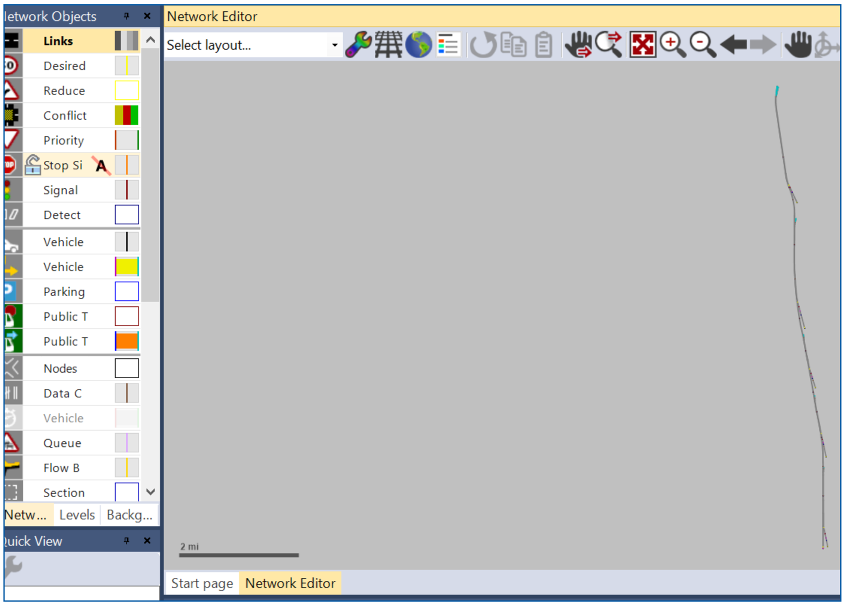
MOUNTAIN-PLAINS CONSORTIUM

MPC 22-486 | Q. Wang and X. Yang

DESIGN AND EVALUATE COORDINATED RAMP METERING STRATEGIES FOR UTAH FREEWAYS



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Technical Report Documentation Page

1. Report No. MPC-641	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Design and Evaluate Coordinated Ramp Metering Strategies for Utah Freeways		5. Report Date September 2022 6. Performing Organization Code
7. Author(s) Qinzheng Wang Xianfeng Yang		8. Performing Organization Report No. MPC 22-486
9. Performing Organization Name and Address University of Utah Salt Lake City, UT 84112		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Mountain-Plains Consortium North Dakota State University PO Box 6050, Fargo, ND 58108		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

During the past few decades, ramp metering control has been widely implemented in many U.S. states, including Utah. Numerous studies and applications have demonstrated that ramp metering control is an effective strategy to reduce overall freeway congestion by managing the amount of traffic entering the freeway. Ramp metering controllers can be implemented as coordinated or uncoordinated systems. Currently, Utah freeway on-ramps are operated in an uncoordinated way. Despite improvements to the operational efficiency of mainline flows, uncoordinated ramp metering will inevitably create additional delays to the ramp flows. Therefore, this project aims to assist the Utah Department of Transportation (UDOT) in deploying coordinated ramp metering systems and evaluating the performance of deployed systems. First, we leverage a method to identify existing freeway bottlenecks using current UDOT datasets, including PeMs and ClearGuide. Based on this, we select the site that may benefit from coordinated ramp metering from those determined locations. A VISSIM model is then developed for this selected corridor and the VISSIM model is calibrated based on collected traffic flow data. We apply the calibrated VISSIM model to conduct simulations to evaluate system performance under different freeway mainline congestion levels. Finally, the calibrated VISSIM model is leveraged to evaluate the coordinated ramp metering strategy of the bottleneck algorithm from both operational and safety aspects.

17. Key Word Ramp metering, Coordinated ramp metering, Bottleneck, Corridor, Bottleneck algorithm.	18. Distribution Statement Public distribution

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 43	22. Price n/a

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Design and Evaluate Coordinated Ramp Metering Strategies for Utah Freeways

Qinzheng Wang
Ph.D.
Department of Civil and Environmental EngineeringUniversity of Utah
Salt Lake City, Utah, 84112
Email: qinzheng.wang@utah.edu

Xianfeng (Terry) Yang
Assistant Professor
Department of Civil and Environmental EngineeringUniversity of Utah
Phone: (801) 585-1290
Salt Lake City, Utah, 84112
Email: x.yang@utah.edu

September 2022

Acknowledgments

This research is sponsored by the US Department of Transportation Regional Transportation Center Mountain-Plains Consortium and the Utah Department of Transportation (as cost share/matching fund).

Disclaimer

ABSTRACT

During the past few decades, ramp metering control has been widely implemented in many U.S. states, including Utah. Numerous studies and applications have demonstrated that ramp metering control is an effective strategy to reduce overall freeway congestion by managing the amount of traffic entering the freeway. Ramp metering controllers can be implemented as coordinated or uncoordinated systems. Currently, Utah freeway on-ramps are operated in an uncoordinated way. Despite improvements to the operational efficiency of mainline flows, uncoordinated ramp metering will inevitably create additional delays to the ramp flows. Therefore, this project aims to assist the Utah Department of Transportation (UDOT) in deploying coordinated ramp metering systems and evaluating the performance of deployed systems. First, we leverage a method to identify existing freeway bottlenecks using current UDOT datasets, including PeMs and ClearGuide. Based on this, we select the site that may benefit from coordinated ramp metering from those determined locations. A VISSIM model is then developed for this selected corridor and the VISSIM model is calibrated based on collected traffic flow data. We apply the calibrated VISSIM model to conduct simulations to evaluate system performance under different freeway mainline congestion levels. Finally, the calibrated VISSIM model is leveraged to evaluate the coordinated ramp metering strategy of the bottleneck algorithm from both operational and safety aspects.

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LIST OF ACRONYMS

ADOT	Arizona Department of Transportation
ARMS	Advanced Real-Time Metering System
HERO	Heuristic Ramp Metering Coordination
LOS	Level of Service
MP	Mileposts
PeMs	Performance Measure System
SWARM	System-Wide Adaptive Ramp Metering
TMS	Traffic Monitoring Stations
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

Ramp metering is an effective strategy to improve freeway mainline operational efficiency by regulating the traffic flow entering the freeway mainstream from on-ramps. In general, ramp metering strategies can be classified as coordinated ramp metering and uncoordinated ramp metering. When operating an uncoordinated ramp metering, the metering rate and on/off statuses will be determined by local traffic conditions. Uncoordinated ramp metering strategies include fixed, local, and corridor-responsive systems. Despite improvements to the operational efficiency of mainline flows, ramp metering will inevitably create additional delays to the ramp flows. As traffic demand for a freeway facility increases, mitigating mainline congestion could move beyond the capability of uncoordinated ramp metering. Recognizing such limitations, the UDOT Traffic Management Division is proposing to deploy coordinated ramp metering systems in Utah, which will integrate several upstream ramp meters (RMs) to alleviate one or several downstream bottlenecks.

This project collects related data from UDOT to first conduct a network-wide analysis to identify current freeway bottlenecks in Utah and select the site that may benefit from coordinated ramp metering techniques. A VISSIM model for performance analysis is created based on the corridor chosen. Before running simulations, we calibrate the VISSIM model using traffic flow data gathered from PeMs. The calibrated VISSIM model is then used to conduct experimental investigations to answer the fundamental question, “To achieve a certain freeway congestion level, how many additional delays will be created on those ramps?”

Finally, the calibrated VISSIM model is applied to test the coordinated ramp metering control strategy of the bottleneck algorithm. According to simulation results, the bottleneck method can reduce freeway mainline time. Sensitivity analysis is used to examine different levels of improvement for freeway mainstream operations. It should be noted that the coordinated ramp metering control technique may result in uneven on-ramp delay distribution. Then we conduct more simulation tests to see how the system performs when the on-ramp delays are within a certain range.

1. INTRODUCTION

1.1 Problem Statement

Ramp metering control has been widely implemented in various places across the United States, including Utah, over the last few decades. It has been established that ramp metering can provide numerous benefits in terms of mobility, safety, and the environment. First, by regulating the volume of vehicles entering the motorway, it can reduce overall freeway congestion and delay while increasing freeway traffic throughput. Second, collisions on the freeway can be prevented by breaking up on-ramp platoons that merge onto the freeway. Finally, reducing long periods of stop-and-go traffic on the freeway due to smooth merging traffic can reduce vehicle emissions and fuel consumption. In general, ramp metering controllers can be designed as coordinated or local systems. The metering rate and on/off statuses of an uncoordinated RM are determined by local traffic conditions. Fixed, local, and corridor-responsive systems are examples of uncoordinated RM techniques. In conclusion, there are at least four levels of RM control measures, three of which are in use in Utah.

Table 1.1 Ramp metering control in Utah

Ramp Control Strategy	Description	Deployment in Utah
Fixed	Fixed time-of-day schedule and rate, no adjustments from mainline detection, queue detectors can modify rate in response to queues.	73%
Local	Fixed time-of-day window of metering operations, responsive to mainline detection to begin metering period. Metering rate fluctuates within 6 occupancy levels from mainline detection. Ramp queue detectors can modify the rate in response to queues.	5%
Corridor-responsive	Fixed time-of-day window of metering operations, responsive to mainline detection to begin and end metering operations. Metering rate fluctuates within 6 occupancy levels from mainline detection. Additionally, downstream bottleneck will create additional metering commands for overall segment volume reduction from on-ramps. Ramp queue detectors can modify the rate in response to queues.	22%
Coordinated	Ramp rates adjust based on adjacent and downstream mainline detectors. Ramp controllers communicate to balance queues and delays. Queue detectors on ramp cannot increase rate.	None

Despite the improvements to the operational efficiency of mainline flows, there are two main limitations for local ramp metering. Firstly, it will be highly efficient if there is an unconstrained vehicle storage space for the on-ramps. However, ramp storage is limited in the real traffic network; this may cause on-ramp queue overspill, resulting in interference with adjacent street traffic. Second, ramp metering will inevitably create additional delays to the ramp flows. As traffic demand for a freeway facility increases, mitigating mainline congestion could move beyond the capability of uncoordinated ramp metering. Recognizing such limitations, the UDOT Traffic Management Division is proposing to deploy coordinated RM systems in Utah, which will integrate several upstream RMs to alleviate one or several downstream bottlenecks.

1.2 Objectives

The primary objective of this research project is to help UDOT identify freeway bottleneck locations that are suitable for coordinated ramp metering control and evaluate both the safety and operational performances of the system.

The secondary objective of this research project is to study the additional delays created to the ramps by ramp metering controls when a certain congestion level on the freeway mainline is expected to be reached.

1.3 Scope

Task 1: Literature Review

Task 1 focuses on conducting a literature review on coordinated ramp metering control methods and field applications (e.g., ADOT strategies).

Task 2: Identify existing freeway bottlenecks

This task provides a system-wide analysis to identify existing freeway bottlenecks using current UDOT datasets (e.g., ClearGuide and PeMS) and determine the locations of freeway-intersection interchanges that may benefit from coordinated ramp metering control.

Task 3: Develop VISSIM model to evaluate the ramp metering system

This task develops a generic VISSIM simulation model to evaluate the coordinated ramp metering system under different traffic flow patterns and answer the key question “To achieve a certain freeway congestion level, how many additional delays to those ramps will be created?”

Task 4: Evaluate the performance of coordinated ramp metering control

Using the simulation data from task 3, this task develops models to evaluate the safety performance of coordinated ramp metering controls in terms of quantifying the potential rear-end and merging crash risks.

Task 5: Extended performance evaluation of coordinated ramp metering control

This task is the extended evaluation of task 4. It aims to leverage the developed VISSIM model to significantly free up mainline capacity at the expense of the ramps. It will test two to three model scenarios showing successively larger benefits to mainline flow, with the queue/delay situation on the ramps recorded for each scenario.

1.4 Outline of Report

This report documents the findings of the research and proceeds with the following sections:

- Introduction
- Literature review
- Existing freeway bottlenecks identification
- VISSIM model development and evaluation
- Evaluation of coordinated ramp metering
- Conclusions and key findings

2. LITERATURE REVIEW

2.1 Overview

This chapter describes the existing ramp metering strategies and algorithms. We begin with local ramp metering and then move on to coordinated ramp metering. Finally, we outline the ramp metering evaluation studies.

2.2 Local Ramp Metering Strategies

Local control is the practice of determining ramp meter rates solely depending on the conditions existing at a single ramp. This section reviews the commonly developed local ramp metering control algorithms.

The earliest algorithm for local ramp metering control implemented in the field is demand–capacity developed by Masher et al. (1975). The metering rate is measured by the downstream occupancy. If it is above the defined critical occupancy, the metering rate is set to the minimum rate. Otherwise, the metering rate is set to the difference between the upstream flow measurements and downstream capacity from the last time interval.

Jia et al. (2001) proposed an occupancy strategy by assuming that the left-hand side of the flow–occupancy fundamental diagram is approximated via a straight line. This strategy uses upstream sensor occupancy to measure congestion and leverages a linear equation to calculate the metering rate.

The above two strategies are open-loop control strategy types that have no feedback mechanism. This is because the output from the system in the current iteration is not used for the next iteration. Therefore, the open-loop control system is unreliable. Considering this, Papageorgiou et al. (1997) proposed a close-loop control strategy called ALINEA. This algorithm considers freeway occupancy as input and takes the metering rate as a control variable that responds to occupancy variation. ALINEA installs detectors on each downstream lane. The downstream detectors measure the occupancy rate and transmit it to the controller at a certain time interval. Then the difference between the measured occupancy and the desired occupancy threshold is calculated and the metering rate for the next time interval is determined. It is noticed that the metering rate for the previous time interval is also considered when computing the metering rate for the next time interval to ensure a smooth operation.

Numerous studies and field tests have demonstrated that ALINEA can achieve a good performance in maintaining a desired flow on the freeway. However, it may cause long queues on the on-ramp. Therefore, Zhang et al. extended ALINEA to avoid the ramp traffic to exceeding the capacity. Moreover, the concept of ALINEA was extended to various levels, including flow-based, upstream-occupancy-based, and upstream-flow-based versions of ALINEA, an adaptive version of ALINEA (Smaragdis et al., 2003).

Taylor et al. (1998) proposed a fuzzy logic to calculate the local metering rate to improve the control effectiveness. This algorithm includes three major components: fuzzification, rule evaluation, and defuzzification. The basic logic is that the numerical input variables are first converted to descriptive variables based on the fuzzy sets. Then those descriptive variables are leveraged to produce control strategies based on the “if-then” rules.

2.3 Coordinated Ramp Metering Strategies

Local ramp metering control strategies are not able to prevent a system-wide formation of congestion because it only responds to local traffic conditions. Therefore, it is essential to consider both local and system-wide information to compute the metering rate of each ramp for a corridor. Up to now, a number of coordinated ramp metering strategies have been proposed and applied.

The bottleneck algorithm was first proposed by Jacobson et al. (1989). This algorithm works at both the local level and system-wide level. At the local level, this algorithm uses historical data to calculate the metering rate to ensure the freeway demand does not exceed capacity. The algorithm at the system level is activated when two criteria are met. First, the occupancy at a potential bottleneck area exceeds a pre-defined occupancy threshold. Second, this area stores vehicles. Then the algorithm calculates the metering rate reductions applied to each meter in the area to reduce the number of vehicles entering the mainline.

Helper algorithm was first developed by Lipp et al. (1991). It includes a local traffic-responsive algorithm and a system-wide implementation with operational override features added. The on-ramps of the entire corridor are divided into six groups. Each meter within the control area selects one of six pre-defined available metering rates based on the localized upstream mainline occupancy. If the queue on a ramp surpasses a defined threshold for three consecutive time intervals, the central override feature reduces the metering rate by one level. This procedure is repeated until the issue is resolved. If the queue continues, all upstream ramps will be overridden, and metering levels will be restricted.

Zone algorithms are applied in Minnesota. This algorithm divides the freeway into multiple zones and the length of each zone varies from three to six miles, including several metered and non-metered ramps. The objective of this algorithm is to maintain the density of the freeway mainline below a certain threshold. The metering rate in the zone is based on the inflow and outflow of the zone. One of representative algorithms is stratified zone metering. This algorithm uses density as measurement and the goal is to control the total volume of a zone. That is to say, the increase in the mainline density is balanced by reducing the metering rates in the particular zone.

The system-wide adaptive ramp metering (SWARM) algorithm was developed by Paesani et al. (1997). The metering rates are calculated by forecasting traffic. This algorithm works in coordinated control level (SWARM1) and local control level (SWARM2). In SWARM1, the future state of traffic density is estimated using linear regression based on collected traffic data. Then the coordinated metering rates are computed according to the current and desired density values. Metering rates in SWRAM2 are computed using density values derived locally from distance headway measurements. The more restrictive metering rate is then used.

The advanced real time metering system (ARMS) was developed by Liu et al. This system applies a proactive metering algorithm to mitigate the risk of congestion. It includes three operational control levels: free-flow control, congestion prediction, and congestion resolution (Messer, 1993). It is assumed that traffic flow varies slowly over time and control decisions are made based on a free flow model. Congestion prediction is intended to predict traffic conditions and potential bottlenecks. Congestion reduction works to balance metering rates and congestion resolution time by considering both freeway and surface street conditions.

Heuristic ramp-metering coordination (HERO), developed by Papamichail et al., is an extended version of ALINEA. In HERO, each on-ramp is controlled by ALINEA, and this system calculates the desired ramp flow and estimates the ramp queue. Moreover, all on-ramps are connected to each other by a central controller. When a bottleneck on the freeway mainline is determined, the central controller assigns the on-ramp in the bottleneck segment as master ramp and others are defined as slaves. Then the algorithm is activated to increase the capacity of the master ramp. The HERO system has been applied in Melbourne, Australia.

2.4 Ramp Metering Evaluation Studies

Within the last several decades, numerical studies have been conducted to evaluate a series of ramp metering strategies, which are summarized in Table 2.1.

Table 2.1 Summarization of ramp metering evaluation

Year	Authors	Control type	Evaluation
1989	Jacobson et al.	Coordinated	Travel time
1991	Louis et al.	Coordinated	Vehicle miles traveled
1994	Liu et al.	Coordinated	Congestion duration
1994	Stephanedes	Coordinated	Travel time
1997	Chen et al.	Local and coordinated	Travel time
1997	Papageorgiou et al.	Local	Travel time
1998	Taylor et al.	Coordinated	Travel time
2000	Taylor et al.	Coordinated	Travel time
2004	Smargdis et al.	Local	Traffic flow and density
2005	Chu et al.	Local	Travel time
2006	Lee et al.	Local	Crash potential
2007	Ahn et al.	Coordinated	Vehicle miles traveled
2008	Papamichail et al.	Local and coordinated	Traffic flow
2009	Ghods et al.	Local	Travel time
2010	Geroliminis et al.	Coordinated	Total delay
2010	Papamichail et al.	Coordinated	Queue length and traffic flow
2011	Demiral et al.	Local	Traffic flow
2011	Zhao et al.	Coordinated	Travel time
2012	Jiang et al.	Local	Travel time
2012	Yu et al.	Local	Travel time
2013	Xu et al.	Local	Traffic flow
2014	Wang et al.	Local	Traffic flow
2015	Agarwal et al.	Coordinated	Traffic density
2015	Landman et al.	Coordinated	Travel time
2016	Abuamer et al.	Local	Travel time and traffic flow
2017	Abuamer et al.	Local	Traffic flow and occupancy
2017	Lu et al.	Local	Travel time
2018	Abuamer et al.	Local	Travel time
2018	Frejo et al.	Local	Travel time
2019	Chen et al.	Coordinated	Travel time
2019	Kontorinaki et al.	Local and coordinated	Traffic flow and density
2019	Wu et al.	Local and coordinated	Traffic flow and delay
2020	Ghanbartehrani et al.	Local	Traffic flow
2020	Han et al.	Coordinated	Traffic flow

3. EXISTING FREEWAY BOTTLENECK IDENTIFICATION

3.1 Overview

This chapter first introduces the methodology of identifying bottlenecks for the freeway. Then we apply this methodology to provide a system-wide analysis to identify existing freeway bottlenecks using current UDOT datasets.

3.2 Methodology

We use the approach suggested by Zhang et al. (2013) to determine the freeway bottleneck in this research. Figure 3.1 depicts a typical motorway segment with traffic detector settings. This layout serves as the foundation for the methodologies outlined in this project. Each detector station, as illustrated in the figure, is made up of a series of inductive loop detectors. Detector stations separate the motorway length into multiple sections. Each sector has only one detector station. In Utah, these detectors may output a variety of traffic-related information such as speed, flow, and occupancy in a short time period. On-ramp detectors are classified into three types: passage, demand, and queuing detectors. Demand detectors are mounted just ahead of the stop bar in each metered ramp lane, and they detect the presence of a vehicle at the stop bar and activate the green traffic signal display for that lane. Passage detectors are mounted directly downstream of the stop bar and are used to count the number of vehicles entering the motorway. Queue detectors are put near the ramp's connection with the neighboring surface street to help determine when queues begin to exceed ramp capacity.

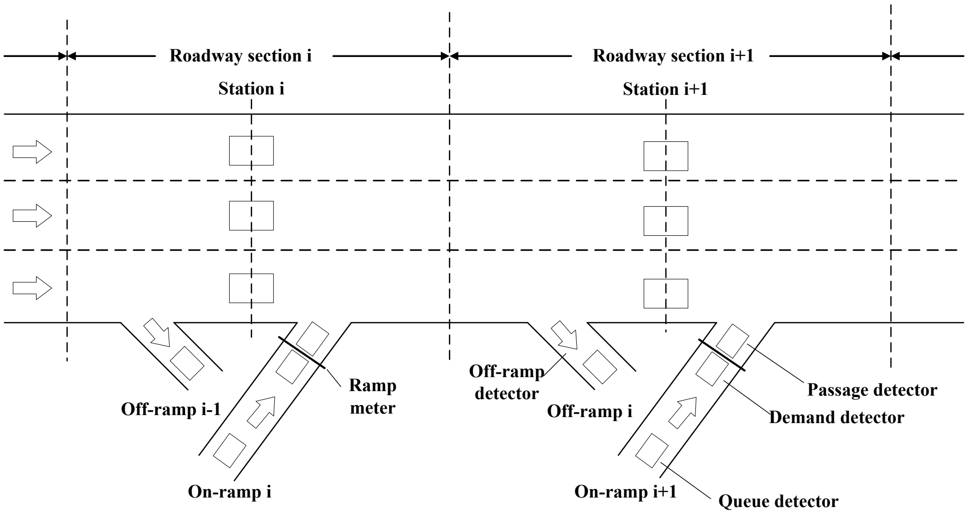


Figure 3.1 The layout of a typical freeway segment

Previously, traffic density was employed as an indicator to calculate the freeway level of services (LOS). LOS is a quantitative stratification of a performance measure or metrics that represent the quality of service. That is, LOS is utilized to determine whether or not the freeway is congested. However, using traffic density as the single variable to quantify congestion may be impractical and even lead to incorrect conclusions. This is because we can see a high density when multiple cars travel at high speeds. As a result, a high density may not accurately portray a congestion scenario, which includes poor speed, volume, and density. As a result, this study uses both density and speed to assess congestion levels.

Since the distance between two adjacent detectors is small (usually 0.5 miles), we assume vehicles can maintain a constant speed within each freeway section. Then the occupancy at the detector station i within time interval k can be represented as Eq. (3.1):

$$O(i,k) = \frac{\sum_{n=1}^{N(i,k)} \frac{l_n}{s_n}}{T} \tag{3.1}$$

where i is the index of detector station; k is the index of time interval; n is the vehicle index; N is the number of vehicles detected by the loop detectors; l_n is the effective length of each vehicle; s_n is the vehicle speed; T is the length of time interval.

Because all vehicles are assumed to travel at a constant speed, Eq. (3.1) can be transferred to

$$O(i,k) = \frac{N(i,k) * \bar{l}(i,k)}{\bar{s}(i,k) * T} \tag{3.2}$$

where $\bar{l}(i,k)$ is the average value of effective vehicle length; $\bar{s}(i,k)$ is the constant speed that vehicles travelling each road section.

Then Eq. (3.2) can be rewritten as

$$O(i,k) = \frac{V(i,k)}{\bar{s}(i,k)} * \bar{l}(i,k) \tag{3.3}$$

where $V(i,k)$ is the hourly traffic volume.

Comparing Eq. (3.1) and Eq. (3.3), the density can be calculated

$$d(i,k) = \frac{O(i,k)}{\bar{l}(i,k)} \tag{3.4}$$

When the density and speed are available, we can apply the following standards to determine if the bottleneck is detected.

$$d(i,k) > d_{cr} \tag{3.5}$$

$$\bar{s}(i,k) < s_{cr} \tag{3.6}$$

where d_{cr} and s_{cr} are the prespecified critical density and critical speed value.

3.3 Experimental Study

In order to make a comprehensive evaluation of the potential bottlenecks within Utah, we selected 14 freeway corridors recommended by UDOT engineers and evaluated them using the methods outlined above. The 14 candidate corridors are shown in Table 3.1.

Table 3.1 Candidate corridors of the potential bottlenecks within Utah

Freeway mainline	Direction	Starting MP	Ending MP	Time of Day
I-15	SB	313	310	AM
SR 201	EB	13	15	PM
I-80	WB	123	125	AM
I-15	NB	305	308	AM and PM
I-15	NB	289	291	AM and PM
I-15	NB	293	297	AM
I-15	SB	295	297	PM
I-15	SB	261	263	PM
I-15	SB	271	273	PM
I-15	NB	312	315	PM
I-80	WB	117	119	PM
I-215	EB	26	29	AM
SR 201	EB	13	15	PM
TOC	EB	12	14	PM
TOC	EB	12	14	PM

Given the impact of COVID 19 on travelers' daily travel, we collected data in October 2019 from performance measurement system (PeMS) for preliminary analysis. The traffic data displayed in PeMS is collected in real time from roadway detector stations. UDOT has over 720 traffic monitoring stations (TMS) installed on state roads, concentrated in urban areas. These sensors collect vehicle speed, volume, and classification data by lane, including ramps. Based on the results of the initial evaluation, the UDOT engineers recommended conducting a detailed analysis of three identified bottlenecks. They are NB of I-15 from Bangerter to 7200 S; SB of I-15 from I-215 to 90th S; WB 201 from I-15 to Bangerter.

For the three identified bottlenecks, we collected state traffic data from PeMS in October in 2017, 2018, 2019, and 2020 for analysis. Moreover, we also collected crash data from the Numetric database for safety analysis.

NB of I-15 from Bangerter to 7200 S

This corridor is approximately eight miles long, with 11 stations and five on-ramps and five off-ramps. Figure 3.2 depicts the general layout of this corridor.

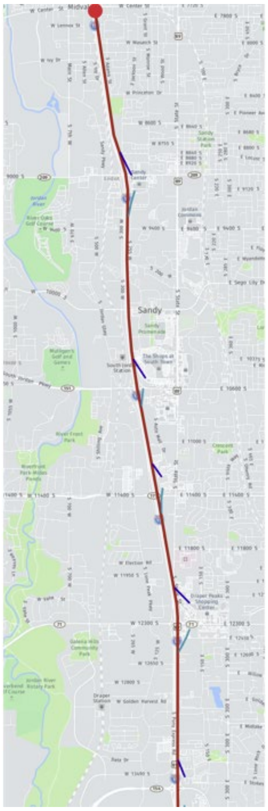


Figure 3.2 Layout of NB of I-15 from Bangerter to 7200 S

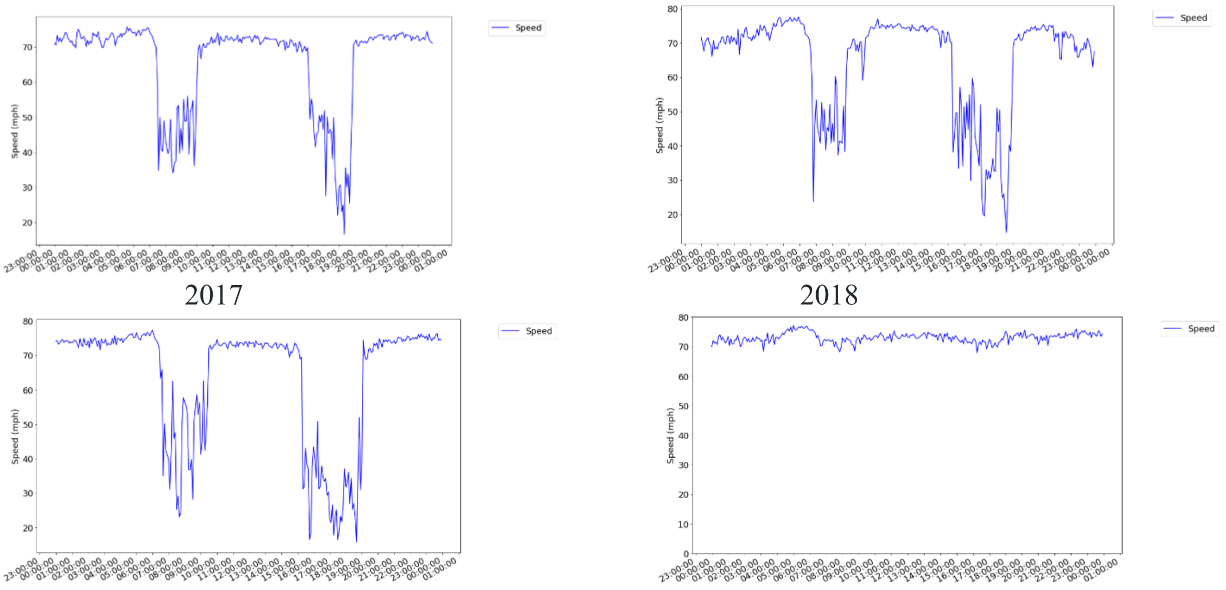
Based on the state traffic data collected from those stations, we can conduct analysis and the results can be summarized as shown in Table 3.2.

Table 3.2 Bottleneck information for NB of I-15 from Bangerter to 7200 S

Year	Number of weekdays	Bottleneck duration	Bottleneck frequency	Queue length (mile)
2017	21	7:05 - 8:30 AM 17:35 - 18:45 PM	66.67% (AM) 85.71% (PM)	7.51
2018	22	7:10 - 8:45 AM 16:40 -18:00 PM	54.54% (AM) 77.27% (PM)	7.81
2019	22	7:00 - 9:00 AM 16:30 - 18:00 PM	68.18% (AM) 90.91% (PM)	7.81
2020	20	None	0	0

Table 3.2 illustrates that this road experienced congestion in both the morning and afternoon in 2017, 2018, and 2019. In 2017, the traffic congestion lasted roughly an hour in both the morning and afternoon. In 2018, the traffic congestion lasted roughly 1.5 hours in both the morning and afternoon. In 2019, the morning congestion period was two hours and the afternoon congestion time was 1.5 hours. Furthermore, over the three years, afternoon congestion had been reported to be more prevalent than morning congestion. There are a few delays in October 2020, and the bottleneck tendency is unnoticeable within the days with bottlenecks owing to COVID-19.

Figure 3.3 depicts the speed distribution of the bottleneck location during a four-year period. We can see there is an obvious decrease in speed in the morning and afternoon in 2017, 2018, and 2019. This is because there was congestion during those time intervals, requiring vehicles to slow down.



2017

2018

2019

2020

Figure 3.3 Speed distribution of a sample day in various years of I-15 from Bangerter to 7200 S

SB of I-15 from I-215 to 90th S

This corridor is approximately 3.55 miles long, with seven stations and three on-ramps and two off-ramps. Figure 3.4 depicts the general layout of this corridor.

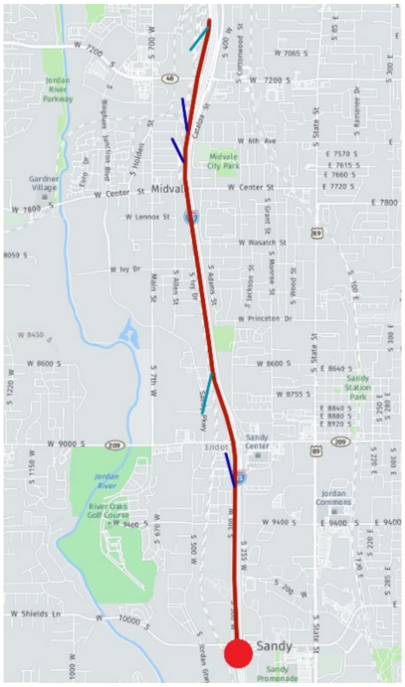


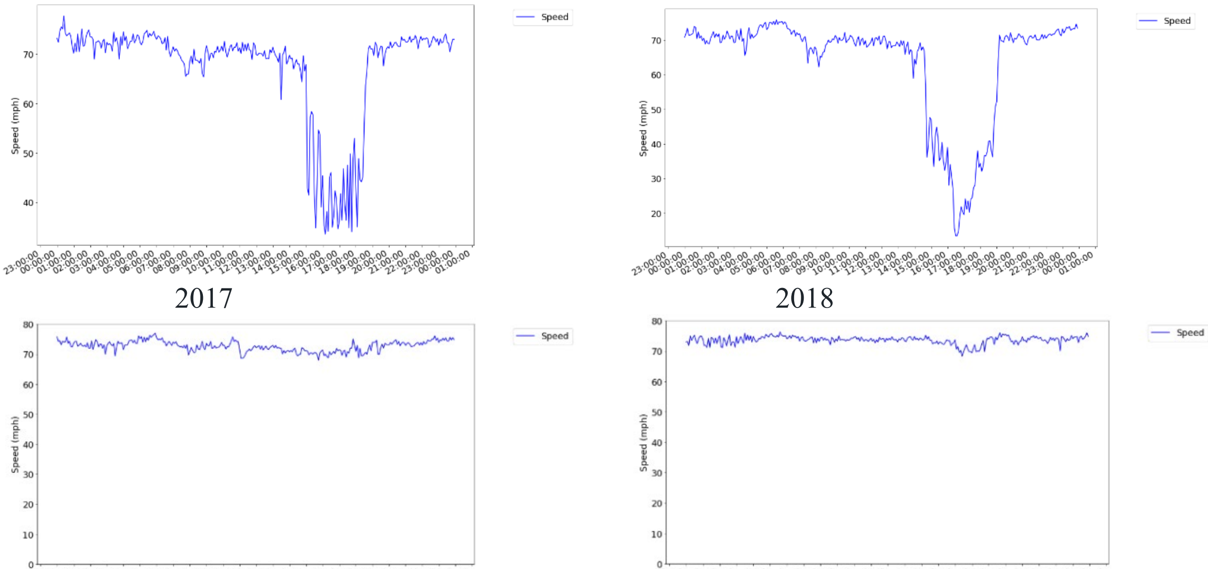
Figure 3.4 Layout of SB of I-15 from I-215 to 90th S

The result for this corridor is shown in Table 3.3. In 2017 and 2018, congestion was only recorded in the afternoon for this corridor. Congestion lasted approximately two hours in 2017 and three hours in 2018. In 2019 and 2020 there was no bottleneck.

Table 3.3 Bottleneck information for SB of I-15 from I-215 to 90th S

Year	Number of weekdays	Bottleneck duration	Bottleneck frequency	Queue length (mile)
2017	21	16:05 - 18:00 PM	95.24%	4.06
2018	22	15:45 -19:00 PM	90.91%	4.06
2019	22	None	0	0
2020	20	None	0	0

Figure 3.5 depicts the speed distribution of the bottleneck location over a four-year period. We can observe that there was a significant decrease in speed in the afternoon in 2017 and 2018 due to congestion. In 2019 and 2020, vehicles could travel along this corridor at high speed.



2017 2018

2017 2018

Figure 3.5 Speed distribution of a sample day in various years of SB of I-15 from I-215 to 90th S

WB 201 from I-15 to Bangerter

This corridor is approximately 3.36 miles long, with five stations and five on-ramps and three off-ramps. Figure 3.6 depicts the general layout of this corridor.

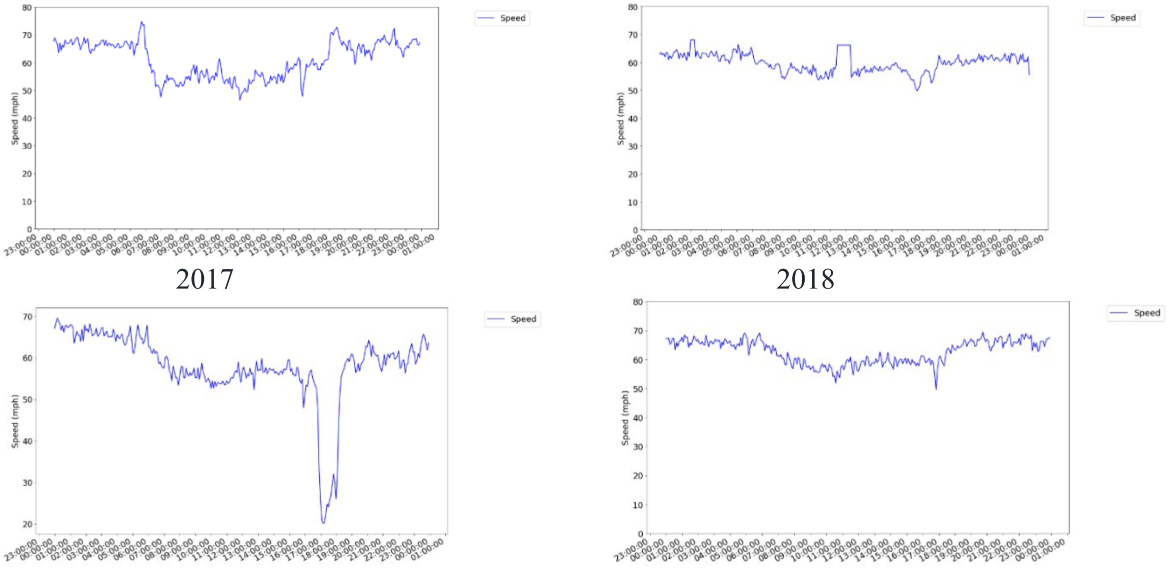
Figure 3.6 Layout of WB 201 from I-15 to Bangerter

Table 3.4 displays the result for this corridor. It can be observed that the congestion only existed in the afternoon for this corridor 2019 and it lasted approximately 1.5 hours. In 2017, 2018, and 2020 there was no bottleneck.

Table 3.4 Bottleneck information for WB 201 from I-15 to Bangerter

Year	Number of weekdays	Bottleneck duration	Bottleneck frequency	Queue length (mile)
2017	21	None	0	0
2018	22	None	0	0
2019	22	16:30 -18:00 PM	90.91%	3.65
2020	20	None	0	0

Figure 3.7 shows the speed distribution of the bottleneck point in the four-year period. We can see there is an obvious reduction tendency of speed in the afternoon 2019 due to congestion. In 2017, 2018 and 2020, vehicles could travel along this corridor at high speed.



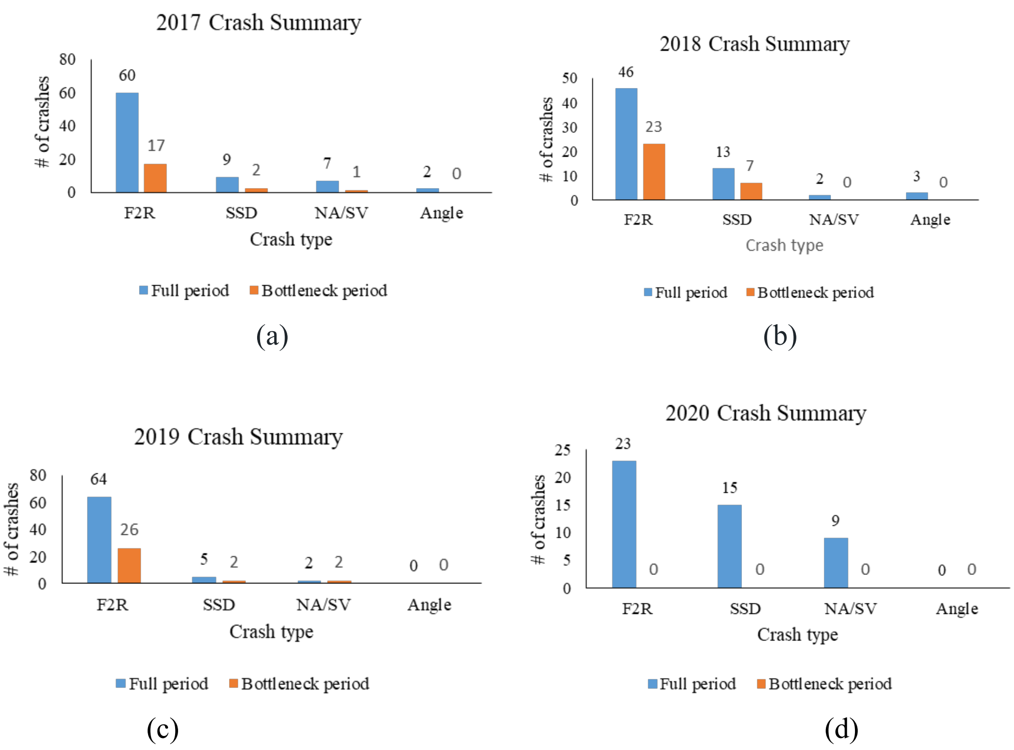
2017 2018

2017 2018

Figure 3.7 Speed distribution of a sample day in various years of WB 201 from I-15 to Bangerter

Safety analysis

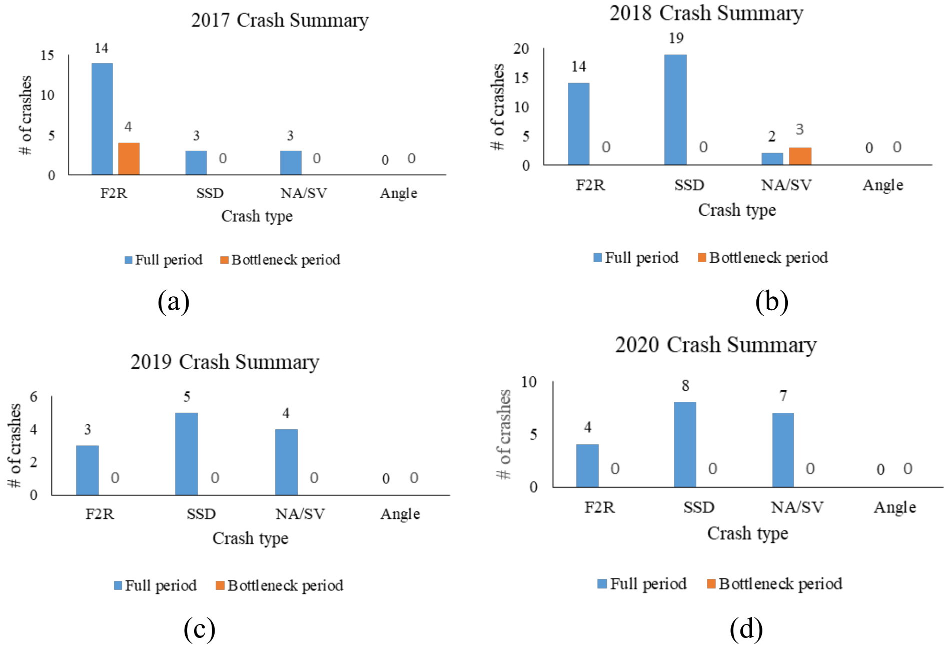
In this part, we conduct safety analysis along the three corridors. The raw data are from the Numetric database. By processing the crash data, we can summarize the number of different crash types incurred in the four years, as shown in Figure 3.8 – Figure 3.10.



(a) (b)

(c) (d)

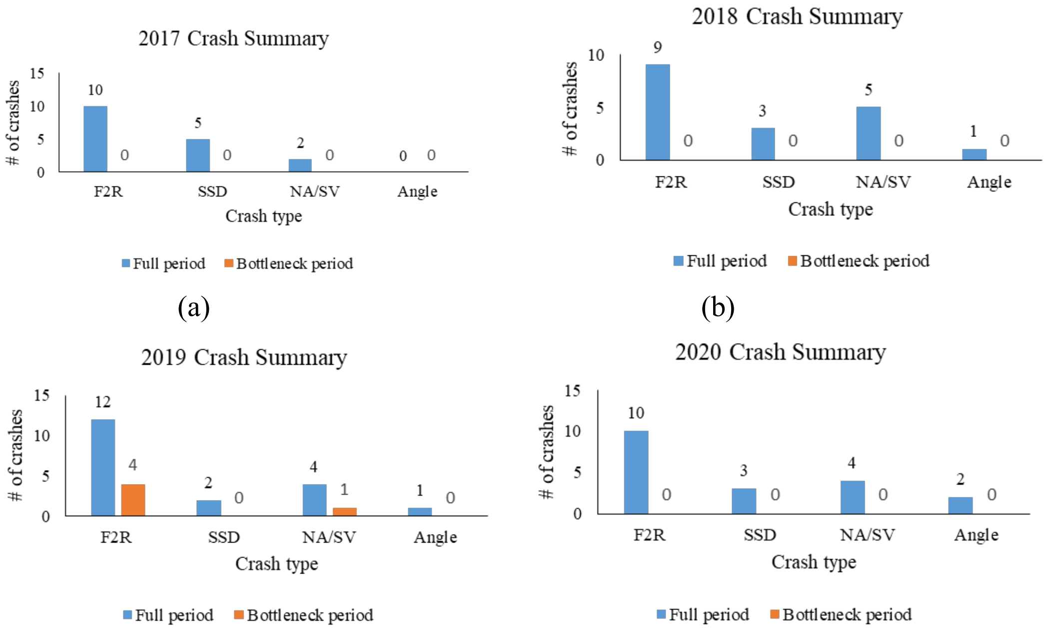
Figure 3.8 Crash summary of NB of I-15 from Bangerter to 7200 S



(a) (b)

(c) (d)

Figure 3.9 Crash summary of SB of I-15 from I-215 to 90thS



(a) (b)

(c) (d)

Figure 3.10 Crash summary of WB 201 from I-15 to Bangerter

Figures 3.8 – 3.10 show that the main crash types during the analysis period for the corridor of NB of I-15 from Bangerter to 7200 S and corridor of SB of I-15 from I-215 to 90th S are those of front to rear. The main crash type for the corridor of SB of I-15 from I-215 to 90th S is sideswipe same direction.

4. VISSIM MODEL DEVELOPMENT AND EVALUATION

4.1 Overview

This chapter first introduces the VISSIM software. Then we develop a VISSIM model that will be used to evaluate the coordinated ramp metering strategy, and the developed VISSIM is calibrated by using different UDOT data. Finally, the calibrated VISSIM model is used to conduct simulation and answer the key question, "To achieve a certain freeway congestion level, how many additional delays to those ramps will be created?"

4.2 VISSIM Software

This project leverages VISSIM to evaluate the current metering control strategy applied in the studied corridor, as well as further evaluate several coordinated ramp metering strategies. VISSIM is a microscopic, time step and behavior-based simulation model developed to model urban traffic and public transport operations and pedestrian flows under various conditions of vehicle demand composition, route decision, signal control, and others. Therefore, VISSIM is a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness (PTV Group 2018). VISSIM can take advantage of a variety of signal control logic. In addition to the built-in fixed-time functionality, there are several vehicle-actuated signal controls identical to signal control software packages installed in the field. In VISSIM some of them are built-in, some can be docked using add-ons and others can be simulated through the external signal state generator that allows the design of user-defined signal control logic. The VISSIM COM interface is a very useful tool that defines a hierarchical model in which the functions and parameters of the simulator originally provided by the GUI can be manipulated by programming.

The quality of vehicle modeling, such as the methods for moving cars across the network, determines the accuracy of a traffic simulation model. Unlike simpler models that use constant speeds and deterministic car following logic, VISSIM employs Wiedemann's psycho-physical driving behavior model. The Wiedemann car-following model is shown in Figure 4.1.

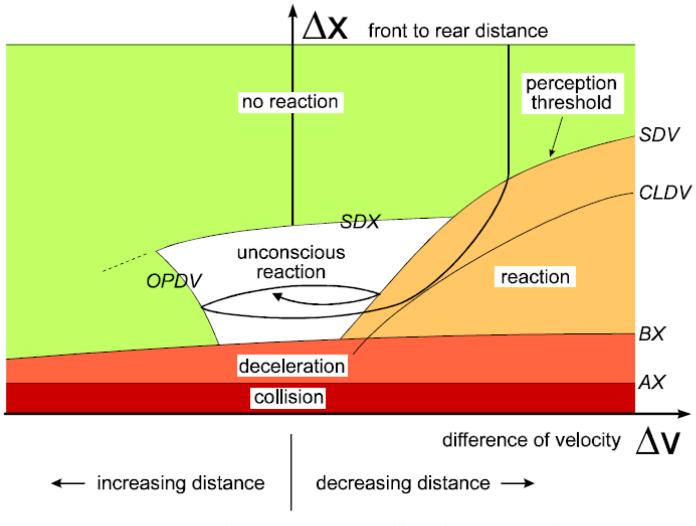


Figure 4.1 Wiedemann car-following model

VISSIM includes two car-following models: Wiedemann 74 and Wiedemann 99. The Wiedemann 74 model is commonly used at merging locations and urban roadways. The Wiedemann 99 model is typically used for highway vehicles. It is composed of numerous factors that can be modified to calibrate the model using real-world traffic data. Table 4.1 shows the parameters in the Wiedemann 99 model and their default values.

Table 4.1 Parameters of Wiedemann 99 model

parameters	Description	Default values
Standstill Distance (CC0)	Desired distance between two concurrent vehicles at zero speed	4.92 ft
Headway Time (CC1)	Desired time in seconds between two concurrent vehicles	0.9 sec
Following Variation (CC2)	Distance over safety distance a following vehicle requires before moving closer to the lead vehicle	13.12 ft
Threshold for Entering “Following” state (CC3)	Time in seconds before a following vehicle start to decelerate to reach safety distance	-8.00 sec
Negative “Following” Threshold (CC4)	The negative variation in speed between two concurrent vehicles	-0.35 ft./s
Positive “Following” Threshold (CC5)	The positive variation in speed between two concurrent vehicles	0.35 ft./s
Speed Dependency of Oscillation (CC6)	Influence of distance on speed oscillation	11.44 l/(ft.*s)
Oscillation Acceleration (CC7)	Oscillation during acceleration	0.82 ft./s^2
Standstill Acceleration (CC8)	Desired acceleration starting from standstill	11.48 ft./s^2
Acceleration with 50 mph (CC9)	Desired acceleration at 50 mph	4.92 ft./s^2

4.3 Model Development and Calibration

Based on the analysis in the last chapter, we selected the corridor of I-15 from Bangerter to 7200 S for analysis. The basic layout of this corridor is modeled in VISSIM. A screenshot of it is shown in Figure 4.2. The five on-ramps are located at Bangerter Hwy, 12400 South, 11400 South, 10600 South, and 9000 South from the south to the north.

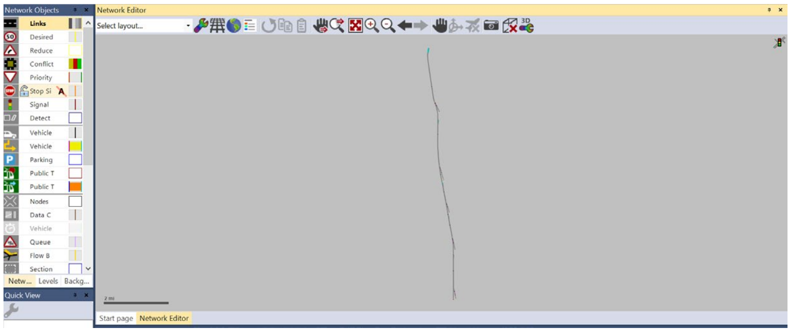


Figure 4.2 VISSIM corridor with mainline & ramp

Control hardware

In addition to displaying the fundamental freeway layout, the model involves the configuration of control hardware elements such as signal heads and loop detectors. In VISSIM, each signal head is associated with a signal group. All signal heads in the same group always have the same signal status. Each signal head in the VISSIM model established in this project has its own signal group, allowing each on-ramp, and even different signal heads on the same on-ramp, to operate independently. A loop detector is installed beyond the metering light on on-ramps to count the number of vehicles entering the motorway. Several detectors are deployed along the motorway mainline to undertake calibration and performance evaluation.

Traffic demand

The VISSIM simulation's traffic "volume inputs" is based on the data collected in 2019. The model's "time intervals" were modified from its 60-minute default to 15 minutes. Using a 15-minute interval could enable it to control or change the traffic demand every 15 minutes during the simulated period. This ensures that the model more accurately represents the real-life fluctuations in traffic volumes.

Vehicle composition

In VISSIM, all vehicles on the network are divided into various vehicle types. Vehicles of the same type share common characteristics, including weight, power, length, minimum and maximum acceleration, etc. In this VISSIM model, vehicle types are based on the basic VISSIM model developed by UDOT. The basic UDOT model defines 55 vehicle types and weight and power information, and speed distributions of each type have been created for selected speeds.

The model's ramp metering control is based on the strategies implemented in the real road network and it was completed through the VISSIM COM interface, which defines a hierarchical model where the functions and parameters of the simulator originally provided by the GUI can be manipulated by programming.

Calibration of the VISSIM simulation model

Note that the simulation system is useful only if it can faithfully reflect the realistic driving environment. To achieve this goal, extensive research has been conducted to calibrate microscopic simulation model, such as verbal description (Jayakrishnan et al., 2001; Hourdakis et al., 2003), heuristic algorithm (Kim et al., 2005; Ma and Abdulhai, 2002; Park and Qi, 2005; Siddharth and Ramadurai, 2013; Park and Schneeberger, 2003), statistical methods (Sun and Elefteriadou, 2010; Yang et al., 2011; Sun et al., 2013; Sun and Elefteriadou, 2014).

In VISSIM, several model parameters related to physical attributes of the vehicles, such as weight and length, are pre-defined, and those parameters are fixed for each model when calibrating the VISSIM model. The parameters related to the driver behavior model are often adjusted to calibrate the VISSIM model. The parameters of driver behavior that are usually changed to calibrate are listed below.

Lane change

Look ahead distance: distance that a vehicle can see forward in order to react to other vehicles either in front or to the side of it (within the same link).

Look back distance: distance that a vehicle can see backwards in order to react to other vehicles behind (within the same link).

CC0 and CC1: They are used to determine the safety distance, which is defined as the minimum distance a driver will keep while following another car, as shown in Eq. (4.1)

$$dx\_safe = \mathrm{CC0} + \mathrm{v} * \mathrm{CC1} \tag{4.1}$$

CC4 and CC5: They are used to control the speed differences during the "following" state. Smaller values result in a more sensitive reaction of drivers to accelerations or decelerations of the preceding car, i.e., the vehicles are more tightly coupled. CC4 is used for negative and CC5 for positive speed differences. The default values result in a fairly tight restriction of the following process.

Necessary lane change

Maximum deceleration: used to define the aggressiveness of lane change.

Waiting time before diffusion: defines the maximum amount of time a vehicle can wait at the emergency stop position waiting for a gap to change lanes in order to stay on its route.

Minimum headway: the minimum distance to the vehicle in front that must be available for a lane change in standstill condition.

Based on the existing studies, this study has performed the calibration by adjusting the above stated parameters of following and lane-changing to minimize the difference between the simulated result and field data in terms of cross-sectional traffic volume. Two error indicators are used to measure the calibration performance: mean absolute percentage error (MAPE), and GEH. The definitions of the two indicators are shown in the following equations.

$$MAPE = \frac{1}{N}\sum_{i=1}^{N} \left|\frac{y_i - \widehat{y_i}}{y_i}\right| \tag{4.2}$$

$$GEH = \sqrt{\frac{2*(y_i - \widehat{y_i})^2}{y_i + \widehat{y_i}}} \tag{4.3}$$

where y_i and $\widehat{y_i}$ denote the ground-truth value and estimated value, respectively; N denotes the number of samples.

The calibration results for VISSIM simulation are listed in Table 4.2.

Table 4.2 Calibration results of VISSIM model

Mile station	Ground truth	Simulated result	MAPE	GEH
MP 290.59	6251	6357	1.69%	1.34
MP 291.55	5528	5930	6.54%	4.79
MP 291.99	6159	6204	0.73%	0.57
MP 292.32	5554	5621	1.21%	0.89
MP 292.98	6678	6378	4.49%	3.71
MP 293.52	5680	5237	6.04%	4.62
MP 294.19	6400	5899	7.83%	6.39

*MP indicates mileposts

It can be observed that MAPE for all stations are small and GEH for all stations are less than 5. This indicates that the VISSIM model is already well calibrated and can reflect the real traffic environment.

4.4 Experimental studies

When the VISSIM model is calibrated, it can be leveraged to conduct simulation to make an evaluation of control strategies. In this section, we test different metering strategies in the calibrated model to evaluate how many additional on-ramp delays will be created to achieve a certain mainline congestion level. We apply LOS to describe the freeway congestion level, as shown in Table 4.3.

Table 4.3 Different levels of LOS and judgment standard (HCM 2010)

LOS	Density (veh/mi/ln)
A	0-11
B	12-18
C	19-26
D	27-35
E	36-45
F	>45

Since Level A and Level F are the most ideal and worst conditions, respectively, this project only tests Level B, Level C, Level D, and Level F. The metering rates of all the five ramps for the four scenarios are shown in Table 4.4.

Table 4.4 Metering rate for different on-ramps under various LOS

Scenarios	Metering rate				
	On -ramp 1	On -ramp 2	On -ramp 3	On -ramp 4	On -ramp 5
Level B	0	0	0	0	0
Level C	280	126	263	140	238
Level D	400	180	375	200	340
Level E	No control	No control	No control	No control	No control

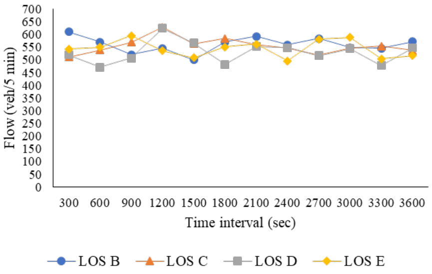
Based on those determined metering rates in Table 4.4, simulations are conducted, and results are shown in Table 4.5 and Figure 4.4.

Table 4.5 Simulation results for different LOS

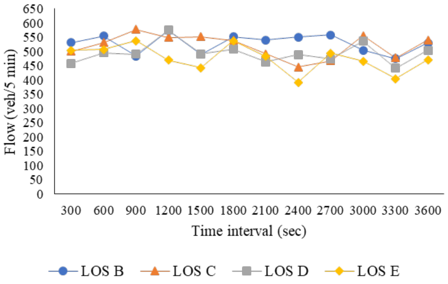
LOS	B	C	D	E
Flow (veh/h)	4775	5375	5578	5482
Speed (mi/h)	65.83	51.11	35.49	28.36
Density (veh/mi/ln)	14.51	21.03	31.43	36.85
Delay of Bangerter Hwy	-	907.29	10.13	0.33
Delay of 12400 South	-	1688.76	625.63	0.02
Delay of 11400 South	-	1449.18	301.3	0.008
Delay of 10600 South	-	1622.73	809.38	0.006
Delay of 9000 South	-	1794.88	1265.97	0.004
Average on-ramp delay	-	1364.09	468.75	0.09

Table 4.5 shows that when the freeway becomes more congested, the average delay for each on-ramp and average delay of all on-ramps reduce. This is because a higher level of congestion means more vehicles on the freeway. Because the freeway mainline demand is stable during the simulation period, it means more vehicles on the on-ramps entering the freeway, so the delay of on-ramp vehicles is reduced.

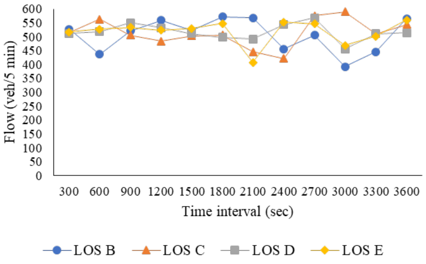
Figure 4.3 shows the time-dependent traffic flow of each station along the freeway mainline. We can see that with the increase of LOS, the traffic flow detected by each station reduces. This is because higher LOS means more vehicles enter the freeway from on-ramps and congestion exists.



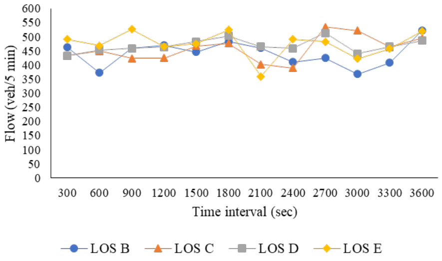
MP 290.59



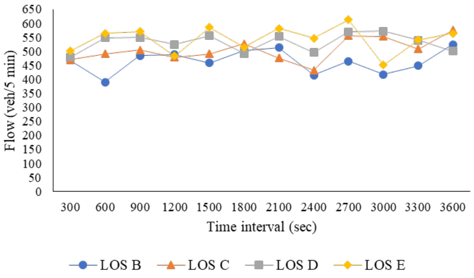
MP 291.55



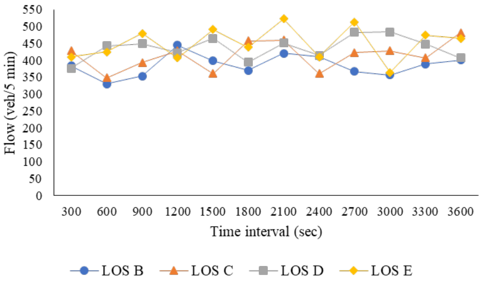
MP 291.99



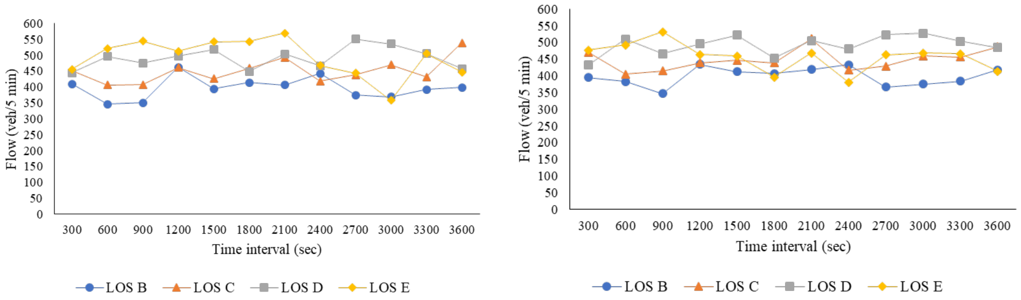
MP 292.32



MP 292.98



MP 293.52



MP 294.19

MP 294.77

*MP indicates mileposts

Figure 4.3 Time-dependent traffic flow for different detector stations

5. MEVALUATION OF COORDINATED RAMP METERING

5.1 Overview

In this section, we first introduce a coordinated ramp metering strategy. Then this metering strategy is tested for the selected Utah freeway corridor. Finally, sensitivity analysis is conducted to evaluate the effectiveness of this metering strategy.

5.2 Methodology

For the comparison analysis, two distinct ramp metering strategies were investigated in this section: (1) fixed time strategy, which is applied in the current traffic environment; (2) bottleneck, a coordinated ramp metering strategy. The two control strategies are described in the following section, and they are encoded using the COM interface of VISSIM.

Fixed ramp metering strategy

The fixed ramp metering strategies are the current control methodology applied in the on-ramps along this I-15 corridor. UDOT set metering rates based on the time of day schedule. This means when the meter is active, which lanes are included, what the controller action should be, and what the metering rate should be. For the metering control, it has minimum green time (e.g., 2s), maximum green time (e.g., 4s), and minimum red time (e.g., 2s). This process will be performed for each ramp lane. The metering rates and control rules for those on-ramps are shown in Table 5.1.

Table 5.1 Metering rates and control rules for all on-ramps

Location	Metering rate	Metering rule
Bangerter Hwy	400	2 vehicles per green each lane
12400 South	180	2 vehicles per green each lane
11400 South	375	1 vehicle per green each lane
10600 South	200	2 vehicles per green each lane
9000 South	340	1 vehicle per green each lane

Bottleneck algorithm

Bottleneck algorithm works at both the local and system-wide level. The framework of this algorithm is shown in Figure 5.1.

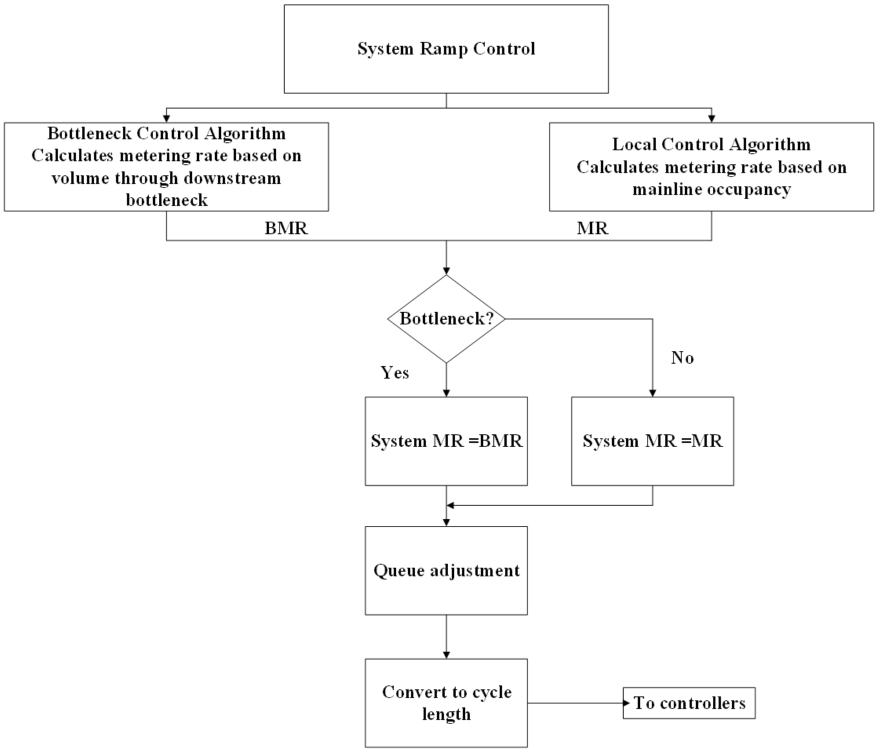


Figure 5.1 Framework of bottleneck algorithm

At the local level, this system calculates metering rates based on historical data to guarantee that freeway demand does not exceed capacity. When two requirements are met, the system-level algorithm is activated. First, the occupancy at a potential bottleneck area exceeds a pre-defined occupancy threshold. Second, this area stores vehicles. Then the algorithm calculates the metering rate reductions applied to each meter in the area to reduce the number of vehicles entering the mainline. The two conditions are shown as follows:

(1) Capacity condition

$$p_{it} > p_{threshold} \tag{5.1}$$

where p_{it} is the average occupancy across the downstream detector i over the previous time interval t; $p_{threshold}$ is the occupancy threshold.

(2) Vehicle storage condition

$$q_{it}^{in} + q_{it}^{on} > q_{it}^{out} + q_{it}^{off} \tag{5.2}$$

where q_{it}^{in} is the volume entering section i across the upstream detector station during last time interval; q_{it}^{on} is the volume that enters section i during the last time interval; q_{it}^{out} is the volume exiting section i across the downstream detector station during the last time interval; q_{it}^{off} is the volume that exits section i during the last time interval.

When the two conditions are fulfilled, the system will calculate the reduced volumes on upstream on-ramps for the next time interval, shown in Eq. (5.3)

$$U_{i(t+1)} = (q_{it}^{in} + q_{it}^{on}) - (q_{it}^{out} + q_{it}^{off}) \tag{5.3}$$

Then the metering rate reduction for each on-ramp is calculated by Eq. (5.4)

$$BMRR_{ji(t+1)} = U_{i(t+1)} * \frac{WF_j}{\sum_j^n (WF_j)_i} \tag{5.4}$$

where $BMRR_{ji(t+1)}$ is the metering rate reduction for ramp j for the next metering interval; WF_j is the weighting factor for ramp j;

Then the metering rate for each on-ramp for the next time interval is calculated by Eq. (5.5)

$$BMR_{ji(t+1)} = q_{jt}^{on} - BMRR_{ji(t+1)} \tag{5.5}$$

5.3 Experimental Study

In this section, we use the same calibrated VISSIM model as in the last chapter to conduct simulations to evaluate system performance. To evaluate the effectiveness of the bottleneck algorithm, we run two different ramp metering control strategies. One is fixed control strategy, and another is the bottleneck algorithm. Each control strategy is tested in VISSIM with total 5400 seconds during which a 900-second of warming period and 4600-second of data collection period. The resulting average traffic delay for the mainline traffic and each on-ramp is shown in Table 5.2.

Table 5.2 Average vehicle delay for freeway mainline and all on-ramps

	Average vehicle delay (min)		
	Fixed strategy	Coordinated strategy	Comparison
Mainline	7.09	6.76	-4.74%
On-ramp1	0.46	2.78	+509.24%
On-ramp2	1.48	3.69	+148.89%
On-ramp3	5.4	9.49	+75.81%
On-ramp4	4.31	5.53	+28.11%
On-ramp5	4.46	6.41	+43.60%
Average on-ramp	3.17	5.41	+70.50%

Tables 5.2 shows average vehicle delay for the entire mainline decrease and delays for all on-ramp increases. The average delay for mainline vehicles is reduced by 4.74%. The average delays of all on-ramps is increased. The average delay of all on-ramps is increased by 70.5%. This is because a coordinated ramp metering strategy can adjust the metering rate of all on-ramps in real time to minimize the total number of vehicles entering the motorway mainline, allowing vehicles on the freeway mainline to travel faster, resulting in a shorter travel time. The average delay of all five on-ramps caused by the coordinated ramp metering control strategy is greater than that of the fixed ramp metering control method. This is because a reduced metering rate is required to relieve mainline congestion, hence more vehicles were stored on on-ramps. This can be observed in Table 5.3, which is the queue length for each on-ramp.

Table 5.3 Queue length for on-ramps

Ramps	Queue length (ft)	
	Fixed strategy	Coordinated strategy
On-ramp 1	67.07607	303.382133
On-ramp 2	158.912399	330.012676
On-ramp 3	484.686689	599.46613
On-ramp 4	390.101039	469.718232
On-ramp 5	341.001117	424.245939

To further evaluate the effectiveness of the coordinated ramp metering strategy, we tested several various scenarios which bring different improvement levels to the mainline delay. The average delay and the average queue length for the mainline and all the on-ramps are shown in Figure 5.2 and Figure 5.3.

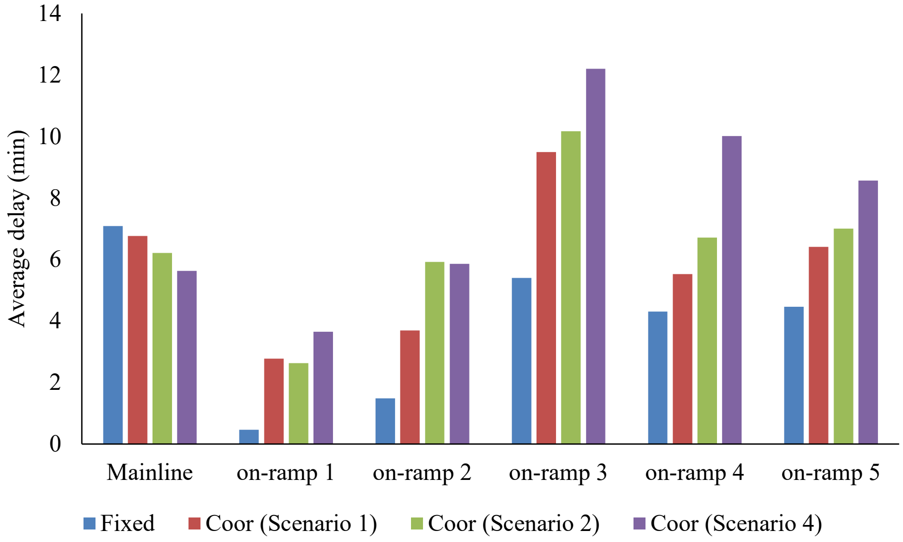


Figure 5.2 Average vehicle delay of freeway mainline and on-ramps for various scenarios

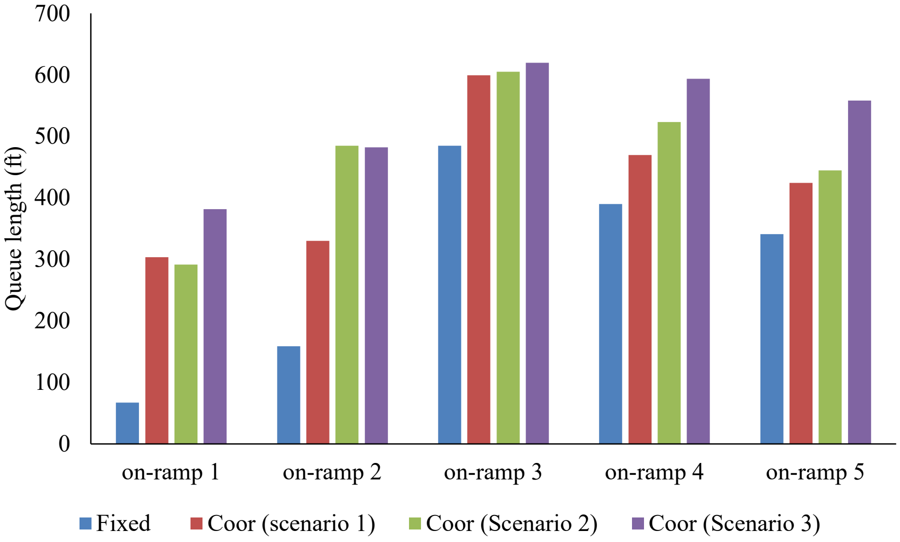


Figure 5.3 Average queue length of freeway mainline and on-ramps for various scenarios

Figure 5.2 shows that, with the decrease in mainline delay, the average vehicle delays for each on-ramp all increase. Therefore, to achieve a lower vehicle delay for the freeway mainline, the coordinated ramp metering strategy needs to adjust metering rates of all on-ramps in real-time to reduce more on-ramp vehicles to enter the freeway mainline. On-ramps will store more vehicles, resulting in longer queues and higher vehicle delays.

We can see that the delay for on-ramp vehicles varies significantly. To make the vehicle delay of each on-ramp distribute evenly, we conducted one more simulation, and the results are shown in Table 5.4 and Table 5.5.

Table 5.4 Average vehicle delay for freeway mainline and all on-ramps

	Average vehicle delay (min)		
	Fixed strategy	Coordinated strategy	Comparison
Mainline	7.09	7.37	+3.94%
On-ramp1	0.46	2.64	+473.91%
On-ramp2	1.48	4.52	+205.41%
On-ramp3	5.4	3.41	-36.85%
On-ramp4	4.31	2.35	-45.48%
On-ramp5	4.46	3.92	-12.11%
Average	3.17	3.32	+4.73%

Table 5.5 Queue length for on-ramps

	Queue length (ft)	
	Fixed strategy	Coordinated strategy
On-ramp 1	67.07607	287.007562
On-ramp 2	158.912399	395.794873
On-ramp 3	484.686689	320.152867
On-ramp 4	390.101039	241.156681
On-ramp 5	341.001117	320.760421

Table 5.4 shows that the delay difference between those on-ramp vehicles is insignificant. However, the average delay for the mainline produced by the coordinated ramp metering strategy is higher than that of the fixed strategy. This is because more vehicles from the last three on-ramps enter the freeway mainline. This means more vehicles traveled along the arterial, which may cause congestion. Therefore, freeway mainline vehicles experience larger vehicle delays.

6. CONCLUSIONS

6.1 Summary

In this project, our research team conducted a system-wide analysis to identify existing freeway bottlenecks based on data collected from PeMs and ClearGuide and determinded the locations that may benefit from coordinated ramp metering. Then we developed a VISSIM model and calibrated it. Based on the calibrated VISSIM model, several simulations were conducted to evaluate the system performance under different freeway congestion levels. Finally, we conducted several simulations to evaluate the coordinated ramp metering strategy of the bottleneck algorithm.

6.2 Findings

Our results revealed that the freeway mainstream is less congested and mainline vehicles travel at a higher speed if fewer vehicles enter the freeway mainline from on-ramps. Simulation results showed that the coordinated ramp metering strategy could reduce the freeway mainline delay compared with fixed coordination strategy. Although the on-ramp delay increases, the queue does not spill over to the local street.

6.3 Limitations and Challenges

In this project, simulations were conducted based on the current traffic demand level. Traffic demand will increase in the future, which will result in different system performance.

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