nonlinear flow model using Cell Transmission Model (CTM) in SUMO. The speed control in this study provides a sufficient gap considering merging vehicles.

Table 2.4 Research on speed control in State−of−the−Art

| Research | Vehicle Type | Methodology | Performance Indices |
|---|---|---|---|
| Lyles et al. (2004) | CAV | Variable speed limit<br>Threshold: speed, occupancy | Average travel time↓ (10%)<br>Minimum safety distance |
| Lin et al. (2004) | CAV | Variable speed limit for regulating inflow<br>Speed limit value for target inflow which is coincident with outflow | Bottleneck throughput↑ (16%)<br>Speed variance |
| Yang et al. (2009) | MV | Multiple variable speed limit with | Speed variance↓<br>Safety effects |
| Shuming et al. (2019) | CAV | Variable speed limit for equilibrium state using discrete−time sliding model | Average travel time↓ (17%)<br>Environmental effects |
| This study (2022) | CAV | Variable speed limit to reserve gap for merging vehicles | Average travel time<br>Bottleneck throughput |

## 2.3. Traffic flow prediction

Work zone traffic control that considers only the current traffic state cannot respond adequately to rapidly changing traffic flow. Therefore, it is necessary to apply traffic state prediction. Dougherty and Cobbett (1997) used Multi Layer Perceptions (MLP) with VDS data from freeway. The study suggested about 24% in RMSE for the flow and 23% in RMSE for the occupancy applying 15 minutes prediction interval. Chen and Chien (2001) utilized Artificial intelligence Neural Network (ANN) more accurate prediction accuracy from path based than link based approach with automatic identification data in the recurrent congested condition. The author reported MARE as 1.1% ~ 7.3% in path based and 2.1% ~ 9.2% in link based prediction. Jia et al. (2017) predicted traffic flow change due to rainfall using a RNN-type Long Short-Term Memory model with consideration of large scale traffic data and the complex relationships among factors. Elfar et al. (2018) reported that congestion patterns can be predicted from individual vehicle data more accurately in a connected environment than when using conventional aggregated data. The results also supported that leveraging connectivity in traffic control systems can contribute to road efficiency and safety. Hajbabaie et al. (2015) produced Free-flow Speed (FFS) model on a freeway work zone based on multi state sensor data. The model predicts FFS using variables such as the speed limit ratio between non-work zone and work zone conditions, the posted work zone speed limit, lane closure severity index, barrier type, day or night condition, and the total number of ramps in the vicinity.

## 2.4. Control logic for work zone traffic control

In recent years, many studies have determined the optimal control values for targeted traffic states in various traffic conditions. Carlson et al. (2013) utilized a variable speed limit to control mainline demand in a highway section subject to recurrently congested area. In order to estimate an appropriate speed limit value, the target flow corresponding to congestion recovery was set as a target value and applied via PI control. Roncoli et al. (2017) implemented feedback control that distributed density to maximize throughput at a bottleneck area. Both studies regulated the control measure according to the target value corresponding to a desired traffic state. Such accurate feedback control is able to prevent excessive control and make drivers use road storage fully.

## 2.5. Differentiation from existing research

Nonetheless, DMC strategies still base a predetermined single merging point regardless of the traffic situation. However, it would be more effective to relocate the merging points responding to the traffic state because there may be spatial and temporal variations in the traffic state along the work zone impact area. This study develops a work zone Merge control that dynamically determines the merging points. A short-term traffic state prediction model and a Proportional-Integral-Derivative (PID) controller are applied to respond to the change in traffic state and the control error. Combined control is composed for Merge control and Speed control to smooth the mandatory merges.

Table 2.5 Summary of Merge and Speed Control Strategies

| Strategy | | Decision | | | Decision based |
|---|---|---|---|---|---|
| | | Merge point | Merge amount | Speed Limit | |
| Merge control | Static Early Merge | - | - | - | Predefined rule |
| | Dynamic Early Merge | O | - | - | Current traffic state |
| | Static Late Merge | - | - | - | Predefined rule |
| | Dynamic Merge | O | - | - | Current traffic state |
| Speed control | Fixed Speed Limit | - | - | O | Predefined rule |
| | Variable Speed Limit | - | - | O | Current traffic state |
| The control in this study | | O | O | O | Predicted traffic state |

# Chapter 3. Work Zone Traffic Control

## 3.1. Framework for work zone traffic control

When vehicles merge from queues in the work zone lane, they create voids in the neighboring lane due to low insertion speed, and heavy congestion occurs at the work zone (Hall and Agyemang−Duah, 1991). Dispersing concentrated merge points and guiding merge before the vehicles join the queue in accordance with the traffic condition can reduce such impact of aggressive merges. By proactively deciding on a merge strategy based on the predicted traffic state, the efficiency of merge management can be improved. In addition, reducing density near the bottleneck can relieve heavy congestion, and while maintaining density below a certain value can even prevent it (Chung et al., 2007). As a parameter, density has the advantage of inherently representing changes in traffic flow, considered in the target number of merging vehicles calculated at a given time point by the Merge control algorithm. Therefore, the proposed merge control uses density as a control measure to relieve heavy congestion caused by road work.

The proposed work zone traffic control consists of Merge control and Speed control for CAVs. The proposed control aims to improve operational efficiency by smoothing merge. Merge control decides the proper amount of merging vehicles at each point. Speed control reserves gap for merging vehicles. Merge control and Speed control (i) predicts the traffic flow of control segments located upstream of the work zone in a short−term period, and (ii) calculates the appropriate control value.

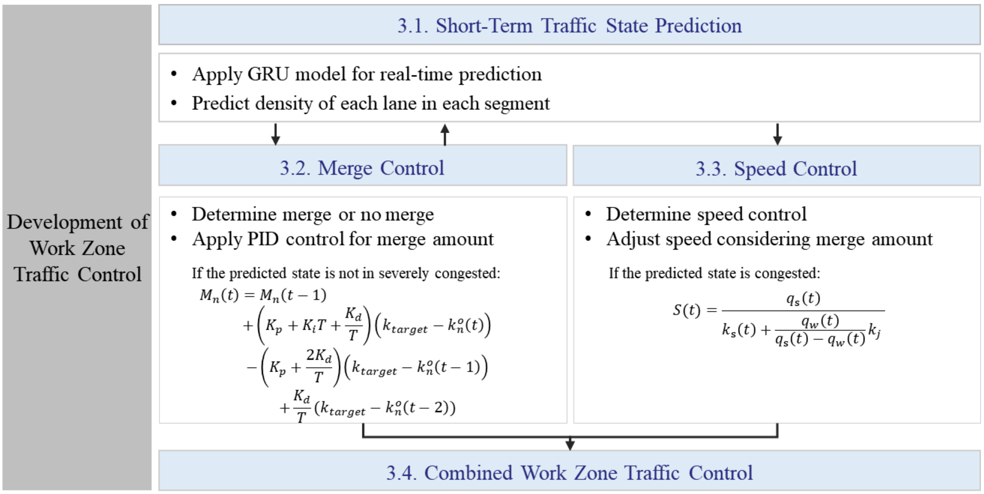


Figure 3.1 Framework of the proposed work zone traffic control

Figure 3.2 shows that the optimal strategy varies depending on the traffic condition. In first example, it is determined that it is difficult to merge in the upstream part due to congested road conditions, and merge is guided in segment 1, which is the section immediately before the work zone. It is to perform control similar to late merge.
In the case of the second example, merge is guided in all upstream segments due to overall smooth traffic conditions. It is to perform control similar to early merge.
Finally, the optimal strategy varies depending on the traffic condition. The negative impact of concentrated merges can be relieved by operating early merge in light congestion. Vehicles on the neighboring lane of the work zone lane slow down to reserve a gap for merging vehicles.
The third case is an example that explains the change in the traffic situation in the upper part of the work zone. At step t, merge is guided in segment 1 and segment 3, and no merge is guided in segment 2. Due to Merge control, traffic conditions for each upstream segment may change in the next time step. The density of each segment rapidly changes according to the upcoming flow and the amount of merge. Vehicles get guidance at time $t$, but merge at time $t+\Delta t$ → predicting the traffic state of time $t+\Delta t$ is needed. Therefore, prediction is necessary to determine whether or not the merge is

appropriate at the next time step.

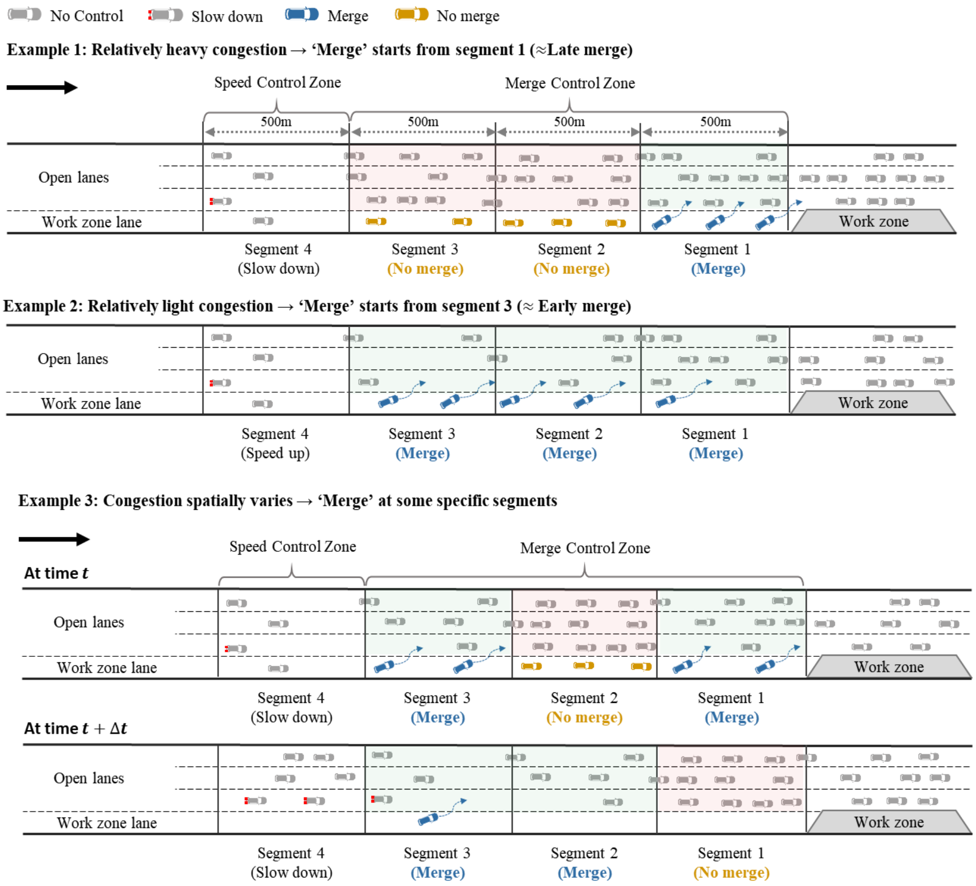



Figure 3.2 Concept of the proposed work zone traffic control

## 3.2. Traffic state prediction

Traffic flow has nonlinear and stochastic nature. There is limit for conventional models (i.e. regression, ARIMA). The proposed merge control responds flexibly to the dynamic state of the traffic system through short-term traffic state prediction. Specifically, flow is predicted for each lane in each upstream segment of the work zone. Traffic flow as represented by lane units has complexity affected by the states of the upstream, downstream, and adjacent lanes in the previous time step.

Among the deep learning prediction models of the RNN series, GRU is appropriate when influencing factors are complex and numerous, and moreover selects some past state variables and considers their ability to increase predictive accuracy. Accordingly, this study applies a GRU model to predict traffic flow in adjacent segments and lanes and decide the target traffic condition of the next time step. Figure 3.3 depicts the composition of the GRU model for predicting segment-lane density.

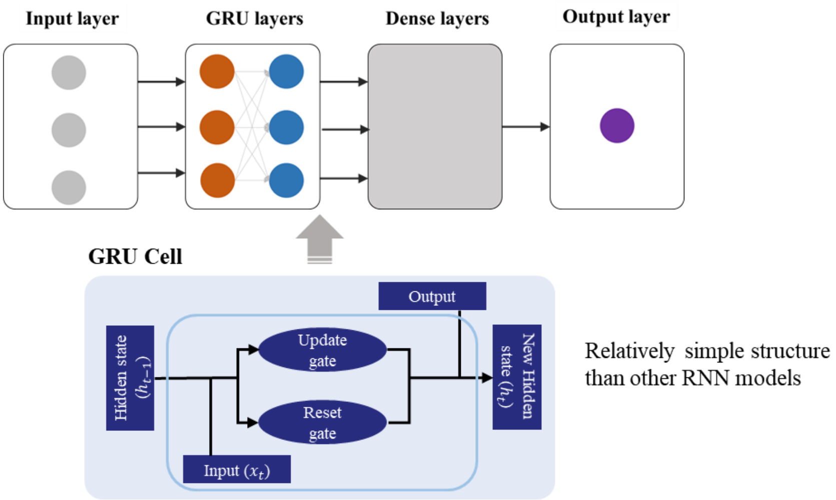



Figure 3.3 GRU model structure

Input nodes in the input layer consist of time series data on traffic volume, speed, and the density of upstream to downstream segments at each time step, which are used to predict the density of each segment−lane through the GRU and dense layers. In other words, when the density on segment n is predicted, the input nodes of the GRU model consist of the volume, speed, and density for the upstream segment n+1, for n itself, and for the downstream segment n−1. Then, the predicted density data is transmitted through the output layer. There is assumption that density of all segments is captured by road infrastructure and connectivity environment in this study.

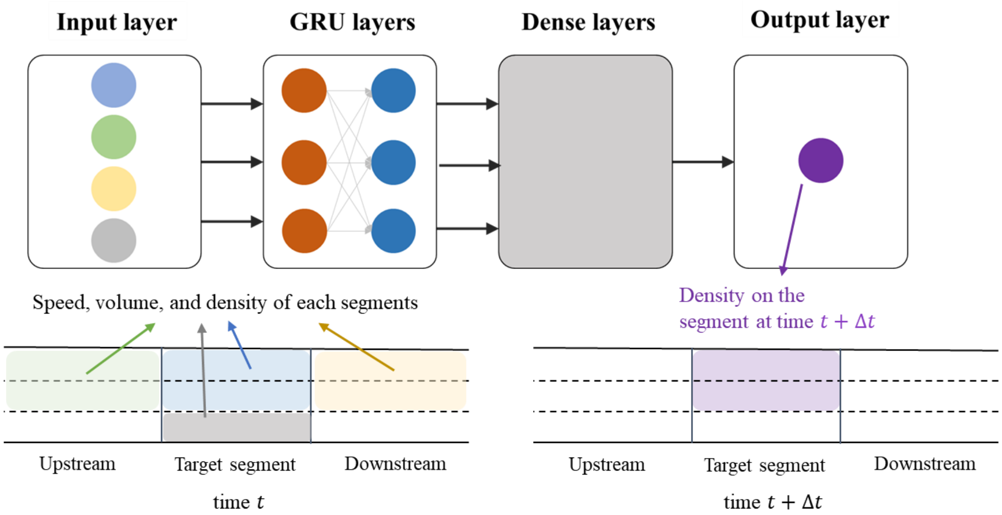



Figure 3.4 GRU Model structure with input and output in this study

When a specific segment is closed due to road work, vehicles can only pass through the work zone by means of open lanes, hence the discharging flow rate of those open lanes becomes the flow rate of the work zone. It is therefore necessary to prevent the open lanes from becoming heavily congested; thus, this study operates two different strategies in accordance with the traffic condition of open lanes, represented as density. The density at which severely congested traffic occurs is the threshold at which discharging flow rate decreases sharply and is used to differentiate light and heavy congestion. Here, which control strategy is operative at a given time is determined by comparing the predicted density with the empirically observed density at which severe congestion occurs. The strategies in question consist of guiding merging (“Merge”) and suppressing merging (“No merge”). “Merge” is adopted for uncongested or light congested states where the predicted density is smaller than the density associated with severe congestion, and “No merge” is adopted for a severely congested state so as to prevent worsening congestion of the open lanes.

## 3.3. Merge control

Merge control aims to relieve the negative impact of merging by dispersing. Figure 3.5 shows that Merge control framework. Merge control consists of merge decision and PID−based merge amount estimation. In the merge decision part, merge or no merge is decided based on the predicted density. In a severely congested state, ‘No merge’. In free−flow and moderately congested states, ‘Merge’. In the PID based merge amount part, an appropriate merge number is calculated.

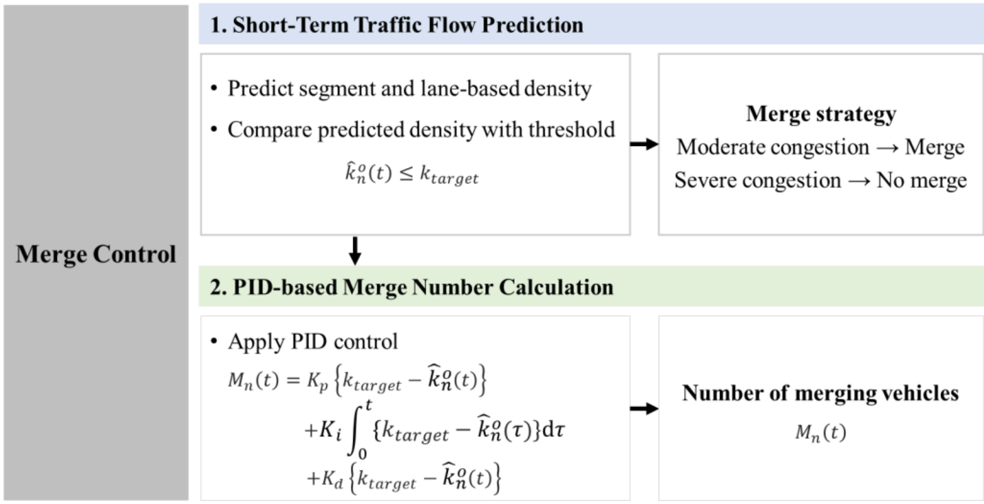


Figure 3.5 Framework of Merge control

Whether to merge or no merge in each segment is determined based on the traffic state at each segment. The figure below shows the traffic state of open lanes. Applying the concept of three−phase model (Bauza et al., 2013), guide merge by a certain level of congestion. Free flow state with green color is the state where there are enough gaps for vehicles to merge. Therefore, it guides vehicles from the work zone lane to merge. On the other hand, the severely congested state with red is the state in which the speed of neighboring vehicles is very low, and it is difficult to merge. Even if the merge is guided, the density of the target lane is high, so it is difficult to actually perform the merge. Therefore, it is decided to no merge the vehicles in the work zone lane. Moderately congested state with yellow means congestion occurs temporarily, but the speed of vehicles is still around 30 to 80 kph, so merge can be guided. In other words, Merge control threshold in this study becomes the boundary value between moderately congested state and severely congested state.

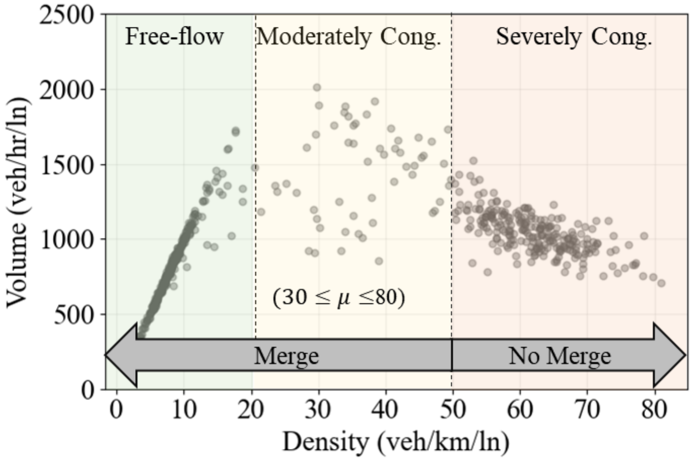



Figure 3.6 Criteria for Merge control

Even when using predicted flow, if the merge situation for each traffic condition on the upstream segment is not considered or if early merge and late merge are operated in the same way (as occurs under existing merge management), excessive merges can deteriorate the flow in open lanes and the overall road network consequently. Therefore, a control logic that changes the control value according to the current traffic situation is required. The table below shows three control logics that are frequently used in traffic management and control.

Table 3.1 Comparison of controllers

| Control | Description | Strengths | Weaknesses |
|---|---|---|---|
| On/Off control | Activate/deactivate according to current value according to target | Enable quick response<br>Simple implementation | Waggle too often |
| Simple feedback control | Estimate a control value according to current error<br>Consider the error between target and current value | Enable quick response<br>Efficient for systems with small changes | Control value and current value are the same(steady state), the target cannot be achieved |
| Proportional–Integral–Derivative (PID) control | Estimate a control value by considering error diversely | Enable quick and accurate response | Request for competence level for gains tuning |

On/Off control is a control method that simply turns on/off the control by comparing the current value with the target value, and is widely used in systems where the change in output by input is not large. Therefore, it is still being used for variable speed limit or merge control in practice due to the advantage of being able to operate simply. However, the On/Off control has a limit in that the activation and deactivation of the control are crossed too frequently. Feedback control is a control system that continuously inputs the current value and updates the control value at each time step.
Simple feedback control is a method of calculating the control value by reflecting the difference between the current value and the target value at each time step. However, when a level similar to the target value is reached, the residual error between the current value and the target value is not considered, so the target may not actually be reached.

Therefore, it needs a factor that determines how much to control by integrating the error over time considering the error in the steady state. In addition, in the case of traffic flow on work zone, where changes are large due to external factors, an element that stabilizes the control system is also required. PID control used in this study considers the error between the current state value and the desired target value in various ways to efficiently control the aforementioned contents.

In a simple loop feedback control, the control value is calculated solely with consideration of present error between the current state variable and control target value; excess action of the controller and remaining error are not considered. In contrast, PID control, which consists of proportional control (P−control), integral control (I−control), and differential control (D−control), calculates the control value while taking into account many types of error such as present error, accumulated error, and the rate of error change, which is the difference between the observed process variable and the target value. This study uses the density causing severe congestion as the target value, and PID control to calculate the number of vehicles to merge from the work zone lane to the neighboring open lane on each segment.

Using the function of CAVs, the road operator can deliver a proper number of merging vehicles determined, and the guided merges will be conducted with a high compliance rate. This study applies practical control logic for determining the proper number of merging vehicles without hindering flow in open lanes flow. Accordingly, when “Merge” is the operative strategy, PID control is activated and estimates the optimal number of merging vehicles by considering the difference between the predicted density of open lanes and the density causing severe congestion.

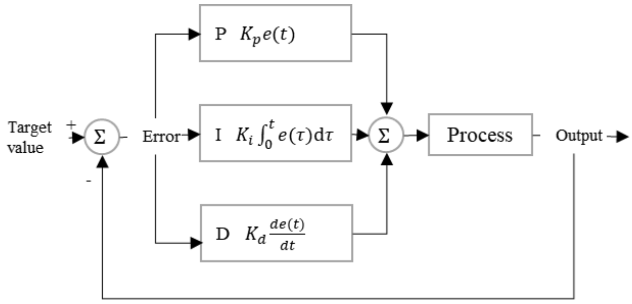


Figure 3.7 PID control algorithm

P−control considers current error and hence considers the error between target density and currently observed density at every time step, enabling determination of the number of merging vehicles needed to rapidly reach the target density. I−control manages the accumulation of residual error for steady state, and also considers the cumulative error over five minutes and any residual merging vehicles, which is not handled in P−control. D−control addresses the rate of error change, which is beneficial in maintaining densities near the target through considering previous and current rates of change in the number of merging vehicles; in particular, it prevents abrupt changes in the number of guided merges.

Table 3.2 Description and application of PID control

| Control | Description |
|---|---|
| P−control | The error between target density and currently observed density at every time step<br>Enables reaching the target density quickly and flexibly |
| I−control | The accumulation of residual error in steady state<br>Enables reaching the target density accurately |
| D−control | The rate of error change<br>Enables immediate response to disturbance on traffic system |

Figure 3.8 illustrates the composition of the PID system for Merge control. Through considering the many types of error $e(t)$ described above, the P, I, and D control modes all operate to

determine the optimal number of merging vehicles, which is then applied to the traffic flow as merge guidance. At each time step, the following control system is activated. In addition, “merge guidance” is delivered first to upstream vehicles, which have relatively more opportunities for merging attempts.

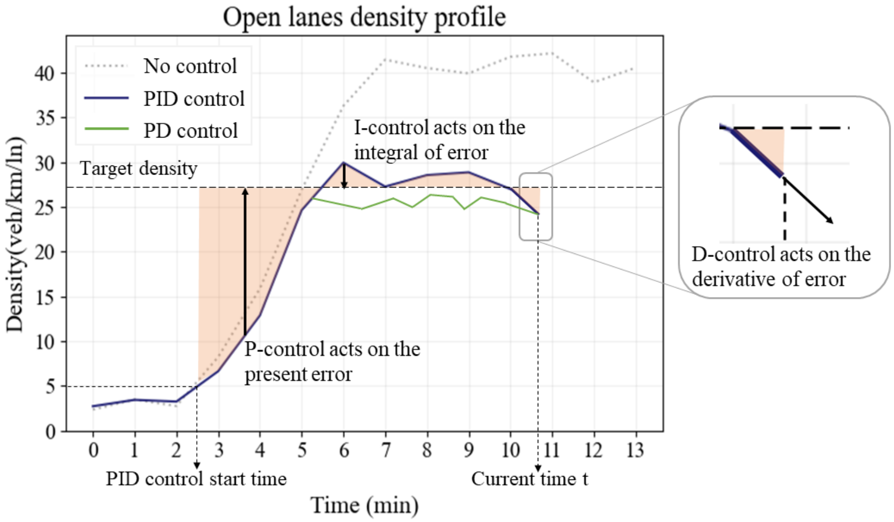



Figure 3.8 Example of PID control for upstream of work zone

The number of vehicles to merge is calculated by the equation governing PID control for each upstream segment of the work zone. It considers the difference between the density threshold and predicted density in open lanes.

$$e_n(t) = \{k_{target} - \hat{k}_n^o(t)\}$$

$$M_n(t) = K_p e_n(t) + K_i \int_0^t e_n(\tau)\mathrm{d}\tau + K_d \frac{de_n(t)}{dt}$$

where, $M_n(t)$ : amount of merging vehicles on segment $n$ at time $t$,
$\mathrm{k_{target}}$ : Control target density (density threshold of severe congestion in this study),
$\hat{k}_n^o(t)$ : Predicted density in open lanes of segment $n$ at time $\mathrm{t}$,
$\mathrm{K_p}$ : Proportional gain, $\mathrm{K_i}$ : Integral gain, $K_d$ : Derivative gain

Discretized time formula for $M_n(t)$ is required in order to implement the PID equation for the number of merging vehicles in simulation.

$$\dot{M}_n(t) = K_p \dot{e}_n(t) + K_i e_n(t) + K_d \ddot{e}_n(t)$$

$$M_n(t) = M_n(t-1) + \left(K_p + K_i T + \frac{K_d}{T}\right)(k_{target} - \hat{k}_n^o(t)) - (K_p + \frac{2K_d}{T})(k_{target} - \hat{k}_n^o(t-1)) + \frac{K_d}{T}(k_{target} - \hat{k}_n^o(t-2))$$

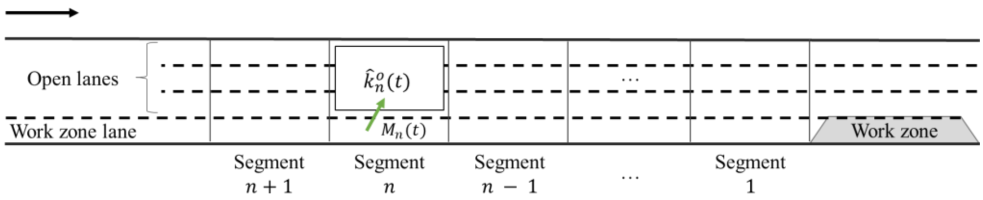



Figure 3.9 Conceptual diagram of Merge control

The merge control developed in this study works with lane closures due to road work. In short, the "Merge" strategy is adopted and PID control is activated when the traffic state prediction model predicts density in the open lanes as being below the level that would guide severe congestion. If traffic demand is low and the open lane density is significantly lower than the target density, PID control would let all vehicles in the work zone lane merge, just as in the early merge strategy of extant merge control (McCoy et al., 2001; Kang et al., 2006). On the other hand, if the difference between the current density and the target density is small, only some vehicles are instructed to merge into the open lane. When the open lanes have no spare capacity to accommodate the vehicles in the work zone lane, the "No merge" strategy is adopted, and merging is prohibited. This decision process is applied to upstream segments within 1.5km of the work zone, and Merge control is terminated when the road work is over. The process of Merge control described above is represented as an algorithm flow chart as follows.

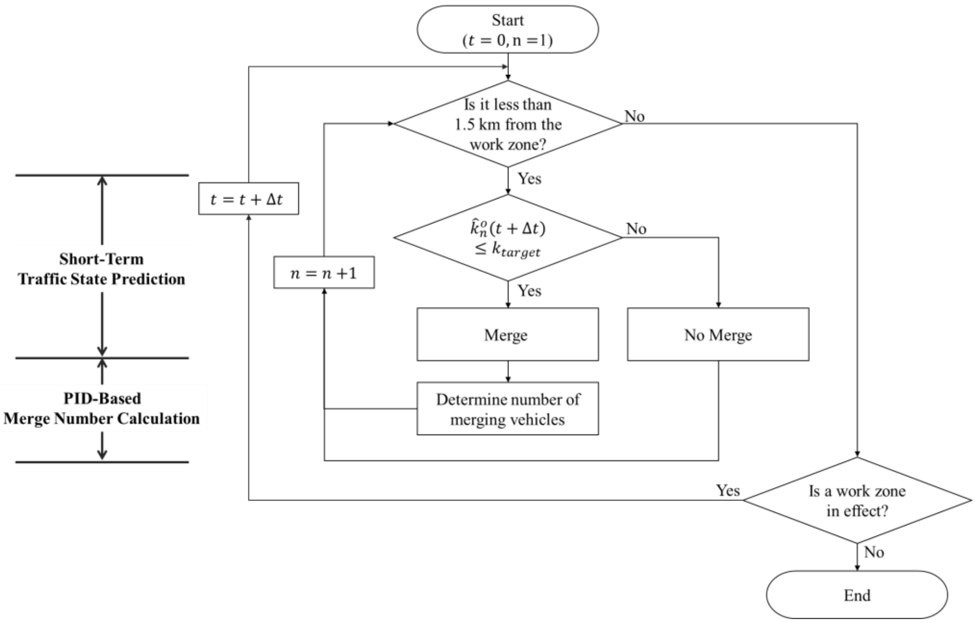



Figure 3.10 Flow chart of Merge control

## 3.4. Speed control

This chapter presents Speed control of work zone traffic control. The speed control in this study is a strategy that changes the inflow of the upstream part by considering the vehicles to be merged in the work zone lane (Figure 3.11). The q−k curve in Figure 3.11 is the q−k diagram at Speed control zone. Since merging vehicles as much as $q_w$ are expected in the merge zone, the inflow is reduced by that much in the speed control zone. In other words, it determines the speed to turn this gray point into the red point. The formula for calculating the appropriate speed limit value for each situation is same as the formula on next page. As a result, the congested state slows down significantly when many merges are expected, and slows down less when relatively few merges are expected.

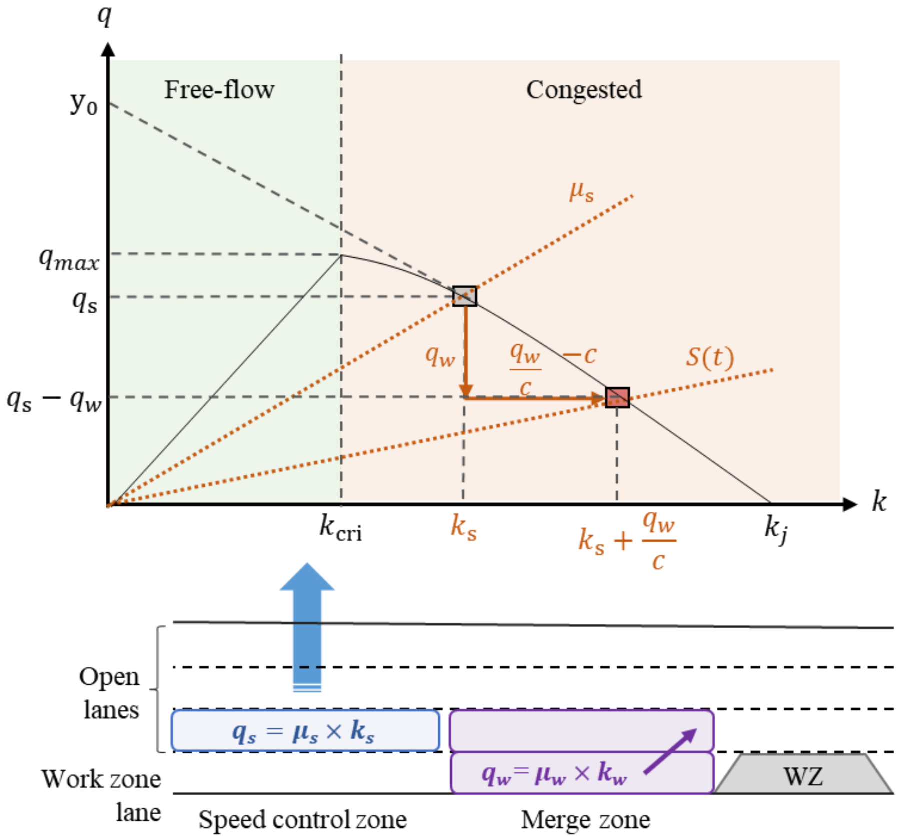



Figure 3.11 Conceptual diagram of the Speed control

In congested state, Speed control value is as below,

$$q = -ck + y_0 \;\Leftrightarrow\; c = \frac{q_s(t)}{k_j - k_s(t)}$$

$$S(t) = \frac{q_s(t) - q_w(t)}{k_s(t) + \frac{q_w}{c}(t)} = \frac{c\{q_s(t) - q_w(t)\}}{c\{k_s(t) + \frac{q_w}{c}(t)\}}$$

$$= \frac{q_s(t) - q_w(t)}{q_w(t) + ck_s(t)} \times \frac{q_s(t)}{k_j(t) - k_s(t)}$$

$$= \frac{q_s(t)}{k_s(t) + \frac{q_w(t)}{q_s(t) - q_w(t)} k_j}$$

where,
$\mu_s(t)$, $q_s(t)$, $k_s(t)$: speed, flow, density of Speed control zone,
$\mu_w(t)$, $q_w(t)$, $k_w(t)$: speed, flow, density of Merge control zone,
$S(t)$: value of speed limit at time $t$

The predicted density is compared to the critical density and the speed is changed according to each traffic situation. Figure 3.12 is the flowchart for Speed control.

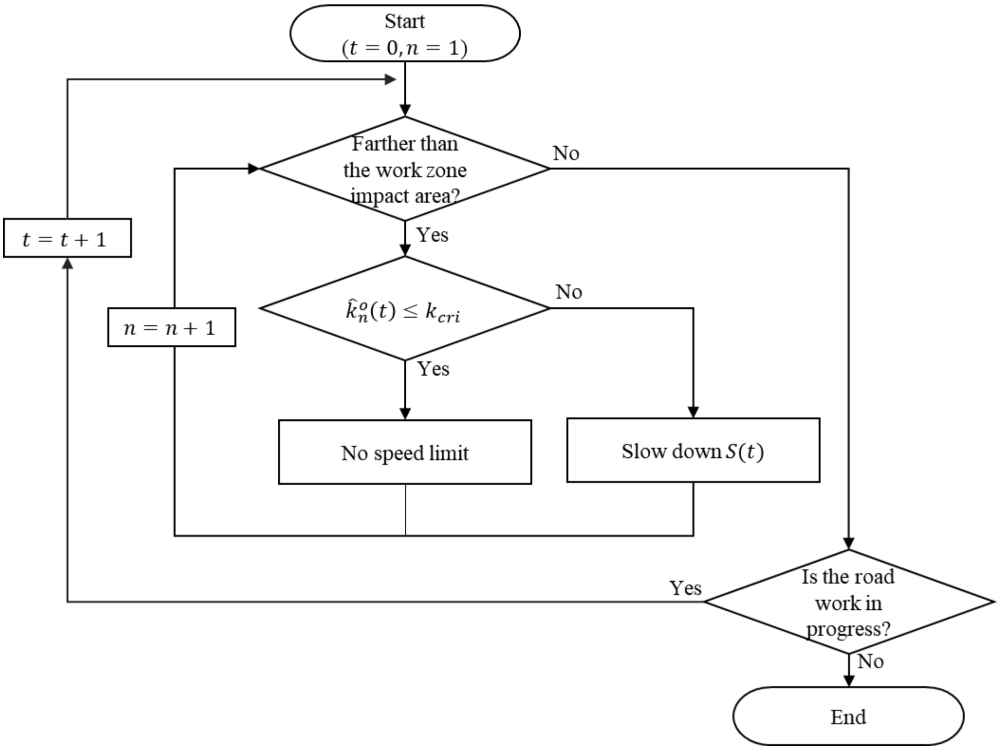



Figure 3.12 Flow chart of the proposed speed control

## 3.5. Combined control of merge and speed controls

Combined control consists of Merge control and Speed control. Speed control is added on the upstream of Merge control zone to facilitate smooth merge with consideration of Merge control $M(t) = \sum_{n=1}^{3} M_n(t)$. Combined control in connection with Merge control and Speed control is as follows. As shown in of Figure 3.13, Speed control is partially operated on neighboring lanes in the upstream part of the Merge control operating section to control the traffic volume and create a gap between vehicles to provide an appropriate situation for merge. To calculate the appropriate speed control value $M(t)$, the sum of the number of merging vehicles by segment by Merge control, is considered in the formula. In other words, the formula reflecting the speed and density of the neighboring lanes in segment 4 and the number of merging vehicles in the work zone lane from segments 1 to 3 to the speed control value is as follows.

$$M(t) = \sum_{n=1}^{3} M_n(t)$$

$$S(t) = \frac{q_s(t)}{k_s(t) + \frac{M(t)}{q_s(t) - M(t)} k_j}$$

As a result, by predicting the traffic flow at step t+1 through the traffic state of step t, calculating what control and how much control value to give, and guiding it at step t+1.

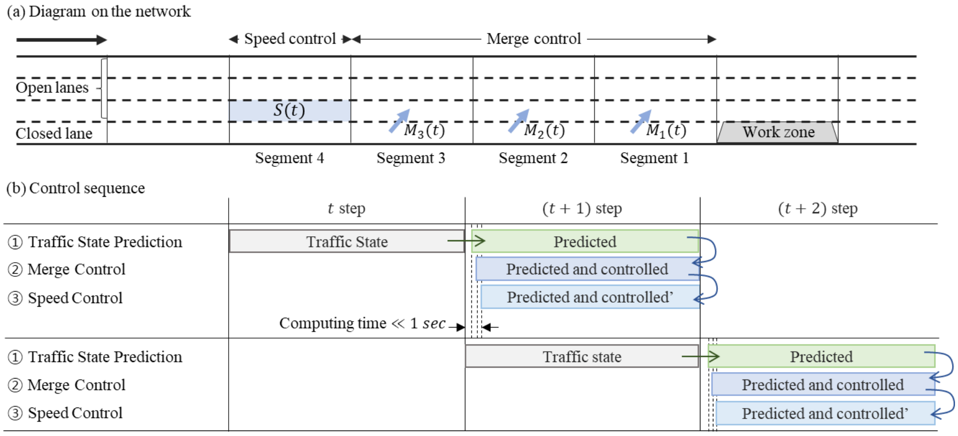



Figure 3.13 Concept of the combined work zone control

Figure 3.14 is the flowchart for Combined control. Predict the density through short term traffic state prediction for each segment. In the work zone impact area, merge or no merge is adopted by comparing the predicted density with the target density. When merge is adopted, the merge amount is estimated through PID control. In the upstream segment of the work zone impact area, the speed is changed considering the calculated merge amount.

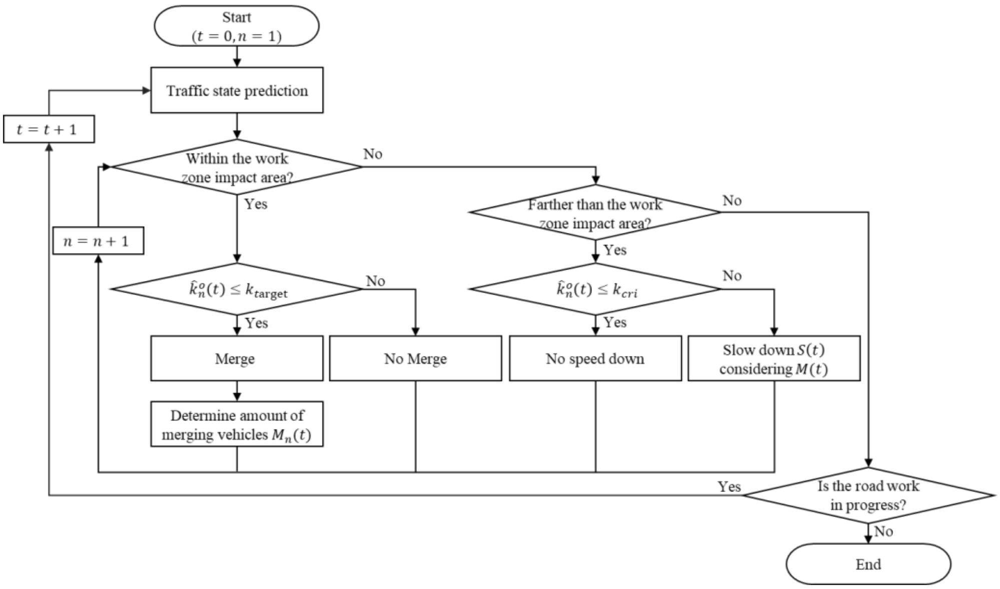



Figure 3.14 Flowchart of the combined work zone traffic control with traffic state prediction

# Chapter 4. Experimental Design

## 4.1. Vehicle modeling

This study used as the input vehicles both passenger car type CAVs capable of two−way V2I communication with road infrastructures and MVs without connectivity, and there was assumed to be no communication delay. VISSIM supports a user friendly Python API environment that can implement CAV modeling based on vehicle data and various traffic management, and many studies have used this functionality (Ge et al., 2013; Radwan et al., 2011; Yang et al., 2009). The CAV implementation used "aggressive automated vehicle (AV)" driving parameters provided by VISSIM (Sukennik and PTV Group, 2018); aggressive AV has the characteristics of more active car following and lane changing compared to normal AV, with the gap for lane changing and the oscillation of car following being smaller. The connectivity parameter was additionally modified by referring to the previous research (ATKINS, 2016). Accordingly, this study used VISSIM and its Python API to implement the road work scenario and conduct effect analysis on the proposed merge control by means of microscopic traffic simulation.

Table 4.1 Vehicle composition used in the simulation analysis

| Vehicle Type | Driver | Simulation Parameter | Traffic control for Work Zone |
|---|---|---|---|
| Manual Vehicle | Human | VISSIM basic freeway parameter | Road signs for work zone information |
| Connected Automated Vehicle | Automated driving system | VISSIM automated vehicle parameter, ATKINS connectivity parameter | Merge control & Speed control |

In this study, as shown in Figure 4.1, an environment in which road work and lane closure information is received through road signs from a point near the work zone identical to that of the actual highway was implemented in the simulation. On the other hand, CAV is implemented under the control of work zone traffic control of Merge control and Speed control described above.

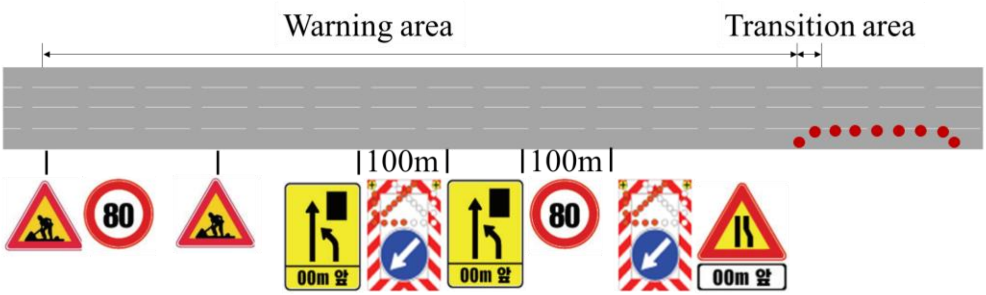


Figure 4.1 Work zone alert service in Korea expressway

Some studies have mentioned that drivers in a section adjacent to a work zone have characteristics distinct from drivers under normal conditions, which difference greatly affects traffic flow (Chatterjee et al., 2009; Yang et al., 2009). Since the driving agent of a CAV is the automated driving system, reaction time and acceleration/deceleration characteristics are constant regardless of situation; it is MVs that have different driving characteristics in a work zone impact area. As shown in the previous figure, MVs that receive diverse signs related to work zones and merge according to guidance change their behavior in the longitudinal and lane changing. Drivers with work zone information have the characteristics distinct from normal conditions such as enough gap distance and aggressive merge attempt. Real merging characteristics with distance gaps between leading and following vehicles of MV were determined based on work zone field data from video recording. Accordingly, this study considered the difference in driving characteristics of MVs between normal conditions and the road work situation to realize a more reasonable simulation; that is, real lane-changing characteristics of human driving were determined from work zone field data obtained by installing video recording devices at and 500m upstream from the starting point of an actual road work zone. In particular, the distance gaps between leading and following vehicles under car-following and merging situations were recorded and applied to the simulation parameters (Table 4.2).

Table 4.2 Simulation parameter calibration for work zone

| VISSIM Parameter | VISSIM Default | This Study |
|---|---|---|
| CC1. Following distance (s) | 1.5 | 1.2 |
| CC2. Longitudinal oscillation (m) | 4 | 4 |
| LC4. Minimum clearance (m) | 0.5 | 1.0<br>(Site investigation) |
| LC5. Safety distance reduction factor | 0.6 | 0.8<br>(Site investigation) |

Finally, Table 4.3 summarize all parameters for CAVs with MVs in normal and work zone condition.

Table 4.3 Driving parameters of each vehicle type

| VISSIM Parameters | | MV | | CAV |
|---|---|---|---|---|
| | | Default | Work zone | |
| **Connectivity** | Observed vehicle (ea) | 2 | 10 | 10 |
| **Car-following** | CC0:<br>Standstill distance (m) | 1.5 | 1.2 | 1.0 |
| | CC1:<br>Following distance (s) | 0.9 | 1.5 | 0.6 |
| | CC2:<br>Longitudinal oscillation (m) | 4.0 | 4.0 | 0 |
| | CC3:<br>Perception threshold for following (s) | -8.0 | -8.0 | -6.0 |
| | CC4:<br>Negative speed difference (m/s) | -0.35 | -0.35 | -0.10 |
| | CC5:<br>Positive speed difference (m/s) | 0.35 | 0.35 | 0.10 |
| | CC6:<br>Influence speed on oscillation (1/m · s) | 11.44 | 11.44 | 0 |
| | CC7:<br>Oscillation acceleration ($m/s^2$) | 0.25 | 0.25 | 0.10 |
| | CC8:<br>Standstill acceleration ($m/s^2$) | 3.5 | 3.5 | 4.0 |
| | CC9:<br>Acceleration at 80kph ($m/s^2$) | 1.5 | 1.5 | 2.0 |
| **Lane changing** | LC2:<br>$-1m/s^2$ per distance | 200 | 200 | 100 |
| | LC4:<br>Minimum clearance (m) | 0.5 | 1.0 | 0.5 |
| | LC5:<br>Safety distance reduction (%) | 60 | 80 | 75 |
| | LC6:<br>Max. deceleration for cooperative braking ($m/s^2$) | -3.0 | -3.0 | -6.0 |

## 4.2. Simulation network and scenarios

As shown in Figure 4.2, the analysis site is a 14km long freeway main line network with a real work zone of 4–to–3 lanes (1st lane from median), and the effect of the proposed merge control was evaluated based on actual traffic demand including congestion occurrence and recovery.

In this study, the stretch of road extending 1.5 km upstream of the work zone was divided into three segments with consideration of the travel speed. In each segment, the density of the work zone lane from which vehicles need to merge and the density of the open lanes that is the merging target are predicted. In order to investigate the impact of the proposed merge control on the further upstream flow, segment 1 to 4 was analyzed.

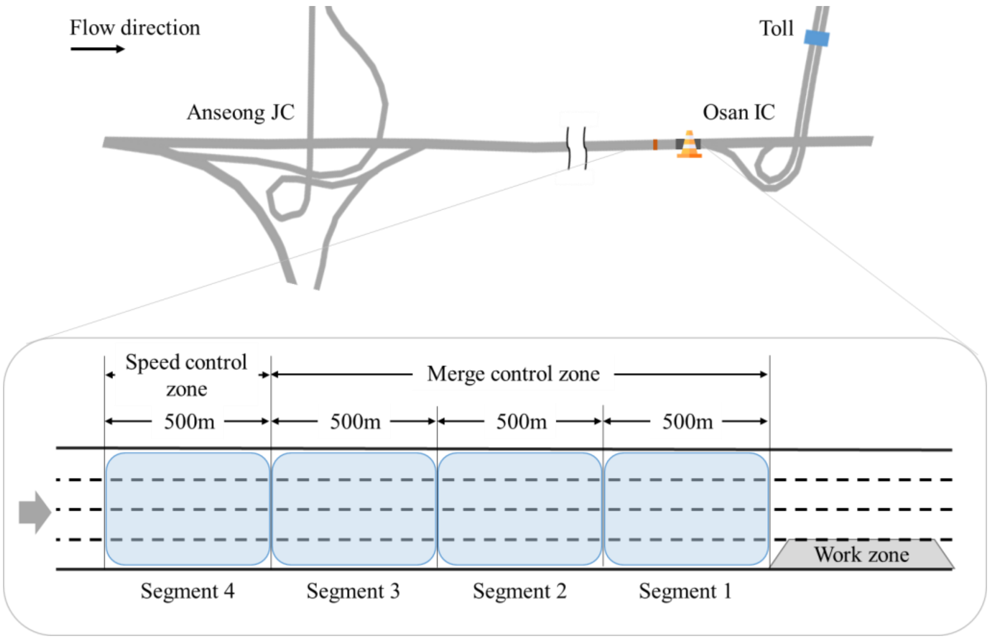



Figure 4.2 Layout of the simulation network

The following is the traffic state of this research site. Road work starts around 15:00, and congestion occurs rapidly, and demand recovers around 18:00. The aforementioned free–flow, moderately congested, and severely congested states can be classified as shown in the figure below. Based on this condition, the standard for free-flow and congestion for Speed control was determined to be 23 vpkpl, and the standard for severe congestion for Merge control was determined to be 50 vpkpl.

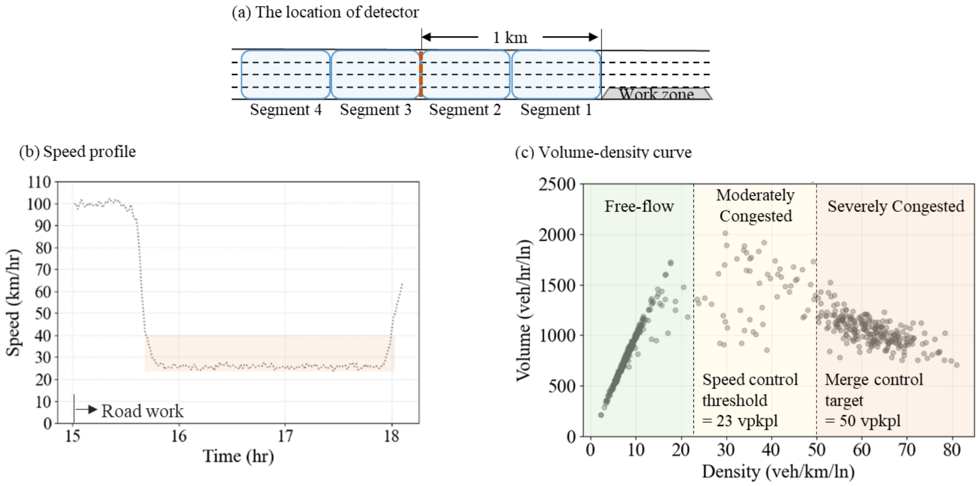



Figure 4.3 Speed profile and volume-density curve at the 1km upstream detector of work zone

Also, traffic characteristics that may occur due to road work such as queue generation and severe congestion were checked for the date on which the actual road work was conducted. Since the proposed merge control triggers “Merge” based on the lane unit density, lane-level calibration is needed. Accordingly, calibration was conducted not only over the whole network but also for each segment-lane (Figure 4.4).

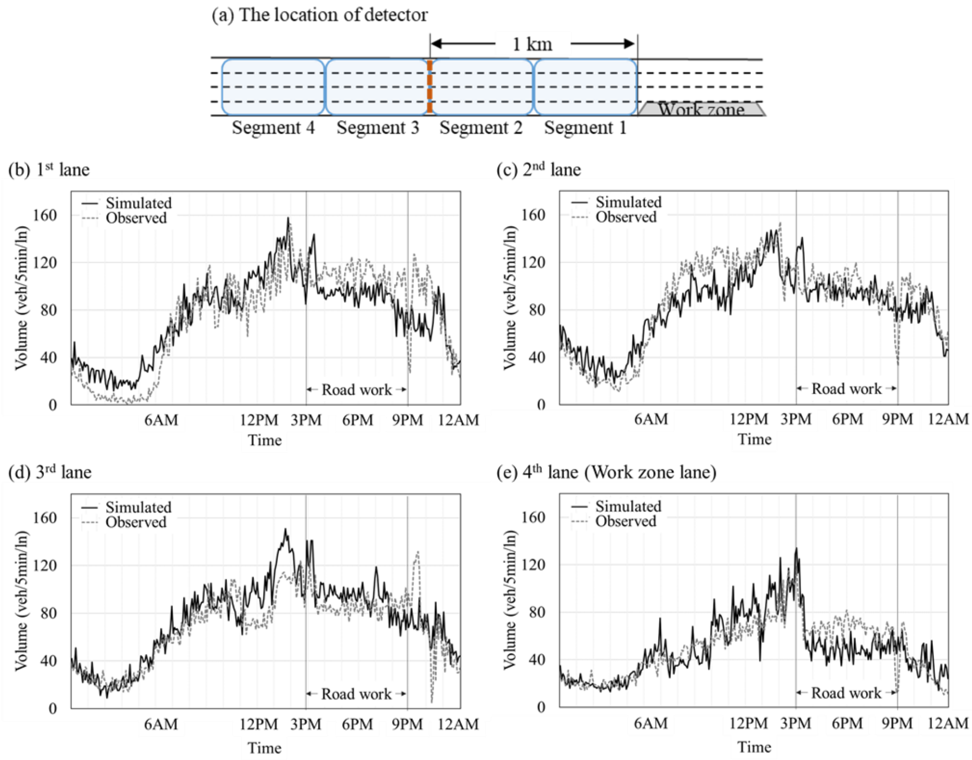



Figure 4.4 Calibration results on each lane for upstream segment from the work zone

Due to the road work, congestion occurred and discharge flow rate was reduced with severe congestion. Thus, the network and traffic conditions are suitable for evaluating the proposed control.

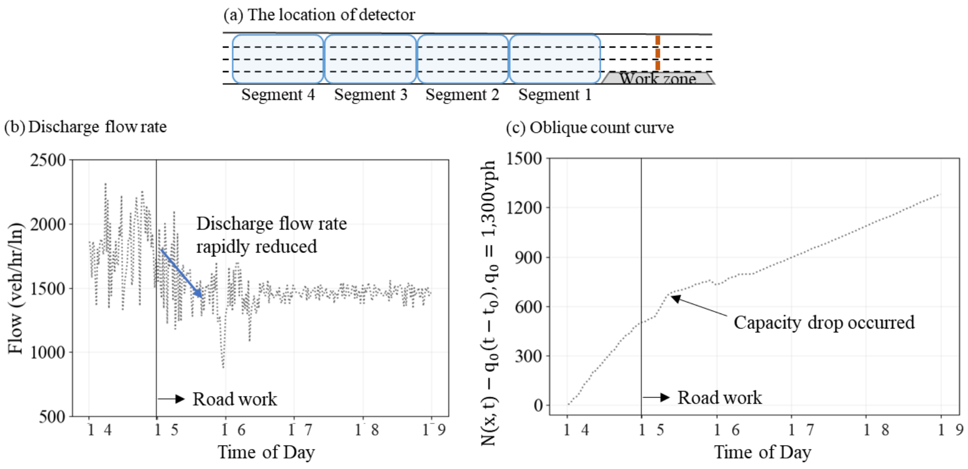



Figure 4.5 Discharge flow rate and oblique count curve at the work zone

Unit length of control segment is 500m that is because expected V2I/I2V range with WAVE is at least 500m. Average speed decreases from about 100 kph to 30 kph when road work starts, and reaches about 60 kph when congestion is restored by demand. Therefore, in order for all vehicles to be under the control environment, a speed of 60 kph must be considered. As a result, the time interval for traffic state prediction and traffic control is 30 seconds considering segment length and travel speed in this study.

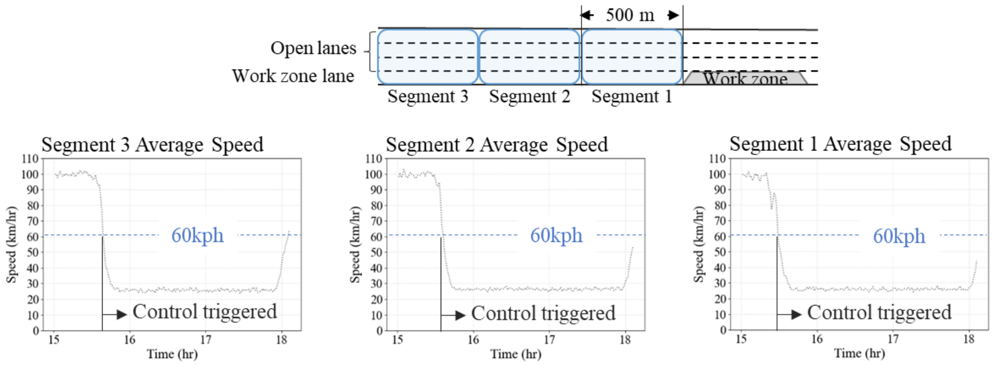



Figure 4.6 Average speed on each upstream segment

Table 4.4 Travel speed on each segment in MV 100%

| Speed in MV environment | Seg. 3 WZ lane | Seg. 3 Open lanes | Seg. 2 WZ lane | Seg. 2 Open lanes | Seg. 1 WZ lane | Seg. 1 Open lanes |
|---|---|---|---|---|---|---|
| Average (kph) | 42.6 | 28.2 | 34.5 | 27.1 | 20.2 | 26.3 |
| 50-percentile (kph) | 34.5 | 18.0 | 26.0 | 19.5 | 14.7 | 22.6 |

The merge control information was sent only to CAVs that can receive guidance through wireless communication. MV with human drivers approaches the work zone start point in the work zone lane until they recognize the lane closure or merge discretionarily. The effect of the proposed merge control was analyzed under mixed traffic flow of CAV and MV.

# Chapter 5. Results and Discussions

## 5.1. Results of traffic state prediction

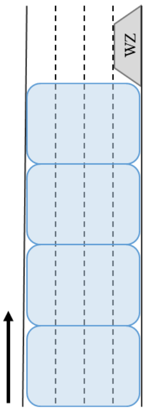
As a result of reviewing the traffic speed of the network in Chapter 4, it was judged that a 30−second period was reasonable for traffic control. Density at open lanes of upstream segments is predicted every 30 seconds. The accuracy of the GRU model for density prediction developed in this study may vary depending on batch size, sequence length, the number of GRU nodes, and the hidden layer configuration of each layer. Therefore, optimal parameters were applied to each segment−lane to increase predictive accuracy. The table below is density prediction results in each segment using GRU with 30 seconds interval (Example of CAV MPR 25%). The accuracy of density prediction was evaluated using the mean absolute percentage error (MAPE), and it is considered acceptable compared to previous studies (Oh et al., 2015; Jia et al., 2017; Elfar et al., 2018.

Table 5.1 Training parameter of GRU model in CAV MPR 25%

| Training Parameter<br>Prediction Target | Batch Size* | Sequence Length** | Drop−out Rate*** | Step Size | MAPE (%) |
|---|---|---|---|---|---|
| Segment 1 open lane<br>(500m upstream from work zone) | 16 | 128 | 0.1 | 16 | 7.1 |
| Segment 2 open lane<br>(1km upstream from work zone) | 16 | 128 | 0.1 | 16 | 5.4 |
| Segment 3 open lane<br>(1.5km upstream from work zone) | 16 | 128 | 0.1 | 16 | 6.4 |
| Segment 4 open lane<br>(2km upstream from work zone) | 16 | 128 | 0.1 | 16 | 6.8 |

* Batch size: Data amount of each batch in the training data
** Sequence length: Length of split input data for learning efficiency
*** Drop−out rate: A measure of the degree to nodes are probabilistically disconnected for reducing learning overfitting

The following figure shows the MAPE of the segment for each time period of traffic state prediction results. As mentioned above, the MAPE across all time steps was low enough. However, since the input node values change greatly at the transition time when the traffic situation changes rapidly, overall accurate traffic control is possible only when the predictive power of this time period is good. Congestion due to road work occurs at the 15:00 boundary, which can be seen as transition time, and the error is approximately 4%. Afterwards, 18:00, when congestion is relieved due to demand, is also a transition time, and the MAPE at this time was also around 6%.




Road work & Congested

| Sim. Time Hour | 14:00~15:00 | | | 15:00~16:00 | | | 16:00~17:00 | | | 17:00~18:00 | | | 18:00~19:00 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min. | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 |
| Segment 1 | 2% | 2% | 2% | 2% | 2% | 2% | 1% | 1% | 1% | 1% | 1% | 2% | 8% | 3% | 2% |
| Segment 2 | 4% | 3% | 4% | 5% | 2% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 8% | 6% | 3% |
| Segment 3 | 3% | 3% | 4% | 4% | 2% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 7% | 12% | 3% |
| Segment 4 | 2% | 3% | 3% | 2% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 4% | 5% | 4% |

Transition Time (14:00~15:00 40~60 – 15:00~16:00 0~20); Transition Time (17:00~18:00 40~60 – 18:00~19:00 0~20)

Error rate increased when road work started

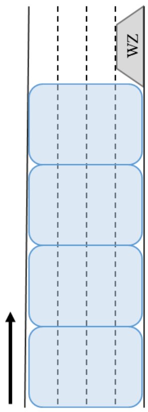
**Relatively low error rate while control operation period**

Error rate increased while traffic flow is being recovered

Figure 5.1 Example of prediction results by GRU under CAV MPR 25% scenario

The following figure shows the result of predicting the density of open lanes in a segment using LSTM at a period of 30 seconds. Traffic state prediction results are expressed by segment MAPE by time zone. At the 15:00 boundary, congestion due to road work occurs. Afterwards, MAPE decreased significantly during the time zones where work zone traffic control was in operation. Afterwards, 18:00, when congestion is resolved due to demand, can also be seen as a transition time, and the MAPE at this time was also around 7%. Compared to the GRU model of the same period, it was confirmed that the predictive power of the transition time was slightly lower, and the learning time of the predictive model was also slightly lower. As a result, for real-time prediction and control, GRU based on 30 seconds is reasonable, and work zone traffic control was analyzed by applying it.

Road work & Congested




| Sim. Time (Hour) | 14:00~15:00 | | | 15:00~16:00 | | | 16:00~17:00 | | | 17:00~18:00 | | | 18:00~19:00 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min. | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 | 0~20 | 20~40 | 40~60 |
| Segment 1 | 2% | 2% | 1% | 2% | 2% | 2% | 1% | 1% | 1% | 1% | 1% | 2% | 8% | 4% | 2% |
| Segment 2 | 4% | 3% | 3% | 5% | 2% | 2% | 2% | 2% | 2% | 1% | 1% | 2% | 8% | 8% | 3% |
| Segment 3 | 4% | 2% | 5% | 5% | 2% | 1% | 2% | 1% | 1% | 1% | 1% | 2% | 5% | 10% | 3% |
| Segment 4 | 2% | 3% | 3% | 3% | 2% | 1% | 1% | 1% | 1% | 1% | 1% | 2% | 5% | 6% | 4% |

Transition Time (14:00~15:00 40~60 – 15:00~16:00 0~20); Transition Time (17:00~18:00 40~60 – 18:00~19:00 0~20)

Error rate increased when road work started

Relatively low error rate while control operation period

Error rate increased while traffic flow is being recovered

Figure 5.2 Example of prediction results by LSTM under CAV MPR 25% scenario

## 5.2. Results of the work zone traffic control

### 5.2.1 Impact on Amount of Merge

The following figure shows the relative frequency of merge positions during the entire simulation time. First of all, in the No control situation, both MV and CAV almost reached the work zone and joined. This is a merge behavior similar to reality, due to the characteristics of drivers driving to secure their own desired speed. Through the proposed combined control operation, it was found that the CAV merge was performed from a relatively upstream point, and that the merge, which was concentrated near the work zone, was dispersed overall.

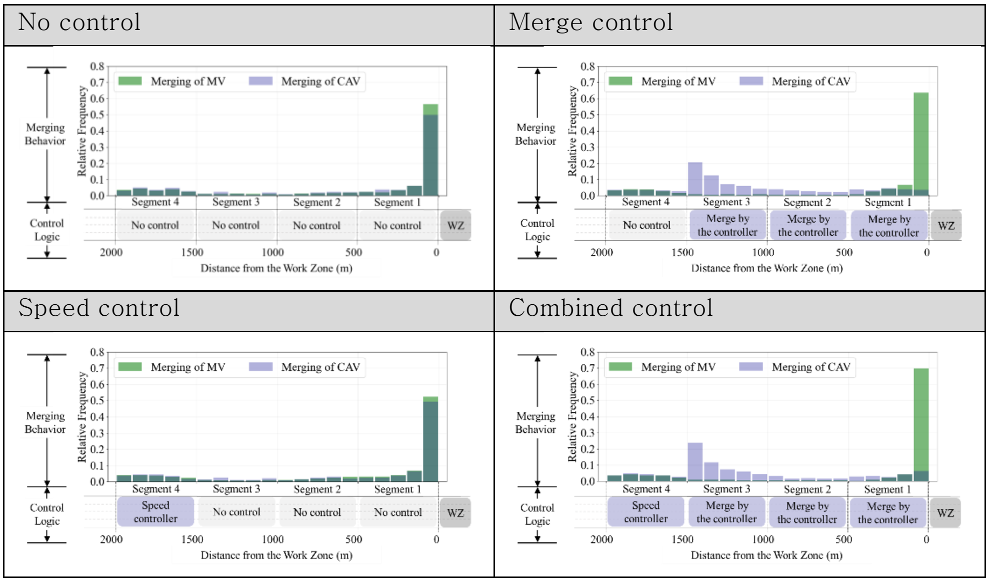


Figure 5.3 Merge frequency at each segment for low MPR scenario

The figure below is an example of a high MPR scenario, the relative frequency of the merge position at 100% MPR. Compared to the Low MPR scenario, the merge has become more dispersed upstream. This is because all vehicles can receive and follow the guidance of the combined control.

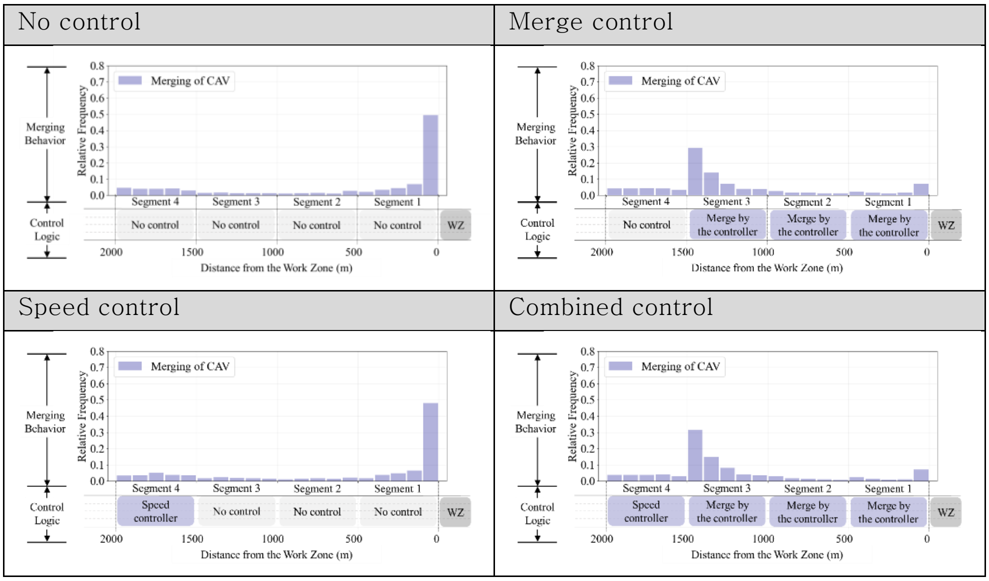



Figure 5.4 Merge frequency at each segment for high MPR scenario

The following is a comparison of the number of merges by segment for primary MPR scenarios.

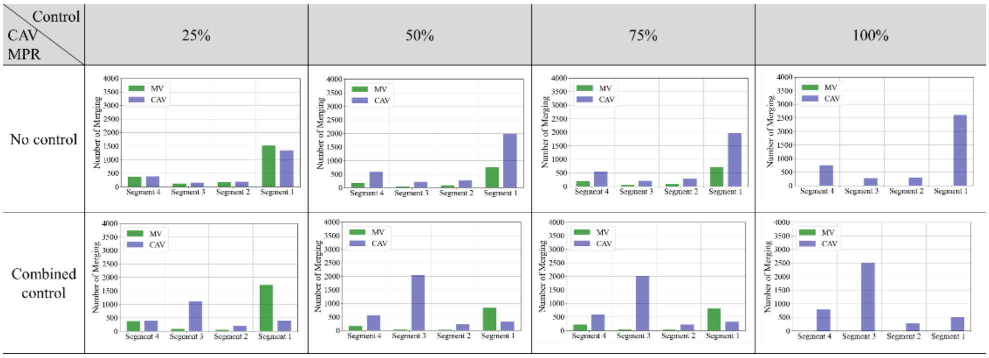



Figure 5.5 Merge number at each segment for different MPR scenario

### 5.2.2 Merge Implementation Number

Through work zone traffic control, an appropriate merge number is calculated for each segment at each time step. However, merge cannot be performed when the gap of the lane to be merged is not sufficient. The guidance number and merging complete number can be different depending on the gap condition. If vehicles fail to merge, the vehicle is controlled again in the next segment considering conditions. Therefore, how often merges are guided for each segment and how many actual merges were implemented compared to the merge number are investigated. The following figure and table compare the merge number due to Combined control when CAV MPR is 100%. The figure below shows a profile of merge guidance number and merge complete number, taking a specific time period for each segment as an example.

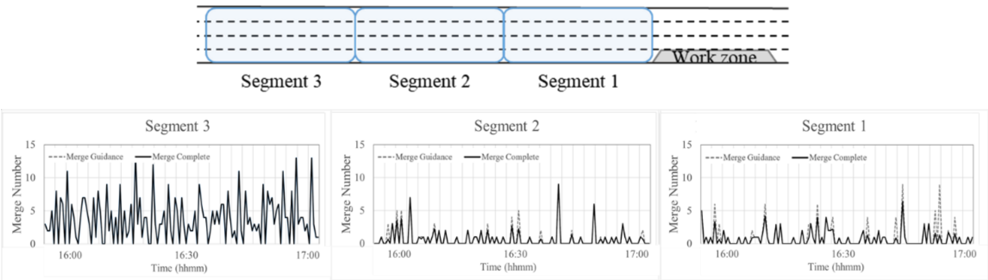



Figure 5.6 Merge number on each upstream segment

The table below compares the guide and implementation of merge during congestion during the road work period. In the case of Segment 1, it is the section immediately upstream of the work zone where congestion and queues continue to exist. Therefore, there was no gap in the lane to be merged, so the merge implement rate based on the merge number was about 67%. On the other hand, the implement rate in segments 2 and 3, which are upstream than segment 1, was relatively high. Segments 2 and 3 have a higher number of merge guidance compared to segment 1, which means that the prediction density is low, and the gap between vehicles is relatively secured to that extent, so the actual merge is smoother.

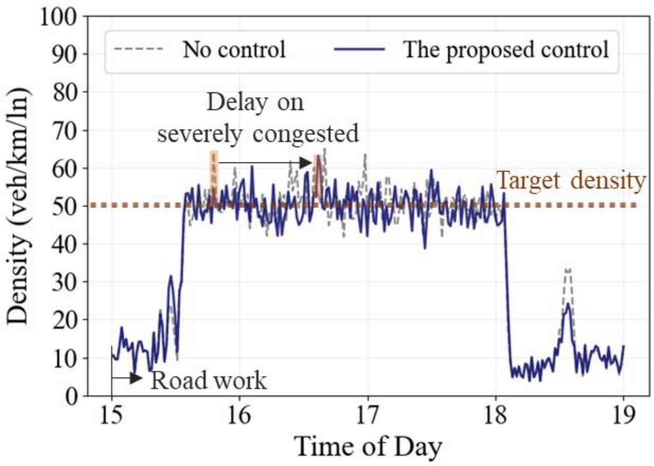
Table 5.2 Merge implementation ratio on each segment

| Combined in MPR 100% | Seg. 3 | Seg. 2 | Seg. 1 |
|---|---|---|---|
| Merge guidance number (vehs) | 1,102 | 328 | 385 |
| Merge implement number (vehs) | 1,083 | 292 | 261 |
| Implementation rate | 98.2% | 84.0% | 67.7% |

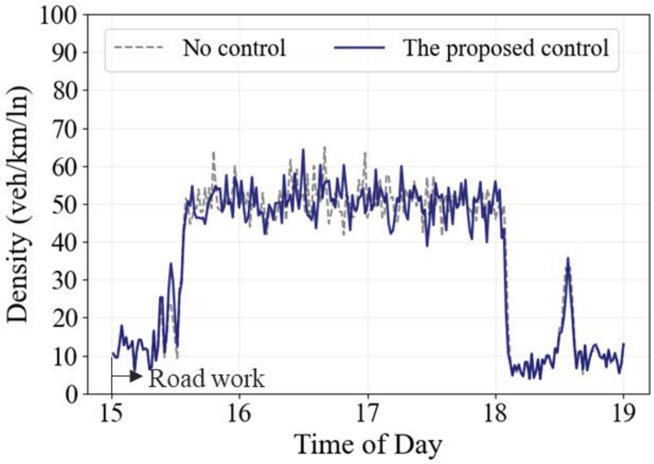
### 5.2.3 Impact on Density in Open Lanes

The density of upstream segments is adjusted through traffic control, and through this, various traffic flow improvements are possible. The following figure shows the density of open lanes in segment 1 adjacent to the work zone in low MPR and high MPR scenarios. Density could not be successfully lowered in CAV MPR 25% as low MPR. However, it was found that the density was maintained below the target density level in CAV 100% where control can be performed for all vehicles. Although there are some time steps that cannot maintain the target density due to excessive congestion, it can be seen that severe congestion has been delayed and relieved. First of all, Speed control has no significant effect on density, but congestion recovers faster than No control case. In the case of Speed control, which does not directly control density, there was no noticeable density reduction effect, but Merge control, which properly determines “Merge” and “No merge” and determines the appropriate merge number, maintained the density at the target level. Results for all MPR are included in the Appendix part.

Merge control




Speed control




Combined control

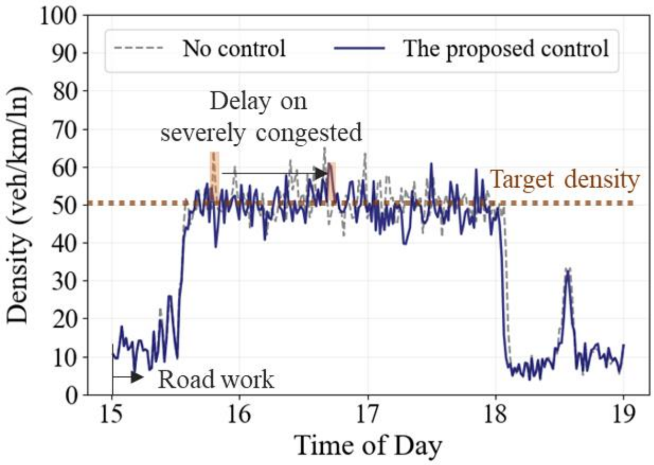
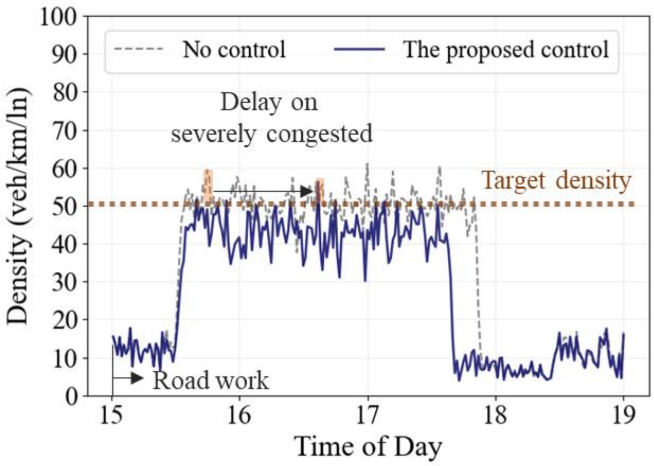


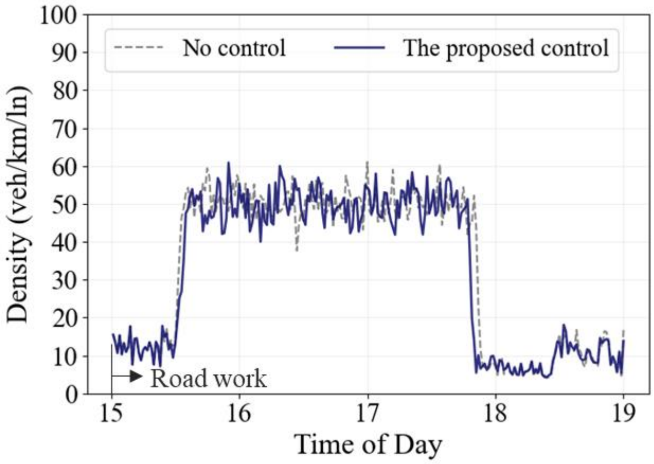

Figure 5.7 Density change by each control for low MPR scenario

These are the result of no merge being guided in situations where the density of the open lane exceeds the target, and vehicles in the work zone lane being merged in situations where the density of the open lane is less than the target and there is some margin.

Merge control




Speed control




Combined control

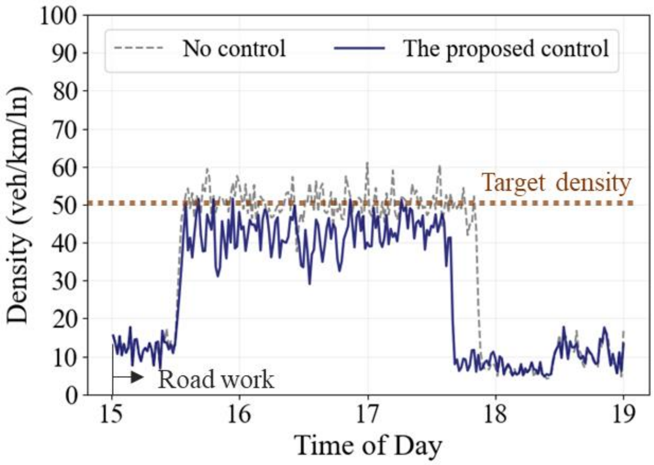



Figure 5.8 Density change by each control in high MPR scenario

The following is the density change by Combined control for each segment. Severely congested state continues in segments 2 and 3 with a high merge implement rate, but the density is lower than that of segment 1, which can be the reason for the high merge implement rate due to the relatively large gap among vehicles. In addition, density was reduced to a level below the density of the severely congested state through PID control, and congestion was quickly recovered.

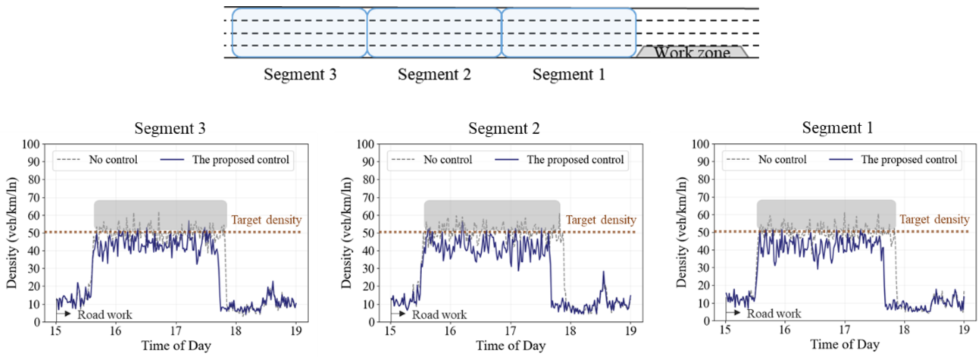
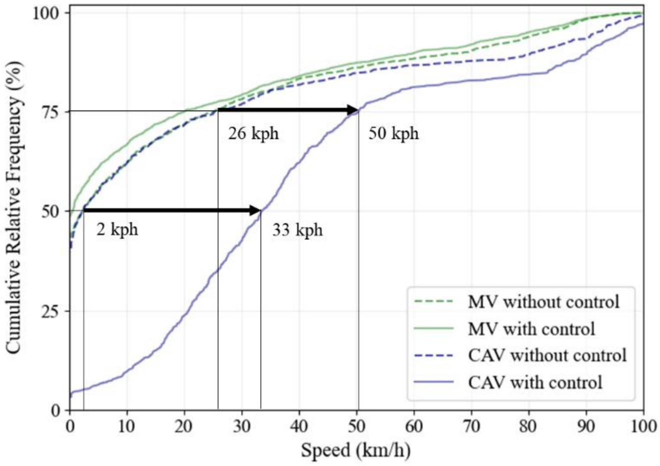



Figure 5.9 Density in open lanes at each segment for Combined control in MPR 100% scenario

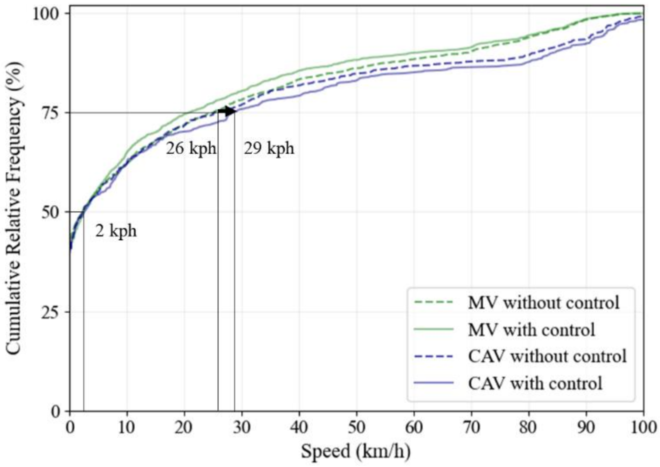
### 5.2.4 Impact on Merge Speed

The following is the result of merging speed from segment 1to segment 3. In general, merges near work zones are performed at low speeds, which further aggravates traffic congestion. It was found that the merge speed of CAV was improved by operating the controls proposed in this study. The proportion of the merges with lower speed is reduced by Merge control as shown in the figure below. The merge control can guide vehicles to merge before approaching queues in the work zone lane. By reducing merge with low speed, Merge control can relieve the negative impact of merge and improve operational efficiency. Combined control also increases the rate of improvement in merging speed by controlling the speed of upstream vehicles to enable smoother merging. As a result of MPR 25%, it can be seen that the 50-percentile value of merging speed increased from 2 kph to 34 kph by Combined control.

Merge control




Speed control




Combined control

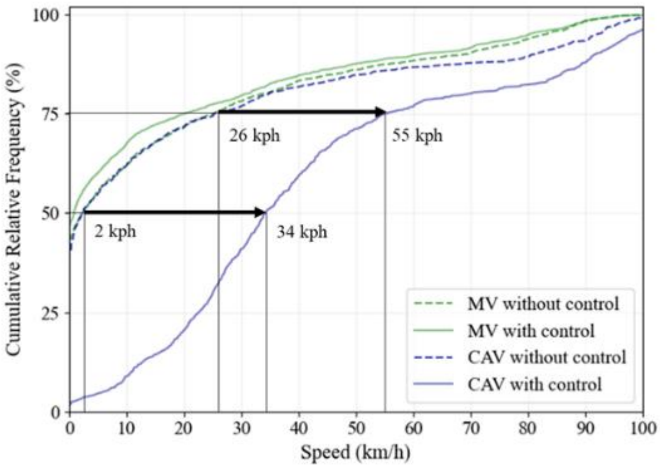
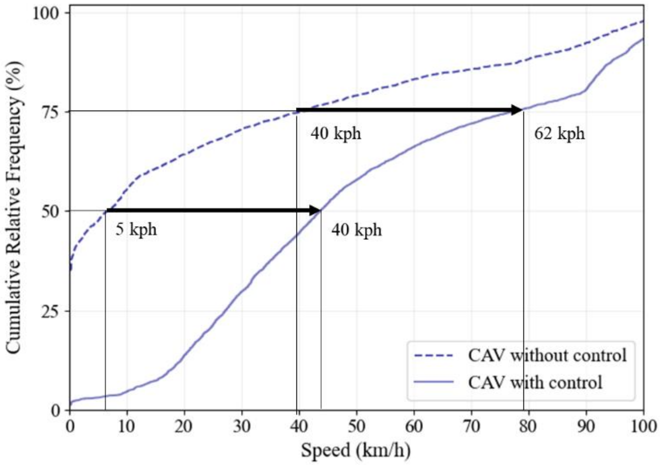


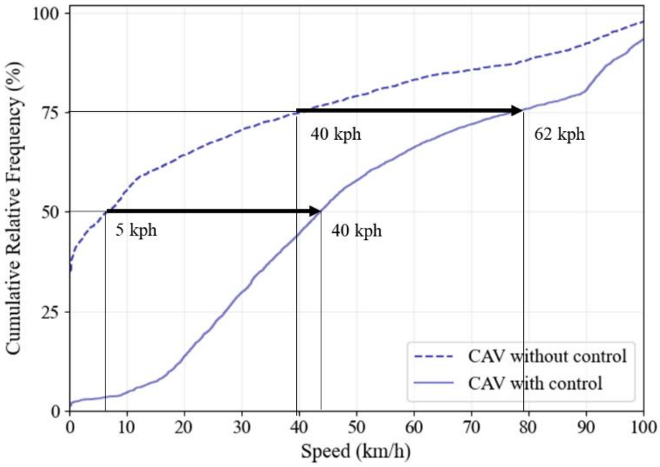

Figure 5.10 Merge speed in low MPR scenario

In addition, the merging speed increase was more noticeable in the CAV 100% that is controllable situation of all vehicles. The 50-percentile value of merging speed increased from 5 kph to 42 kph.

Merge control




Speed control




Combined control

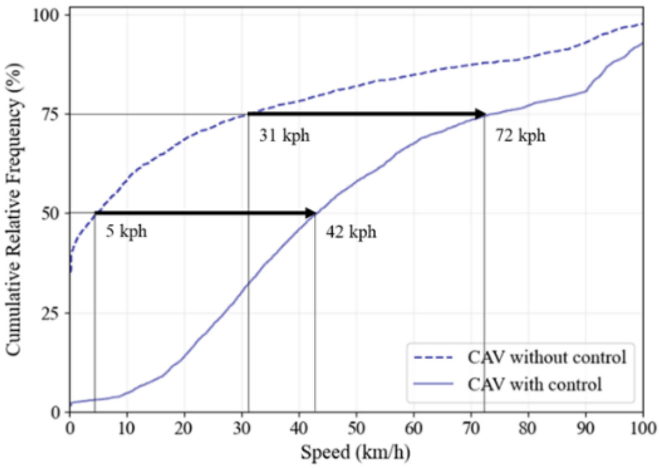



Figure 5.11 Merge speed in high MPR scenario

### 5.2.5 Impact on Queue Length

The effect of Combined control, in which merging speed is improved through appropriate merge location and number adjustment, was also shown in the queue length of each segment. The queue length reached about 1.5 km when severely congested without control. Combined control reduces the merge behavior with low speed. In other words, the number of merging vehicles in the queue decreased. As a result, Vehicles approaching the queue are merged preemptively, and the speed of upstream vehicles is controlled to suppress the expansion of the queue. As shown in the table below, average queue length decreases by about 60%.

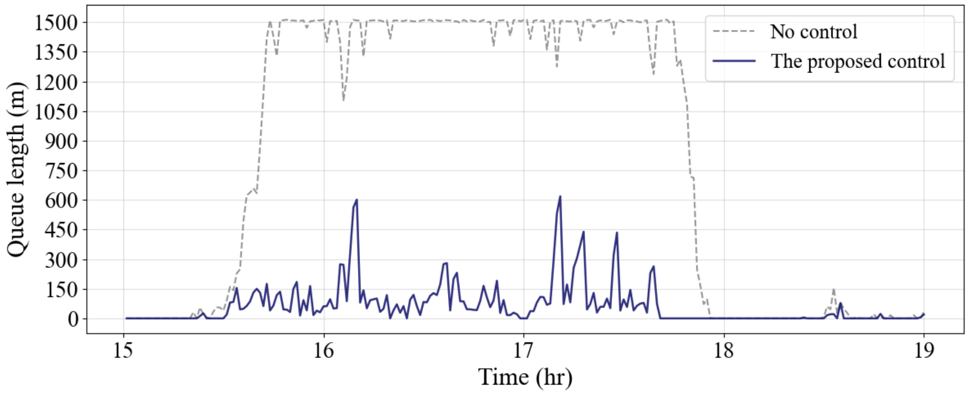



Figure 5.12 Maximum queue length profile for Combined control in MPR 100%

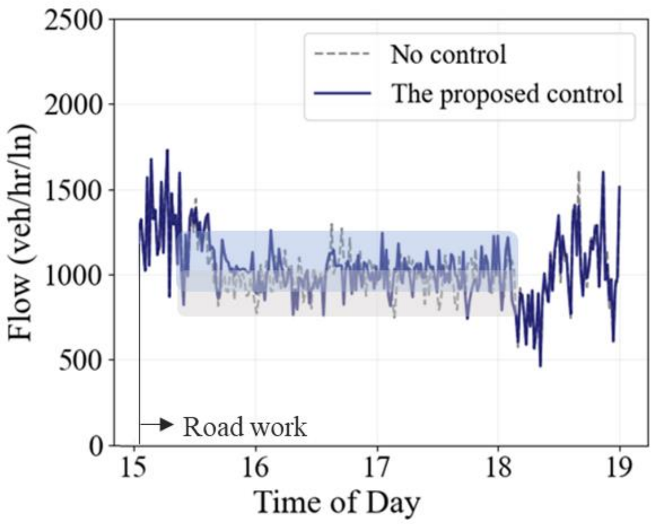
Table 5.3 Average Queue length on each segment

| MPR 100% | Average queue length (m) | Reduction rate (%) |
|---|---|---|
| No control | 852.9 | – |
| Combined control | 343.4 | 59.7 |

### 5.2.6 Impact on Discharge Flow

Discharge flow rate at the work zone is improved by Combined control. By reducing the negative impact of merge, severe congestion is relieved and discharge flow is increased.

Combined control in MPR 25%




Combined control in MPR 100%

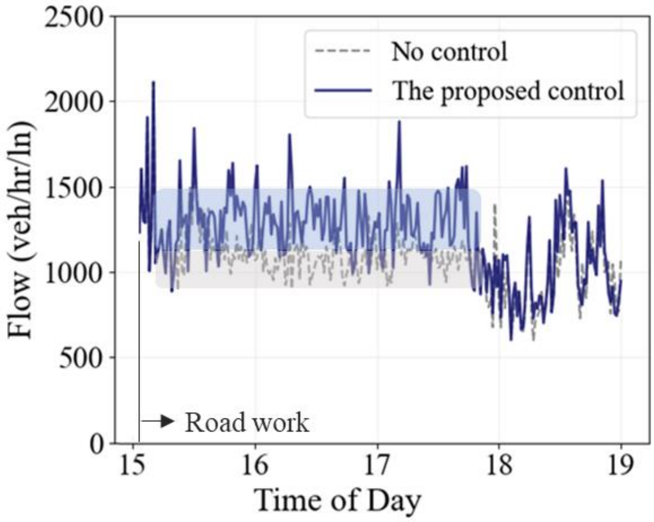



Figure 5.13 Discharge flow rate by Combined control in low and high MPR scenarios

### 5.2.7 Impact on Travel Time of Individual Vehicles

The network travel time of individual vehicles was improved through Combined control. The x−axis is the time each individual vehicle entered the work zone impact area, and the y−axis is the time it took for those vehicles to completely cross the work zone. The smooth merge is guided, and the merge with low speed was reduced by the proposed control. It can be seen that the travel time of most vehicles by time zone was improved through Combined control, and congestion was also recovered more quickly.

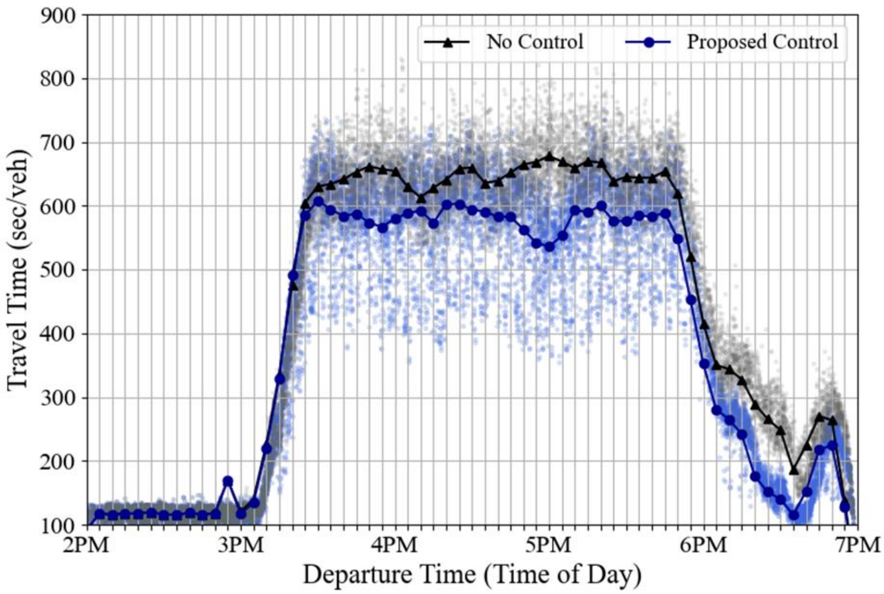



Figure 5.14 Travel time of individual vehicles and average for Combined control in MPR 100% scenario

## 5.3. Results under mixed traffic environment

### 5.3.1 Travel Time Improvement

The following are the results of travel time depending on CAV MPR and traffic controls. In Speed control, Merge control, and Combined control, the travel time improvement effect is higher as MPR increases. This is because the number of CAVs which can receive and guide by the control information increases. Merge control directly controls merging behavior, which is the main reason of traffic flow deterioration under road work. Merge control greatly improved travel time compared to Speed control. Combined control had a better operational improvement effect than Merge control in all MPR scenarios. And in particular, the effect of Combined control is greater than the sum of the improvement rates of Speed and Merge control at 75% MPR. It is also noteworthy that Combined control can be applied even at very low MPRs from 1% to 10%. As a result, it can be seen that the proposed work zone traffic control can be a reliable traffic management strategy in mixed flow.

Table 5.4 Average travel time results for each CAV MPR

| CAV MPR (%) | Travel Time (sec) | | | |
|---|---|---|---|---|
| | No control | Speed control | Merge control | Combined control |
| 0 | 431.7 | 431.7 | 431.7 | 431.7 |
| 1 | 430.5 | 427.1 | 427.6 | 427.1 |
| 3 | 429.1 | 424.1 | 422.4 | 422.0 |
| 5 | 427.3 | 421.3 | 419.1 | 418.2 |
| 10 | 426.3 | 419.8 | 417.3 | 412.5 |
| 25 | 415.0 | 404.0 | 401.0 | 392.3 |
| 50 | 396.4 | 382.2 | 374.8 | 362.7 |
| 75 | 375.9 | 353.9 | 345.1 | 329.5 |
| 90 | 362.9 | 333.1 | 312.7 | 305.3 |
| 95 | 361.3 | 326.4 | 307.7 | 300.4 |
| 97 | 359.4 | 321.1 | 305.1 | 297.0 |
| 99 | 359.0 | 319.1 | 304.8 | 295.1 |
| 100 | 358.3 | 318.5 | 302.3 | 291.8 |

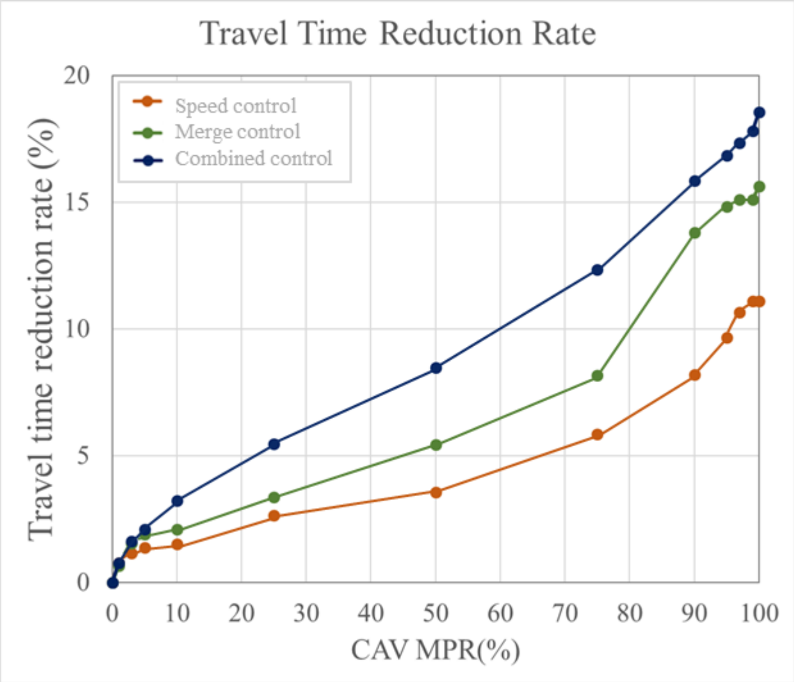


Figure 5.15 Improvement rate of travel time in all MPR scenarios

### 5.3.2 Conflicts Number Improvement

The following is the result of safety index by the proposed control. The number of conflicts was analyzed for each control for all MPR scenarios using FHWA's SSAM. Number of conflicts is the longitudinal and lateral potential crash numbers per vehicle and is the most affected indicator by the gap between two vehicles. As one of the SSM indicators, it is the most frequently used indicator in safety related studies. Merge control greatly reduces the number of merging vehicles in front of the work zone with the narrowest gap, and reserves the gap between cars in the upstream through Speed control. As a result, these control directly affected the conflicts number. The smooth merge was guided in the work zone impact area which had the most conflicts risk.

Table 5.5 Average conflicts number for each CAV MPR

| CAV MPR (%) | Number of Conflicts | | | |
|---|---|---|---|---|
| | No control | Speed control | Merge control | Combined control |
| 0 | 5,941 | 5,941 | 5,941 | 5,941 |
| 1 | 5,385 | 5,322 | 5,330 | 5,273 |
| 3 | 5,421 | 5,307 | 5,301 | 5,250 |
| 5 | 5,390 | 5,219 | 5,195 | 5,006 |
| 10 | 6,106 | 5,642 | 5,517 | 5,172 |
| 25 | 6,213 | 5,497 | 5,302 | 4,786 |
| 50 | 5,989 | 5,024 | 4,689 | 4,222 |
| 75 | 5,811 | 4,513 | 4,108 | 3,687 |
| 90 | 6,170 | 4,103 | 3,922 | 3,621 |
| 95 | 5,785 | 3,699 | 3,422 | 3,150 |
| 97 | 5,629 | 3,522 | 3,230 | 3,011 |
| 99 | 5,812 | 3,588 | 3,297 | 3,099 |
| 100 | 5,850 | 3,427 | 3,164 | 3,079 |

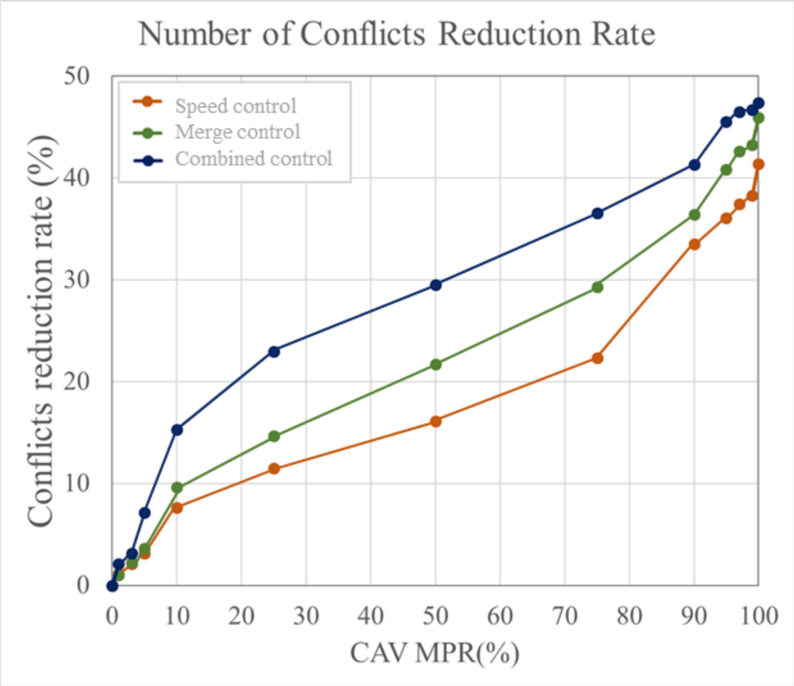


Figure 5.16 Improvement rate of number of conflicts in all MPR scenarios

### 5.3.3 $CO_2$ emissions Improvement

The following are the results of investigating whether environmental performance can be improved through this control. CO2 emissions were compared using CMEM. Speed control, Merge control, and Combined control are all improved in all MPRs. $CO_2$ emissions are most affected by acceleration and deceleration frequency and their magnitude. Improved merging speed through the control means reduced interference among vehicles, and since it directly affects the acceleration and deceleration behavior of individual vehicles. Additionally, the improvement rate also increases as the number of CAVs to be controlled increases.

Table 5.6 Average $CO_2$ emissions for each CAV MPR

| CAV MPR (%) | Number of Conflicts | | | |
|---|---|---|---|---|
| | No control | Speed control | Merge control | Combined control |
| 0 | 372.0 | 371.6 | 371.6 | 371.6 |
| 1 | 372.3 | 369.1 | 370.0 | 369.1 |
| 3 | 374.0 | 368.0 | 368.3 | 365.9 |
| 5 | 372.8 | 366.1 | 365.5 | 360.6 |
| 10 | 377.0 | 368.8 | 365.5 | 358.7 |
| 25 | 378.5 | 369.2 | 363.1 | 356.0 |
| 50 | 383.1 | 369.8 | 364.0 | 356.1 |
| 75 | 397.0 | 370.4 | 363.1 | 356.0 |
| 90 | 403.0 | 363.6 | 357.9 | 343.0 |
| 95 | 408.2 | 364.1 | 356.1 | 344.0 |
| 97 | 409.3 | 363.5 | 353.7 | 342.2 |
| 99 | 412.0 | 364.0 | 352.9 | 342.2 |
| 100 | 411.2 | 363.2 | 353.1 | 341.0 |

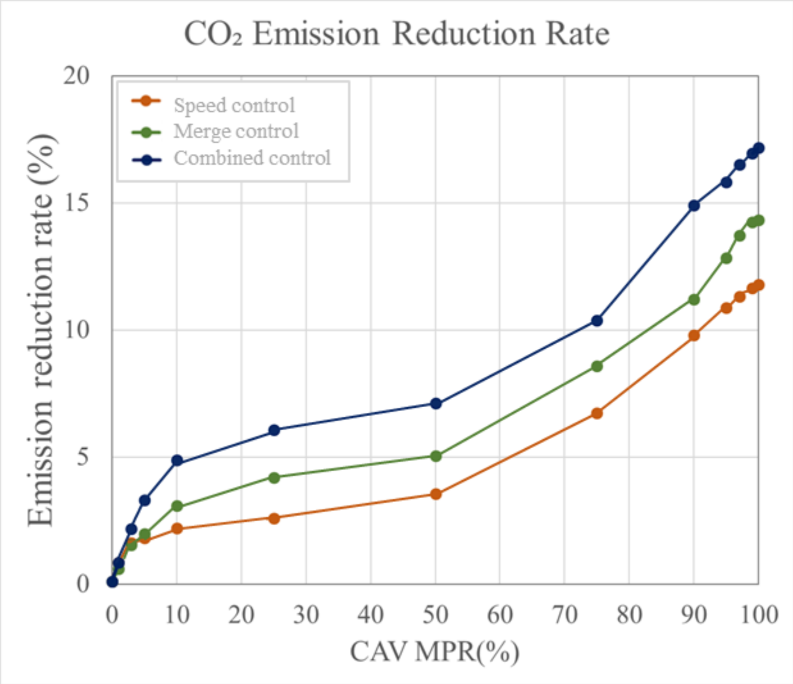


Figure 5.17 Improvement rate of $CO_2$ emissions in all MPR scenarios

# Chapter 6. Conclusions

This study suggests the work zone traffic control. The work zone traffic control consists of Merge control and Speed control. The merge control determines the traffic state through the predicted density of open lanes at each segment, and can flexibly respond to the traffic situation by determining “Merge” or “No merge”. The purpose of Speed control is to provide a sufficient vehicle gap to merging vehicles through “Slow down” or “No speed limit” control depending on the predicted density of open lanes for upstream vehicles. A short−term prediction model and a PID controller are applied to Merge control for work zones. The prediction model is used for a number of upstream segments from a work zone in order to respond sensitively to traffic flow changes in the road work situations. Traffic state prediction using GRU models is being used on having high accuracy even in a complex situation that is affected by the traffic flow in neighboring segments and lanes. The proposed method decides whether merging in open lanes can be allowed by comparing predicted density with the density that would cause severe congestion, and hence suppresses unnecessary merging. In a road work situation, vehicles can only pass through the work zone by open lanes. Since the discharge flow rate of open lanes becomes the flow rate of the work zone, it is necessary to prevent severe congestion at those open lanes by efficient control logic. Therefore, the proposed work zone traffic control also applies PID control for each segment to relieve the reduction in road capacity. This study considers the error into PID control to prevent the density of open lanes from exceeding the threshold that causes congestion to worsen. When the “Merge” strategy is chosen, PID control can prevent excessive merging.

Using microsimulation VISSIM, the work zone traffic control was implemented on a calibrated real world network that includes an actual work zone network of 4−to−3 lanes. To obtain reasonable simulation results, the calibration was conducted for not only the general traffic flow but also the work zone impact for each lane. The results indicated that negative impact of merge in work zones was relieved. The proposed work zone traffic control dispersed and relocated the concentrated number of merging vehicles from the closest segment near the work zone to the upstream segments. The speed at which vehicles merge increased, while the density in open lanes was maintained below the severe congestion threshold. The analysis for different levels of CAV MPR shows that the work zone traffic control can be the surest means to manage work zone when CAVs are adopted in early stage. The larger the CAV MPR, the larger improvement in travel time.

The work zone traffic control provides merge guidance and speed limit only for CAVs and does not perform any control for MVs that do not have any connectivity. However, MVs also can receive the information of merge points and speed limit through a variable message sign or navigation system although the issues on the compliance rate remain. Therefore, more comprehensive work zone traffic control may be required considering MVs and their compliance behaviors.

# BIBLIOGRAPHY

ATKINS. (2016). Research on the Impacts of Connected and Autonomous Vehicles(CAVs) on Traffic Flow, Report of Department for Transport, United Kingdom.

Beacher, A. G., Fontaine, M. D., & Garber, N. J. (2004). Evaluation of the late merge work zone traffic control strategy (No. FHWA/VTRC 05-R6). Virginia Transportation Research Council.

Bauza, R., & Gozálvez, J. (2013). Traffic congestion detection in large-scale scenarios using vehicle-to-vehicle communications. Journal of Network and Computer Applications, 36(5), 1295-1307.

Cassidy, M. J., & Bertini, R. L. (1999). Some traffic features at freeway bottlenecks. Transportation Research Part B: Methodological, 33(1), 25-42.

Chen, M., & Chien, S. I. (2001). Dynamic freeway travel-time prediction with probe vehicle data: Link based versus path based. Transportation Research Record: Journal of the Transportation Research Board, 1768(1), 157–161.

Chung, K., Rudjanakanoknad, J., Cassidy, M. J. (2007). Relation between traffic density and capacity drop at three freeway bottlenecks. Transportation Research Part B: Methodological, 41(1), 82–95. https://doi.org/10.1016/j.trb.2006.02.011

Chatterjee, I., Edara, P., Menneni, S., & Sun, C. (2009). Replication of work zone capacity values in a simulation model. Transportation research record, 2130(1), 138-148.

Carlson, R. C., Papamichail, I., & Papageorgiou, M. (2013). Comparison of local feedback controllers for the mainstream traffic flow on freeways using variable speed limits. Journal of Intelligent Transportation Systems, 17(4), 268-281.

Cho, K., Van Merriënboer, B., Gulcehre, C., Bahdanau, D., Bougares, F., Schwenk, H., & Bengio, Y. (2014). Learning phrase representations using RNN encoder-decoder for statistical machine translation. arXiv preprint arXiv:1406.1078.

Cho, K., Van Merriënboer, B., Gulcehre, C., Bahdanau, D., Bougares, F., Schwenk, H., & Bengio, Y. (2014). Learning phrase representations using RNN encoder–decoder for statistical machine translation. arXiv preprint arXiv:1406.1078.

Dougherty, M. S., & Cobbett, M. R. (1997). Short–term inter–urban traffic forecasts using neural networks. International Journal of Forecasting, 13(1), 21–31.

Du, S., & Razavi, S. (2019). Variable speed limit for freeway work zone with capacity drop using discrete–time sliding mode control. Journal of Computing in Civil Engineering, 33(2), 04019001.

Ding, J., Li, L., Peng, H., & Zhang, Y. (2020). A rule–based cooperative merging strategy for connected and Automated Vehicles. IEEE Transactions on Intelligent Transportation Systems, 21(8), 3436–3446. https://doi.org/10.1109/tits.2019.2928969

Elfar, A., Talebpour, A., & Mahmassani, H. S. (2018). Machine learning approach to short–term traffic congestion prediction in a connected environment. Transportation Research Record, 2672(45), 185–195.

Ge, Q., & Menendez, M. (2013). A simulation study for the static early merge and late merge controls at freeway work zones. In 13th Swiss Transport Research Conference (STRC 2013). STRC.

Ghiasi, A., Ma, J., Zhou, F., & Li, X. (2017, January). Speed harmonization algorithm using connected autonomous vehicles. In 96th Annual Meeting of the Transportation Research Board (No. 17–02568)

Gao, S., Huang, Y., Zhang, S., Han, J., Wang, G., Zhang, M., & Lin, Q. (2020). Short–term runoff prediction with GRU and LSTM networks without requiring time step optimization during sample generation. Journal of Hydrology, 589, 125188.

Hall, F. L., & Agyemang–Duah, K. (1991). Freeway capacity drop and the definition of capacity. Transportation research record, (1320).

Hajbabaie, A., Yeom, C., Rouphail, N. M., Rasdorf, W., & Schroeder,

B. J. (2015). Freeway work zone free−flow speed prediction from multi−state sensor data (No. 15−2004).

Jia, Y., Wu, J., & Xu, M. (2017). Traffic flow prediction with rainfall impact using a deep learning method. Journal of advanced transportation, 2017.

Kang, K. P., Chang, G. L., & Paracha, J. (2006). Dynamic late merge control at highway work zones: evaluations, observations, and suggestions. Transportation Research Record, 1948(1), 86−95.

Kwon, E., Brannan, D., Shouman, K., Isackson, C., & Arseneau, B. (2007). Development and field evaluation of variable advisory speed limit system for work zones. Transportation research record, 2015(1), 12−18.

Kuhn, B., Balke, K., Brydia, R., Theiss, L., Tsapakis, I., Ruback, L., & Le, M. (2016). Evaluation of variable speed limit pilot projects for Texas department of transportation. Transportation research procedia, 15, 676−693.

Karimi, M., Roncoli, C., Alecsandru, C., & Papageorgiou, M. (2020). Cooperative merging control via trajectory optimization in mixed vehicular traffic. Transportation Research Part C: Emerging Technologies, 116, 102663. https://doi.org/10.1016/j.trc.2020.102663

Lin, P. W., Kang, K. P. Kang, and Chang, G. L., "Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work−Zone Operations" In Journal of Intelligent Transportation Systems, Vol. 8 (3), pp 155−168, July 2004.

Lyles, R. W., Taylor, W. C., Lavansiri, D., & Grossklaus, J. (2004, January). A field test and evaluation of variable speed limits in work zones. In Transportation Research Board Annual Meeting (CD−ROM), Washington, DC.

Migletz, J., Graham, J. L., Anderson, I. B., Harwood, D. W., and Bauer, K. M. Work Zone Speed Limit Procedure. In Transportation Research Record 1657, TRB, National Research Council, Washington, D.C., 1999, pp. 24−30.

McCoy, P. T., & Pesti, G. (2001). Dynamic Late Merge−Control Concept for Work Zones on Rural Interstate

Highways. Transportation Research Record, 1745(1), 20-26.

Meyer, E. (2004). Construction area late merge (CALM) system. Technology Evaluation Report. Midwest Smart Work Zone Deployment Initiative. FHWA Pooled Fund study.

Oh, S., Byon, Y. J., Jang, K., & Yeo, H. (2015). Short-term travel-time prediction on highway: a review of the data-driven approach. Transport Reviews, 35(1), 4-32.

Pesti, G., Wiles, P., Cheu, R. L. K., Songchitruksa, P., Shelton, J., & Cooner, S. (2008). Traffic control strategies for congested freeways and work zones (No. FHWA/TX-08/0-5326-2). Texas Transportation Institute.

Radwan, E., Zaidi, Z., Harb, R. (2011). Operational evaluation of dynamic lane merging in work zones with variable speed limits. Procedia - Social and Behavioral Sciences, 16, 460–469. https://doi.org/10.1016/j.sbspro.2011.04.467

Roncoli, C., Bekiaris-Liberis, N., & Papageorgiou, M. (2017). Lane-changing feedback control for efficient lane assignment at motorway bottlenecks. Transportation Research Record, 2625(1), 20-31.

Rios-Torres, J., & Malikopoulos, A. A. (2018). Impact of partial penetrations of connected and automated vehicles on fuel consumption and traffic flow. IEEE Transactions on Intelligent Vehicles, 3(4), 453-462.

Ren, T., Xie, Y., & Jiang, L. (2020). Cooperative highway work zone merge control based on reinforcement learning in a connected and automated environment. Transportation research record, 2674(10), 363-374.

Shladover, S. E., Nowakowski, C., Lu, X. Y., & Hoogendoorn, R. (2014). Using cooperative adaptive cruise control (CACC) to form high-performance vehicle streams. California PATH Research Report (UCB-ITS-PRR-2014-7)

Sukennik, P., & PTV Group. (2018). Micro-simulation guide for automated vehicles. COEXIST (h2020-coexist. eu).

Saha, T., & Sisiopiku, V. P. (2020). Assessing work zone traffic control options for 3-to-1 lane closures. Journal of

transportation technologies, 10(01), 50.
Tarko, A. P., Kanipakapatnam, S. R., & Wasson, J. S. (1998). Modeling and Optimization of the Indiana Lane Merge Control System on Approaches to Freeway Work Zones, Part I. Joint Transportation Research Program, 345.
Taavola, D., Jackels, J., & Swenson, T. (2004). Dynamic late merge system evaluation: initial deployment on US route 10 summer 2003. In At the Crossroads: Integrating Mobility Safety and Security. ITS America 2004, 14th Annual Meeting and ExpositionITS America.
Tympakianaki, A., Spiliopoulou, A., Kouvelas, A., Papamichail, I., Papageorgiou, M., Wang, Y. (2014). Real-time merging traffic control for throughput maximization at Motorway Work Zones. Transportation Research Part C: Emerging Technologies, 44, 242-252. https://doi.org/10.1016/j.trc.2014.04.006
Talebpour, A., & Mahmassani, H. S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. Transportation Research Part C: Emerging Technologies, 71, 143-163.
Ullman, G. L., Schroeder, J. L., & Gopalakrishna, D. (2014). Use of technology and data for effective work zone management: Work zone ITS implementation guide (No. FHWA-HOP-14-008). United States. Federal Highway Administration. Office of Operations.
Van Jura, J., Haines, D., & Gemperline, A. (2018). Use of portable and dynamic variable speed limits in construction zones. Transportation research record, 2672(16), 35-45.
Walters, C. H., Pezoldt, V. J., Womack, K. N., Cooner, S. A., & Kuhn, B. T. (2000). Understanding road rage: Summary of first-year project activities (No. TX-01/4945-1,).
Xie, Y., Zhang, H., Gartner, N. H., & Arsava, T. (2017). Collaborative merging strategy for freeway ramp operations in a connected and autonomous vehicles environment. Journal of Intelligent Transportation Systems, 21(2), 136-147.
Xu, L., Lu, J., Ran, B., Yang, F., & Zhang, J. (2019). Cooperative

merging strategy for connected vehicles at highway on-ramps. Journal of Transportation Engineering, Part A: Systems, 145(6), 04019022.

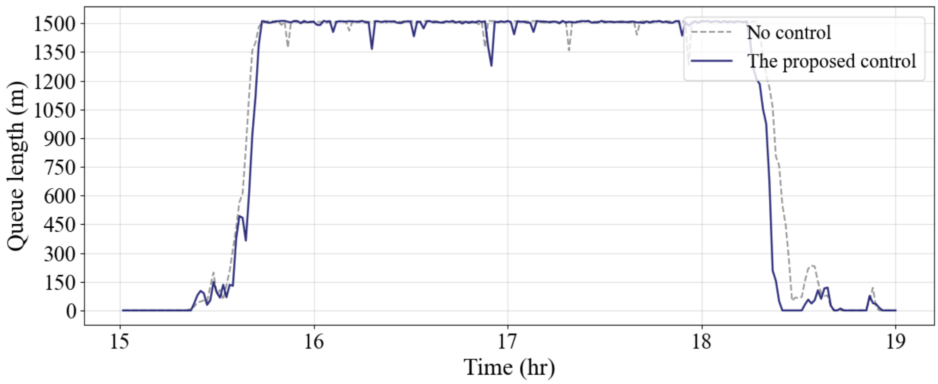
Yang, N., Chang, G.-L., Kang, K.-P. (2009). Simulation-Based study on A LANE-BASED signal system for Merge control at Freeway work zones. Journal of Transportation Engineering, 135(1), 9–17. https://doi.org/10.1061/(asce)0733-947x(2009)135:1(9)

Yang, X., Lu, Y., & Lin, Y. (2017). Optimal variable speed limit control system for freeway work zone operations. Journal of computing in civil engineering, 31(1), 04016044.

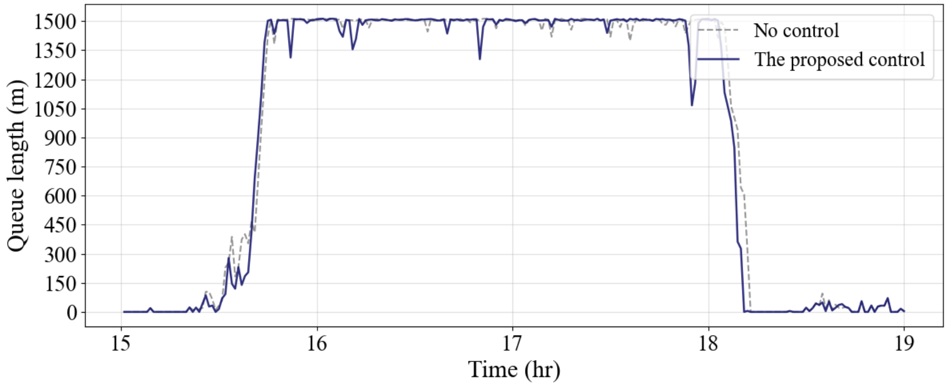
# APPENDIX

## Appendix A. Impact on Queue Length

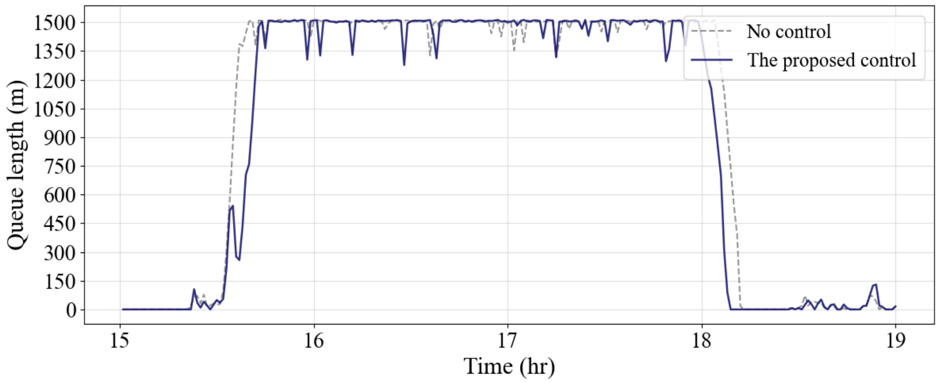
Combined control in MPR 1%




Combined control in MPR 3%

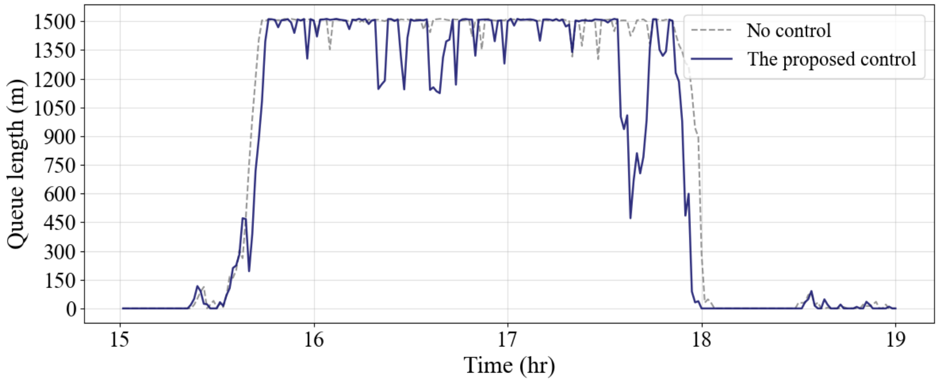



Combined control in MPR 5%

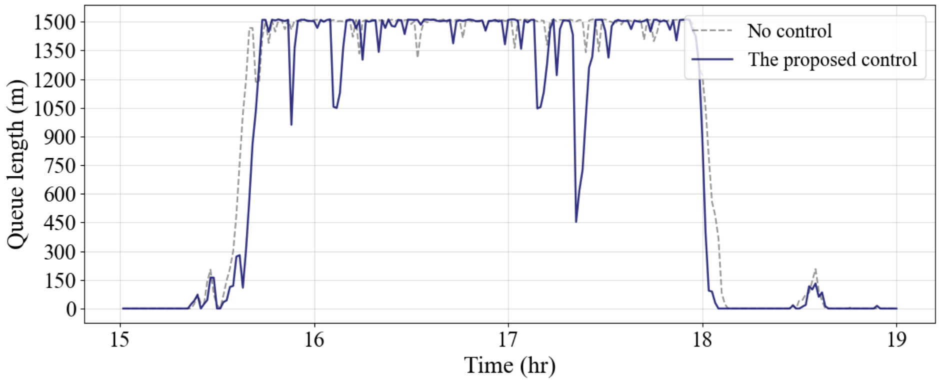



Appendix A.1. Maximum queue length profile in low MPR scenarios

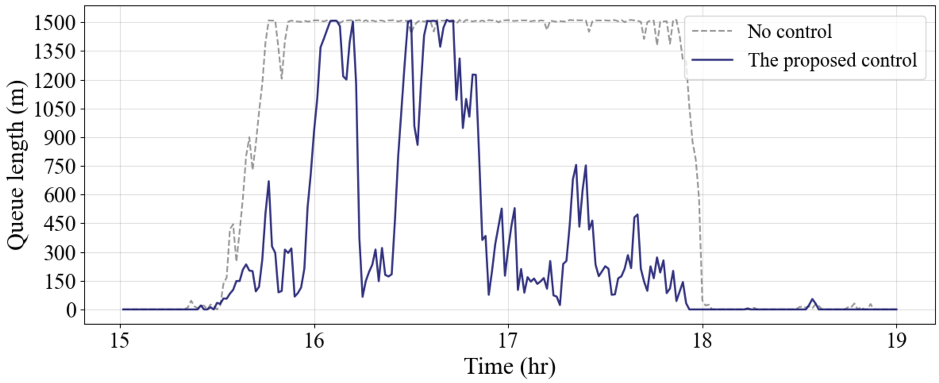
Combined control in MPR 10%




Combined control in MPR 25%

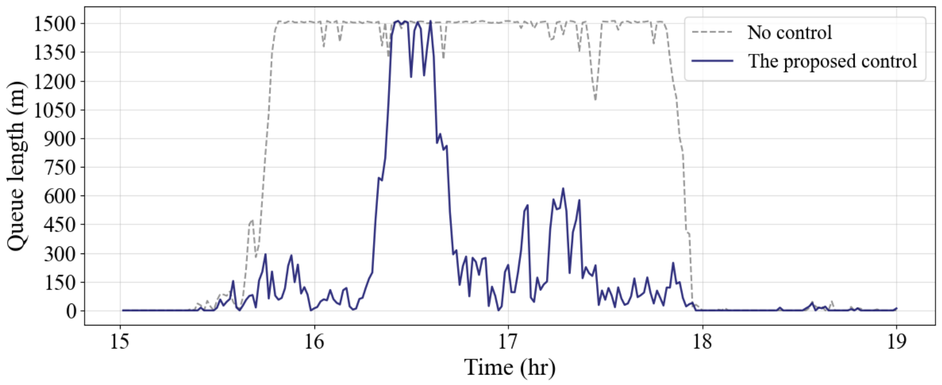



Combined control in MPR 50%

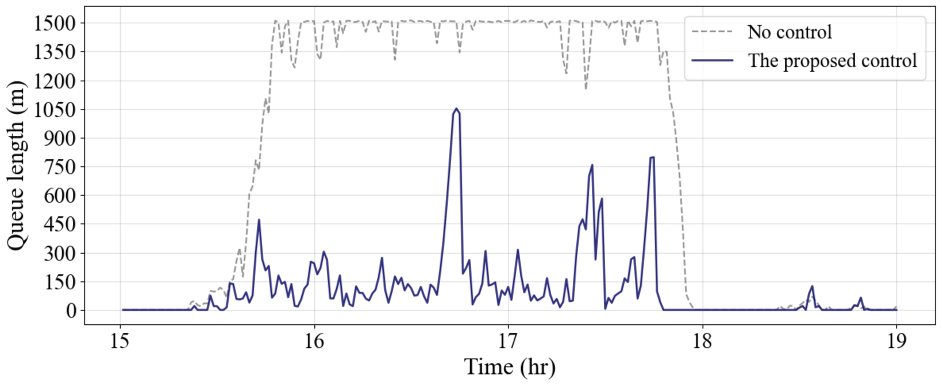



Appendix A.1. Maximum queue length profile in low MPR scenarios (Cont.)

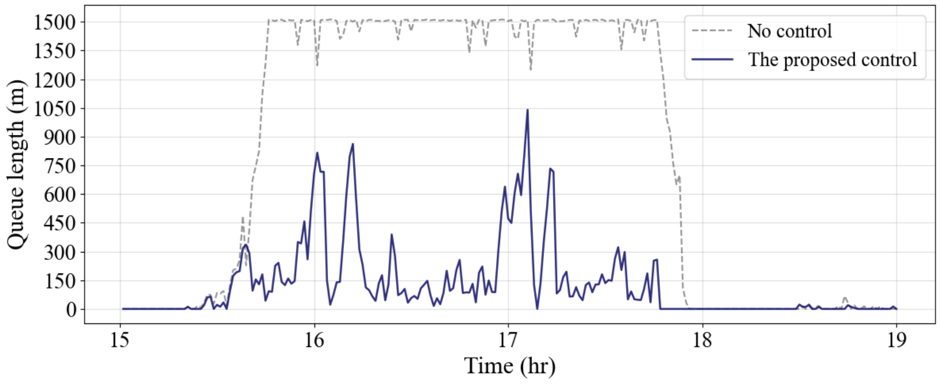
Combined control in MPR 75%




Combined control in MPR 90%

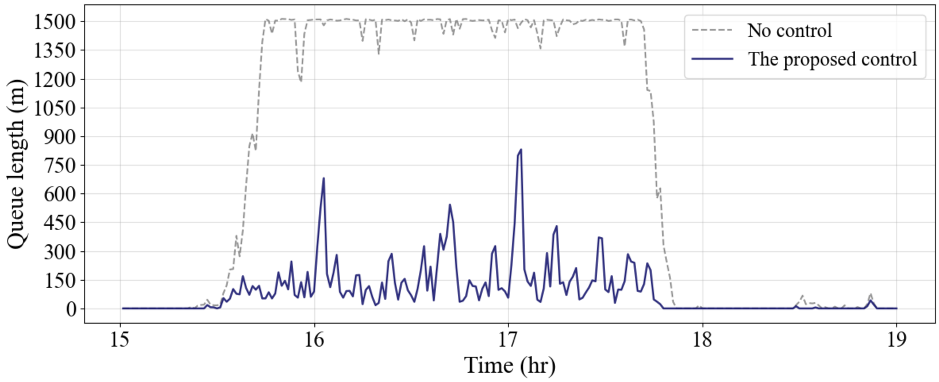



Combined control in MPR 95%

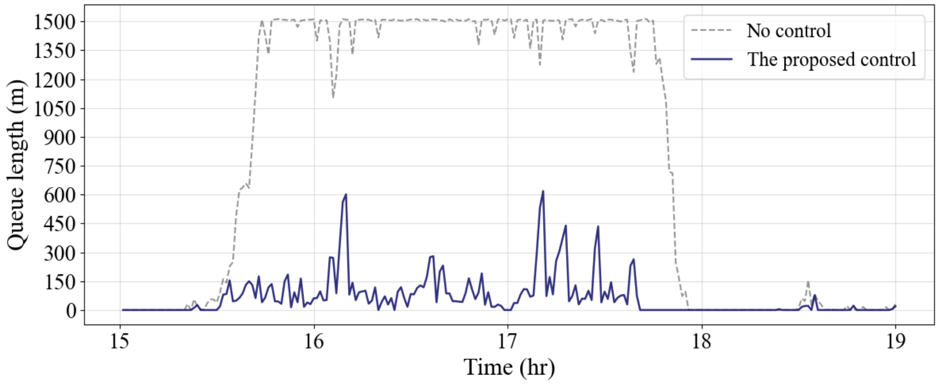



Appendix A.2. Maximum queue length profile in high MPR scenarios

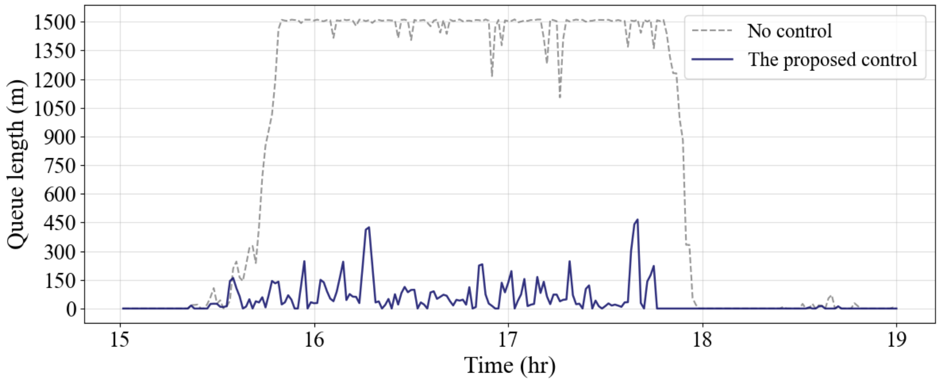
Combined control in MPR 97%




Combined control in MPR 99%



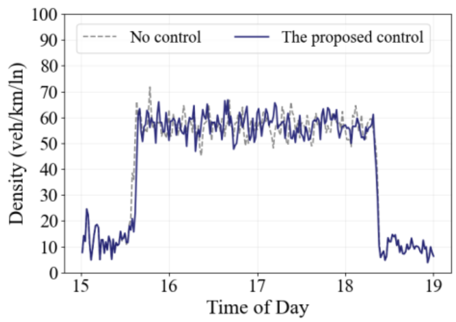

Combined control in MPR 100%



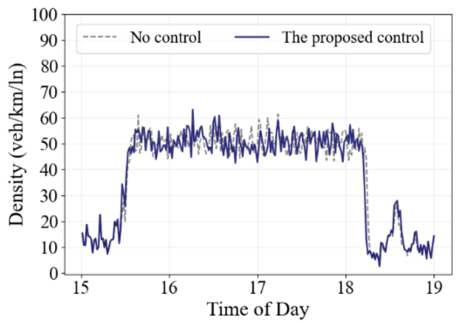

Appendix A.2. Maximum queue length profile in high MPR scenarios (Cont.)

# Appendix B. Impact on Density in Open Lanes

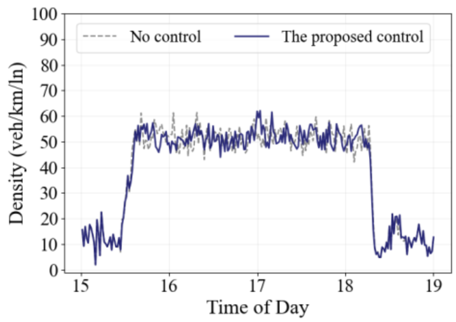
Combined control in MPR 1%



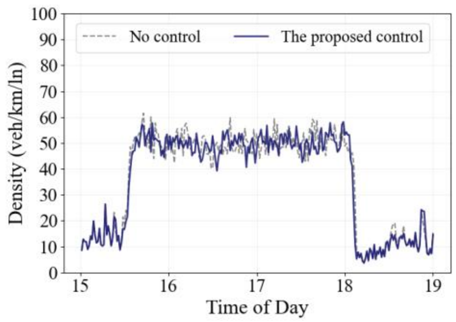

Combined control in MPR 3%



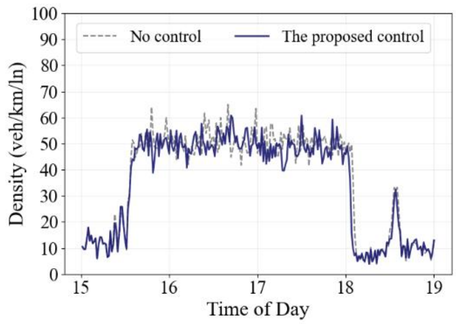

Combined control in MPR 5%



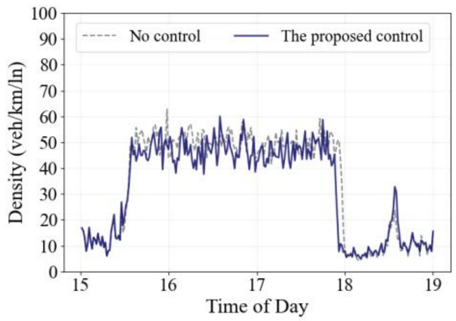

Combined control in MPR 10%




Combined control in MPR 25%

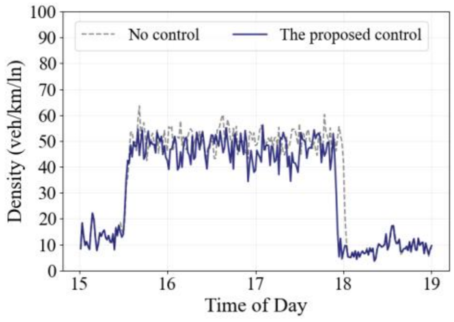



Combined control in MPR 50%

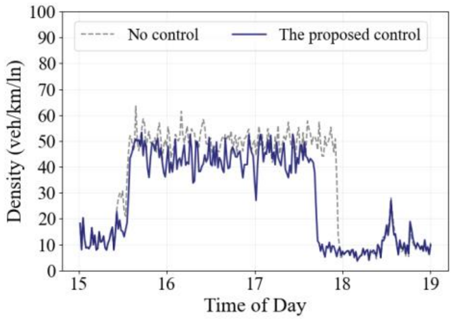



Appendix B.1. Merge relative frequency in low MPR scenarios

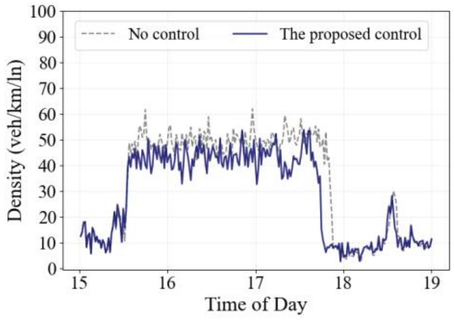
Combined control in MPR 75%



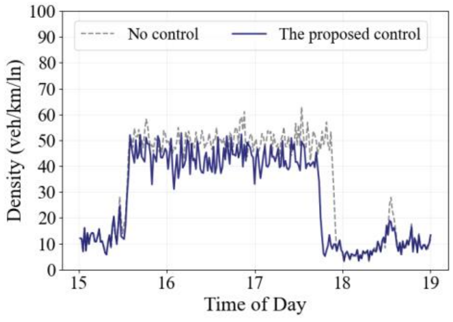

Combined control in MPR 90%



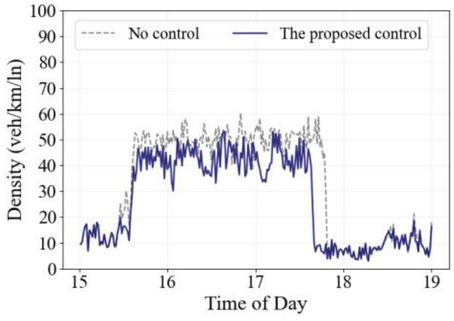

Combined control in MPR 95%



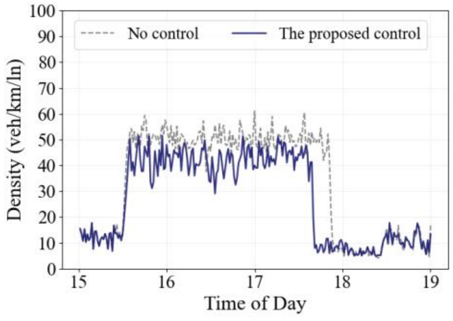

Combined control in MPR 97%




Combined control in MPR 99%




Combined control in MPR 100%




Appendix B.2. Merge relative frequency in high MPR scenarios

# 초 록

# PID-Based Freeway Work Zone Traffic Control with Short-Term Traffic State Prediction under Mixed Traffic Flow of CAV and MV

서울대학교 대학원
공과대학 건설환경공학부
김 선 호

도로공사로 인한 차로 폐쇄는 도로용량 감소의 주요 원인이다. 폐쇄차로의 대기행렬에 속한 차량들의 합류는 정체를 더 악화시킬 수 있다. 본 연구는 connected automated vehicles (CAV)가 혼재된 상황에서 정체를 완화하고 교통 효율을 개선하기 위한 고속도로 공사구간의 교통관리를 제안한다. 고속도로 공사구간 교통관리는 합류제어와 속도제어로 구성된다. 고속도로 공사구간 합류제어에는 Short-term 교통류 예측 모델과 Proportional-Integral-Derivative (PID) controller가 적용되었다. 본 합류제어는 각 segment 별 일반차로의 예측밀도를 통해 교통류 상태를 판단하고, “Merge” 혹은 “No merge”를 결정하여 교통상황에 유연하게 대응할 수 있다. “Merge”가 결정되었을 때, 극심한 혼잡의 임계값을 목표값으로 사용하는 PID control을 통해 적절한 합류차량 대수가 산정된다. 속도제어는 상류부 차량들에게 일반차로의 예측밀도에 따라 “Slow down” 혹은 “No speed limit”의 제어를 통해 합류차량들에게 충분한 차량간격을 제공하는데 목적이 있다. 본 연구에서 제안하는 공사구간 교통관리는 미시교통 시뮬레이션을 활용하여 현실에 맞춰 보정된 실제 고속도로 네트워크에 CAV와 일반차량이 혼재된 상황을 구현하여 효과분석 되었다. 시뮬레이션 결과에서 공사구간 교통관리가 공사구간 차량들의 합류행태를 개선시키는 것이 나타났다. 우선 공사구간 인근에 집중된 합류차량 대수가 상류부로 분산되었다. 또한 차량들의 저속 합류 비율이 감소했고, 일반차로의 밀도가 극심한 혼잡을 유발하는 임계값 이하로 유지되었다. 결과적으로 본 연구에서 제안하는 공사구간 교통관리는 교통상황에 알맞는 합류차량 대수와 속도제한 값을 제공하여 공사구간의 운영성, 안전성, 환경성 지표를 개선시켰다.

**주요어** : 공사구간, 교통관리, 교통류 예측, 자율협력주행차, 합류제어, 속도제어
**학 번** : 2015-22919