ENHANCING AIRPORT CURBSIDE EFFICIENCY WITH VARIABLE MESSAGE SIGN STRATEGIES

A Thesis in
Civil Engineering
by
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Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

May 2024
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ABSTRACT

Airports handle significant arrival and departure traffic, and inefficient curb space allocation for this traffic increases congestion and emissions. Variable Message Signs (VMS) are one way to help alleviate this issue, guiding vehicles away from crowded areas. Despite this, VMS effectiveness hinges on the correct activation and deactivation timing. This master’s thesis uses a validated Seattle-Tacoma International Airport microsimulation model to simulate sixteen VMS management scenarios to determine the best VMS operation to enhance curb performance and minimize congestion and emissions. The scenarios encompass different activation/deactivation approaches, sending (access from where vehicles are diverted) and receiving (access to where vehicles are diverted) links, traffic condition levels, and driver compliance rates (DCRs). The findings suggest that airports can maximize VMS benefits by timely activation and deactivation, even with driver compliance of as low as 5%. Across all scenarios, a reduction in queue length (100-1,150 ft) and queue duration (15-144 minutes) was observed at the sending link. In particular, activating VMS before congestion started in the sending link and deactivating it before congestion began on the receiving link led to the most substantial improvements in curb performance (8-10% increase), delay (29-78% decrease), and emissions (12-14% decrease). Yet, it was shown that activating VMS might not always improve curb performance. The improvements were non-significant when the receiving link was congested, and activating VMS after the queue formed in the sending link and deactivating it when the receiving link got congested even worsened curb performance (6-62%) and delay (96-595%). The proposed framework and the wide range of input values and scenarios provide valuable insights into how airports could successfully exploit VMS technologies.
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ACKNOWLEDGEMENTS

This master’s thesis is based on the work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) through the Pacific Northwest National Laboratory (PNNL) under contract number DE-AC05-76RL01830. Findings and conclusions of this research do not necessarily reflect the view of the funding agency.

I express my eternal gratitude to my advisor, Dr. Andisheh Ranjbari, for her guidance, patience, and support. Without her guidance, this research would not be possible.

A special thank you to my fiancé, Cesar, for your invaluable support during stressful moments, meticulous support, constant guidance, and eternal encouragement. To my family—Ma, Pa, Gra, and Sebas—your continuous support and infinite patience have propelled me further than I ever imagined. I extend appreciation to friends Diana, Carmona, Eli, Caro, Jacky, Guan, and Gloria, who always lend a helping hand and a listening ear. Even miles apart, you remain my greatest support. Thank you for everything.

Moreover, I acknowledge the dedicated personnel at PNNL, with special thanks to Dr. Nawaf Nazir. Their support, insightful comments, and provision of resources, including computational infrastructure, significantly elevated the quality of this research. Special thanks to Mr. Thomas Maxner for his assistance during the estimation of emission indices and analysis process.

Heartfelt acknowledgment goes to Mr. Nicola Longo from the aviation planning team at the Seattle-Tacoma International Airport (SEA) for his support. His collaboration greatly enhanced my understanding of airport curbside operations, from providing the model and data to offering valuable insights. Finally, I am grateful to Mr. Alex Chambers at Ricondo, the consulting firm who updated the VISSIM model for SEA, for helping validate and troubleshoot the model.
DEDICATION

This master’s thesis is dedicated to my dear Esposote, Dr. Cesar A. Nieves Sanabria.

Without you, I would not be who I am and where I am.
Chapter 1
Introduction

This introduction serves as a gateway to understanding this master thesis. Within this chapter, readers will find the research problem, objectives, significance, scope, limitations, and methodology that underpin this study. Additionally, this chapter explores the context in which this research unfolds and finalizes with a roadmap that guides readers through the subsequent chapters.

Context and Research Problem

Curbs facilitate vehicle access and egress for individuals in densely congested environments (Girón-Valderrama et al., 2019). Given the ongoing urban growth and rapid expansion of transportation network companies (TNC) (Girón-Valderrama et al., 2019; Ranjbari et al., 2020), authorities face the complex task of efficiently allocating scarce curb resources to meet an increasing demand. An inefficient allocation of scarce curb spaces decreases parking accessibility and productivity and increases congestion, travel times, and emissions (Butrina et al., 2020; Girón-Valderrama et al., 2019; Nazir, Dowling, et al., 2022; Nazir, Vasisht, et al., 2022; Zalewski et al., 2012).

In particular, airport curbs rank among the most heavily congested areas where effective curb management policies can yield significant benefits. Typical curb management strategies deployed at airports include geofencing, banning double parking, providing alternative parking, enforcing maximum dwell times, and prioritizing electric, autonomous, TNC, and transit vehicles (Harris et al., 2017; Machado-León et al., 2023; National Academies of Sciences Engineering and Medicine, 2010; Ugirumurera et al., 2021). However, it is worth noting that most airports have already implemented these policies and are now struggling to provide curb resources to the increasing demand.
As a result, some airports have increased their curb infrastructure, a strategy that has proven effective in managing curb demand (National Academies of Sciences Engineering and Medicine, 2010). However, expanding curb infrastructure requires significant investments. Thus, airports continually explore cost-effective alternatives for curb management, including technological innovations (Hamzawi, 1992).

A potential cost-effective strategy involves the redistribution of curb demand between various access levels. Research has found that effectively relocating airport curb demand can mitigate congestion and increase the level of service (Al-Deek et al., 2009; Duncan & Johnson, 2012). This strategy is effective because airports experience an unbalanced demand: passengers arrive simultaneously at specific entrances at certain hours, leaving some curbs underutilized while others experience congestion (National Academies of Sciences Engineering and Medicine, 2010). Consequently, one approach to curb management is redirecting exceeding flows to underutilized curbs using intelligent traffic systems (ITS). ITS can increase curb capacity by helping drivers make informed decisions (Ardeshiri, 2014).

The most visible ITS is the Variable Message Sign (VMS), which can provide real-time information by modifying its displayed message (Kimlinger, 2022). The VMS strategy has been deployed in airports to improve congestion by deviating traffic between arrival and departure curbs when one is congested. A notable example of this can be observed at the Seattle-Tacoma International Airport (SEA), where a VMS was implemented to address high congestion at the terminal.

Despite the potential of VMS to enhance airport curb performance, its effectiveness faces two primary challenges. First, drivers may ignore the parking guidance displayed on the sign (Sun et al., 2015). SEA, for example, showed only a 5.5-9.1% driver compliance rate when drivers were instructed to divert from departures to arrivals and an even lower rate (1.9-4.2%) in the opposite scenario (Vasisht et al., 2022). Second, if VMS is not activated and deactivated at the right timing, it will not operate at its full potential. Typically, airports use VMS heuristically and by intuition rather than through a systematic, evidence-based approach (Nazir, Vasisht, et al., 2022; Vasisht et al., 2022). If they infer that one of the ramps is significantly more congested than the other, they ask drivers to use the other curbside. However, this approach does not fully harness the tool’s capabilities and may even exacerbate congestion while reducing curb performance.
The research problem this study addresses is the need for a comprehensive analysis of the impact of VMS on airport curb performance. Although VMS has been previously used at airports, there is a gap in our understanding of the optimal activation and deactivation times for these signs, aiming to improve curb performance while mitigating undesired externalities. By using a validated microsimulation model of the Seattle-Tacoma International Airport and simulating sixteen VMS management scenarios, this research aims to improve curb performance at airports, thereby reducing congestion, enhancing passenger experiences, and decreasing environmental impact.

Objectives and Research Questions

The primary objectives that underpin this master’s thesis are the following:

1) Examine the impacts of using variable message signs to deviate traffic at the airport curbs on traffic congestion, curb performance, and emissions.

2) Determine the optimal activation and deactivation strategy for VMS at airports to improve curb performance while mitigating undesired externalities.

3) Provide recommendations for the Seattle-Tacoma airport for optimizing VMS deployment to enhance curb performance.

To achieve these objectives, this study will address the following research questions:

1) How do the activation and deactivation of variable message signs impact vehicle delay and the duration and lengths of queues at airport access ramps?

2) How do the activation and deactivation of variable message signs influence curb productivity and curb accessibility in airport curb areas?

3) How do activating and deactivating variable message signs affect airport emissions?
4) What is the most effective VMS management scenario for enhancing curb performance?

5) What is the optimal timing for variable message sign activation and deactivation, considering its unique infrastructure and traffic patterns?

Through the pursuit of these objectives and research questions, this research aims to deliver recommendations for optimizing curb performance at airports.

**Significance of the Study**

This research is a pioneering exploration into the influence of using VMS on airports. In particular, it enriches the existing body of knowledge on curb management by addressing the challenge of improving curb performance at airports while minimizing unintended negative consequences. It successfully bridges a substantial void in the literature by quantifying the VMS trade-offs, offering insights into when airports should activate and deactivate VMS. In addition, this research presents an analytical framework that other researchers or practitioners can adopt to tailor studies aimed at airport curb performance analysis.

Beyond its academic significance, the findings hold direct applications for enhancing traffic management at airports. These insights can be used to improve airport passenger flow rates. In addition, the results from this study can guide informed decision-making and the development of evidence-based airport VMS operational strategies. Consequently, instead of relying on heuristic or intuition-based methods, airport officials can now employ a systematic approach founded on scientific evidence.

Lastly, this research impacts society by offering strategies to promote efficiency in utilizing a finite resource—curb availability. Doing so contributes to enhancing passenger experience and minimizing the overall environmental impact of airports, reducing vehicle emissions, delays, and congestion.

Consequently, the significance of this research extends across academic knowledge, practical implications, and societal impacts. By analyzing the effects of VMS on airport curb management, this master’s thesis offers a foundation for informed decision-making from policymakers and airport officials.
Scope, Methodology, and Limitations

This research’s scope encompasses examining the impacts of Variable Message Signs on airport curb performance. The analysis uses the Seattle-Tacoma International Airport (SEA), WA, as a case study, including a microsimulation model of the airport developed in 2023 with traffic data spanning 2022 and 2023. The analysis incorporates six key metrics: three traffic performance indicators (vehicle delay and queue length and duration), two curb performance metrics (curb productivity index and curb accessibility), and an emission index.

The research methodology hinges on microsimulation as the primary approach. The analyzed model was developed by and calibrated by Ricondo & Associates, Inc. (2023), using VISSIM 2021 (Service Pack 11), and was provided by SEA’s planning team. The validation of the model was conducted as part of this research project as detailed in the Validation of the model section.

The model was employed to simulate sixteen VMS management scenarios alongside a baseline scenario without VMS deployment. Each scenario was built considering different driver compliance rates and traffic states and was tested for four periods: early morning, morning, afternoon, and night.

It’s crucial to acknowledge the limitations of this research. Using a case study and a microsimulation model limits the generalizability of the findings. Airports with different infrastructures may necessitate a more tailored analysis using the framework proposed in this master’s thesis. Finally, the analysis did not include other performance metrics due to resource constraints.

Thesis Structure

Firstly, Chapter 2 Literature Review conducts a comprehensive literature review focusing on curbside management, with specific attention to airport curbside management. Moreover, it explores the utilization of VMS in airport contexts for enhancing traffic operations and concludes by examining the use of simulation techniques in evaluating curbside management.
Then, **Chapter 3 Case Study: Microsimulation Model Description and Validation** delves into the specifics of the case study, providing essential background information and insights into the Seattle-Tacoma International Airport’s (SEA) VMS, infrastructure, and traffic conditions. It also provides a detailed description of the analyzed microsimulation model, encompassing its infrastructure, input parameters, and the validation process.

The described model is then used to simulate multiple VMS management scenarios. **Chapter 4 Study Approach** describes these scenarios and the metrics employed to evaluate them from the perspectives of traffic performance, curb performance, and emissions. The results from each VMS management scenario are compared to a baseline in **Chapter 5 Results and Discussion**. Through this comparison, the impacts of VMS are assessed. In addition, Chapter 5 employs the scenario with the best-performing results to determine the optimal timing for VMS activation and deactivation at SEA.

Finally, **Chapter 6 Conclusions** summarizes the primary findings of this research, their implications for VMS deployment and future applications. Furthermore, the limitations of this research and suggestions for future studies are provided.

This thesis is designed to guide the reader through a systematic exploration of VMS impacts on curb performance, building from the literature review to the final implications discussed in Chapter 6.
Chapter 2

Literature Review

This literature review explores curbside management literature in airport contexts, emphasizing simulation techniques and evaluation metrics. It concludes by assessing the current state of the art regarding Variable Message Signs in Transportation. This chapter provides an overview of the existing literature and identifies gaps in recent research.

Airport Curb Management

There is a range of in-depth research regarding curb management, mainly focused on short- and long-term parking for personal, TNC, transit, and freight vehicles in urban areas. In particular, parking behavior (Girón-Valderrama et al., 2019; Machado-León et al., 2023; Schmid et al., 2018), parking policies (Butrina et al., 2020; Jaller et al., 2013; Zalewski et al., 2012), capacity requirements (Arnott et al., 2015; Jaller et al., 2013; Nazir, Dowling, et al., 2022), curb allocation (Maxner et al., 2023; Nazir, Dowling, et al., 2022; Yu & Bayram, 2021), passenger pick-up and drop-off (Fehr and Peers, 2018, 2019; Ranjbari et al., 2020), cruising for parking (Geroliminis, 2015), and pricing (Arnott & Rowse, 2013) are recurring topics in the literature around curb management in urban areas.

While urban curb management literature is abundant, its findings may not directly apply to airport curbs. This discrepancy arises from differences in airport curb dwell times, vehicle maneuvers, and demand variability compared to urban curbs. Furthermore, airport curb capacity is constrained by factors such as terminal length and landside infrastructure, which do not affect urban curbs (Galagedera et al., 2014; Harris et al., 2017). Consequently, there is a separate body of curb management literature tailored to airport environments, albeit not as prolific as its urban counterpart. This specialized literature primarily concentrates on qualitative outcomes and airport curb design.
Qualitative research on airport curb management provides insights into the level of service and examples of successful policies (Galagedera et al., 2014; Hamzawi, 1992; Ison et al., 2014; National Academies of Sciences Engineering and Medicine, 2010). Some mode choice literature also allows for understanding passengers’ landside transportation choices and describes the impacts of alternative, non-motorized, and transit modes on airport accessibility (Budd et al., 2011, 2014; Hermawan & Regan, 2018; Kamga et al., 2012; M. L. Tam et al., 2010; M.-L. Tam et al., 2011; Ugirumurera et al., 2021). Several researchers have demonstrated the effectiveness of curb policies at airports, including geofencing, banning double parking, providing alternative parking, enforcing maximum dwell times, and prioritizing electric, autonomous, TNC, and transit vehicles (Harris et al., 2017; Machado-León et al., 2023; National Academies of Sciences Engineering and Medicine, 2010; Ugirumurera et al., 2021).

On the other hand, literature analyzing curb design and construction provides insights into expanding infrastructure to meet the constantly increasing demand. The Airport Cooperative Research Program (ACRP) provides methods such as widening curbside lanes, increasing curb length, constructing additional curbside levels, and providing alternative curb areas (National Academies of Sciences Engineering and Medicine, 2010). Similarly, Parizi and Braaksma (1994) developed a curb design computer program to determine the optimal number and location of doors, curbside check-in positions, and effective curb length. Moreover, Kleywegt and Liu (2021) compared different curb layouts at airports, finding the optimal configuration—number of parking spots, parking angle, access control, and double parking—to increase capacity for different vehicle speeds and dwell times.

In summary, curb management literature predominantly centers on urban areas. The examination of airport curbs is restricted and primarily emphasizes qualitative analysis, particularly regarding airport infrastructure. This research aims to bridge the lack of quantitative literature by investigating the utilization of VMS signs to enhance curb productivity at airports.
Simulation in Curbside Management

In curb literature, microsimulation models consistently deliver reliable and detailed results (National Academies of Sciences Engineering and Medicine, 2010). They allow the analysis of future or hypothetical scenarios and are a cost-saving alternative to pilot projects without traffic disruptions (Maxner et al., 2023). In this way, the impacts of curb management policies can be understood by analyzing individual vehicles and aggregated data and testing hard-to-measure variables, such as vehicle behavior (Maxner et al., 2023; Ugirumurera et al., 2021).

Researchers have employed microsimulation to analyze curb performance metrics and optimal curb allocations in urban areas (Martens & Benenson, 2008; Maxner et al., 2023; Young & Henao, 2020) and airport contexts (Harris et al., 2017; Trueblood, 2006; Ugirumurera et al., 2021). In particular, Ugirumera et al. (2021) used a microsimulation model to evaluate the effects of six curbside management scenarios and policies—TNC electrification, TNC queuing, increased transit ridership, implementing a bus-only lane policy, and one scenario simulating the impacts of autonomous vehicles and another simulating the effects of the COVID-19 pandemic. Their results revealed the impact of these policies on traffic congestion, fuel consumption, and emissions and, based on them, the infrastructure requirements for the Dallas-Fort Worth International Airport.

Trueblood (2006) compared the results from a microsimulation model to real data collected at Sky Harbor International Airport in Phoenix, AZ, to estimate the accuracy of the modelation approach. This comparison encompassed various factors, including simulated and actual dwell times, pedestrian interactions, link configurations, and lane and curb selections. The study concluded that microsimulation is a reliable and viable tool for analyzing curbside operations at airport terminals.

Harris et al. (2017) used a mesoscopic simulation to analyze the effects of four curb management policies—double parking, alternative parking space allocation, increased passenger demand, and enforced dwell times—on the curb utilization ratio, the volume-to-capacity ratio, waiting times, and access distance
at the Pearson International Airport in Toronto, Canada. Their results showed that double parking and reducing the allowed parking time decreased passenger waiting times and increased vehicle circulation.

**Curb Performance Evaluation**

The literature also provides insights into evaluating curb performance, yet no universal curb metric exists for that (Maxner et al., 2023). While cities use the number of passengers loading and unloading, congestion, emissions, and parking revenue as metrics (Butrina et al., 2020), researchers analyze advanced metrics such as occupancy, double parking, cruising behavior, traffic conflicts, dwell time, emissions, unauthorized parking, availability, accessibility, and turnover rates (Fehr and Peers, 2018, 2019; Mitman et al., 2018; Ranjbari et al., 2020). In particular, Maxner et al. (2023) developed metrics to measure the impacts of various curb allocations, including the Curb Productivity Index (CPI) and the Curb Accessibility for both people and goods.

**Variable Message Signs in Transportation**

Intelligent traffic systems (ITS) are information technologies that increase the capacity of roadways by temporarily and spatially assigning vehicle demand (Jin & Lam, 2003). ITS guides drivers to make informed decisions about departure times, route choices, and congestion avoidance (Ardeshiri, 2014; Peeta et al., 2000). In particular, the most visible manifestation of ITS is the VMS, also called Dynamic Message (DMS) or Changeable Message Sign (CMS) (Peeta et al., 2000).

VMS can be defined as “a traffic control device whose message can be changed manually, electronically, mechanically, or electromechanically” (Kimlinger, 2022). They provide quick, real-time traffic information to the public and have been used across the U.S. to improve road safety and overall roadway performance (Boyle & Mannering, 2004). In particular, authorities have used them to alert drivers about adverse weather, road and traffic conditions, traffic incidents, speed control, managed lanes, traffic
regulations, work zone hazards, travel times, lower-traffic volumes routes, parking availability, public transport, environment, among others (Banerjee et al., 2019; Boyle & Mannering, 2004; Chatterjee et al., 2002; Jeihani et al., 2017; Ullman et al., 2008; Yan & Wu, 2014).

Most of the research regarding VMS has been focused on observing drivers’ behavior in the presence of the sign (Jin & Lam, 2003). In particular, researchers have studied the effects of VMS on speed (Banerjee et al., 2019; Kolisetty et al., 2006; Selby Ryan, 2016), traffic safety (Banerjee et al., 2019; Haghani et al., 2013; Kolisetty et al., 2006; Selby Ryan, 2016), and routing decisions (Ardeshiri, 2014; Haghani et al., 2013).

Firstly, researchers have observed a substantial impact of VMS on drivers’ speed decisions. Studies by Banerjee et al. (2019), Erke et al. (2007), and Kolisetty et al. (2006) have shown that, in the presence of VMS, vehicles exhibit a significant decrease in both their average speed and standard deviation. However, the effectiveness of this reduction diminishes as cars move farther from the sign. This is attributed to drivers compensating for the initial slowdowns by subsequently increasing their speed when the message is no longer applicable (Boyle & Mannering, 2004; Erke et al., 2007).

Next, concerning traffic safety, VMS can increase driver distractions. Drivers often divert their attention to read and comprehend these signs, as noted by Erke et al. (2007). This diversion can lead to speed reductions around the VMS, potentially resulting in traffic conflicts due to the drivers’ inability to predict abrupt changes, such as short headways, lane changes, and risky maneuvers (Banerjee et al., 2019; Erke et al., 2007). Yet, Haghani et al. (2013) reached a different conclusion. They found that VMS did not increase the likelihood of accidents (crashes) in their study. Moreover, they also found that vehicles considerably decreased their speeds after a VMS showed Danger/Warning messages (Haghani et al., 2013).

Numerous studies have investigated VMS impacts on routing decisions. Erke et al. (2007) found that the presence of VMS significantly influences drivers’ choices to divert onto alternative routes at different rates. In particular, the compliance rate reaches 100% when a route closure is displayed (Erke et al., 2007). This compliance rate is contingent upon various factors, including the specific message conveyed, driver’s exposure, potential travel time savings, the perceived reliability of the information,
individual driver perceptions and past experiences, driver inertia, personal characteristics, the positioning of the sign, and the format of the information provided (Ardeshiri, 2014; Harder et al., 2003; Peeta et al., 2000; Yan & Wu, 2014).

Given that VMS effectiveness depends on the specific message, researchers have analyzed the most effective format to deliver the delivery format. The studies have involved the wording (Ullman et al., 2008) and the evaluation of multiple factors, including the sign’s location, the units of information, message length, lighting, and the use of flashing signs, colors, patterns, pictograms, and symbols (Dudek & Ullman, 2002; Erke et al., 2007; Ullman et al., 2008).

Regarding curb management and parking, researchers have analyzed the implications of deploying VMS using driving simulators (Ahangari et al., 2018; Holton & Fisher, 1998), agent-based simulations (Sun et al., 2015), and mathematical frameworks (Ahangari et al., 2018; Caicedo, 2010; Mei et al., 2012; Mei & Tian, 2011). Some of those studies demonstrated that using VMS does not improve parking performance when supply exceeds demand but decreases circulation time and turnover rates when supply is close to or less than demand (Ahangari et al., 2018; Caicedo, 2010; Mei et al., 2012; Mei & Tian, 2011).

In particular, the VMS strategy has been deployed at airports to improve curb management by deviating traffic between arrival and departure curbs when one is congested. Vasisht et al. (2022) studied the effectiveness of the VMS at the Seattle-Tacoma International Airport (SEA) in Seattle, WA, by analyzing four-month vehicle data, finding that VMS decreased congestion and increased mean vehicle speed. Nazir et al. (2022) modeled SEA’s VMS operation using a macroscopic dynamic model. They found that VMS improved the ramp speed up to three times, saving 80 vehicle-hours per hour and reducing idle time, fuel waste, and emissions.

In summary, there remains a dearth of quantitative data on how VMS impacts curb performance at airports. Moreover, the optimal approach for maximizing VMS benefits remains elusive. This research addresses these gaps in the body of knowledge of transportation literature.
Chapter 3

Case Study: Microsimulation Model Description and Validation

Using a microsimulation model of the Seattle-Tacoma International Airport (SEA), this research aims to understand a) how VMS impacts airport curb performance and b) when VMS should be activated and deactivated to enhance curb performance. This chapter introduces SEA as a case study, providing insights into its traffic volumes, landside infrastructure, highway accesses, and variable message sign. Additionally, a description of the microsimulation model is included, encompassing the simulated infrastructure, inputs, and validation process.

Case Study: Seattle-Tacoma International Airport

With 45.9 million passengers and a revenue of $22.5 billion in 2022, the Seattle-Tacoma International Airport (SEA) is the eighth busiest airport in the U.S. (Port of Seattle, 2023). SEA has a broad network of 33 airlines and serves as a crucial hub connecting Seattle, WA, with 92 domestic and 28 international destinations (Port of Seattle, 2023).

The airport comprises three access levels: arrivals, departures, and shuttles. This research focuses on the arrivals and departures access levels. Ground data from SEA’s planning team reveals that during the early morning, morning, afternoon, and night, the departure access serves an average of 360, 990, 840, and 520 veh/hr, respectively. Similarly, the arrival access level traffic shows an average of 280, 670, 910, and 1,110 veh/hr for the abovementioned periods. The departure access experiences significant congestion from 5:00 a.m. to 10:00 a.m. and from 2:00 p.m. to 4:00 p.m. In contrast, the arrival access faces congestion from 9:00 a.m. to 12:00 m.d. and from 7:00 p.m. to 11:00 p.m. In some occasions, the high congestion levels
creates a queue that spills back beyond the terminal. Figure 3-1 exemplifies the terminal’s congestion spilling back to the highway.

Figure 3-1: Traffic at the Seattle-Tacoma International Airport

Overview of the Seattle-Tacoma International Airport’s landside access

The airport main terminal comprises six concourses, one shuttle access, two vehicular access levels (arrivals and departures), and seven access doors. Curb spaces are available at the shuttle, arrival, and departure access levels. In particular, shuttle curb spaces are reserved for hotel, parking, crew-member, and airport shuttle vehicles. Similarly, Taxis and Transportation Network Company (TNC) vehicles can take advantage of exclusive parking spaces at the adjacent Central Garage. Despite this, many shuttles, taxis, and TNC vehicles still handle passenger loading and unloading at the arrival and departure access levels.
Thus, the model includes some of these vehicles in the vehicle type composition. Please refer to the Model Input Parameters section for further discussion about the vehicle type compositions. Finally, buses and personal-vehicle curbs are available at the arrival and departure access levels.

Figure 3-2 illustrates the shuttle, arrival, and departure access levels. The shuttle access level comprises one travel lane and one non-signalized parking lane. In contrast, the arrival access level features three parking and three travel lanes, each spanning 1,000 ft, and the departure access level consists of two parking and two travel lanes, each 1,600 ft long. Travel lanes are designated by a horizontal “THRU” sign and an arrow, while parking lanes display a horizontal “LOAD AND UNLOAD ONLY” sign along with yellow curbs to prevent long-term parking. Vertical signs also prohibit permanent parking. Finally, the parking lanes lack individual spaces; instead, vehicles can park anywhere within the designated lanes.

Figure 3-2: Seattle-Tacoma International Airport’s curbs at the shuttle, arrival and departure access levels
Vehicles can reach the access levels using the Airport Expressway, which connects SEA to Seattle’s road network via International Boulevard and Route 518. This expressway spans 0.83 miles and features four lanes, with on-ramps at 0.25 and 0.625 miles, along with one off-ramp at 0.42 miles. At approximately 0.83 miles, 0.3 miles upstream of the terminal, the Airport Expressway splits into the arrival and departure access levels, each of them featuring two lanes, as illustrated in Figure 3-3.

Figure 3-3: Overview of the Seattle-Tacoma International Airport’s microsimulation model [Model provided by the Seattle Tacoma Airport]
Two variable message signs (VMS) were implemented on the Airport Expressway (red dots on Figure 3-3.A) to address high congestion at the terminal by diverging incoming vehicles from congested to uncongested curbs. The VMSs display messages such as “Arrivals full, use departures” and “Departures full, use arrivals.” Figure 3-4 illustrates SEA’s VMSs.

Figure 3-4: Variable Message Signs at the Seattle-Tacoma International Airport.
[Source: and SEA (2023)]

Model Description and Inputs

This master thesis was based on traffic volume and speed data collected from January to May 2022, along with a micro-simulation model of SEA’s landside network. The model, provided by SEA’s planning team, was developed by the consulting firm Ricondo & Associates, Inc. (2023) using VISSIM 2021, Service Pack 11, an agent-based multi-purpose traffic flow simulator. Moreover, it underwent calibration at the Terminal approaches and Airport Expressway, using data from August 5th, 2022, representing the busiest day of the year, and resulted in an average GEH of 2.0 over 24 hours.

1 The GEH statistic, named after Geoffrey E. Havers, measures the goodness of fit of a micro-simulation model (Feldman, 2012). It considers the absolute and percentual differences between the modeled ($M_j$) and the ground-truth ($K_j$) traffic flows. The GEH parameter is estimated using the following equation.

$$GEH_j = \sqrt{\frac{2(K_j - M_j)^2}{K_j + M_j}}$$
Model Description

The airport model simulates a total of 39.05 miles of highway, encompassing the airport’s infrastructure and the surrounding roads—International Boulevard, Airport Expressway, and Route 518 (see Figure 3-3.A.). Within these neighboring highways, there are 38 designated points for vehicle generation. The generated vehicles include airport-related traffic and a dynamic background flow that varies throughout the day. The inclusion of the surrounding highways and the background flow provides stochasticity to the terminal’s traffic patterns and “prevents artifacts due to vehicle generation and removal at the simulation boundaries from influencing the results” (Maxner et al., 2023).

Furthermore, the model replicates the airport’s infrastructure, encompassing features like the VMS, the shuttle, departure and arrival parking and travel lanes, parking lots and garages, bus curbs, and prohibited and reserved parking spaces. In particular, departure and arrival parking lanes are simulated as a continuous set of 20-ft parking spaces. Finally, the model simulates VMS by modifying the decision routes of an adjustable vehicle fraction without changing their dwell times. This approach ensures that the behavior of diverted vehicles remains consistent, regardless of their parking destination.

Model Input Parameters

Model inputs were estimated using ground-truth data. They include vehicle flow, speed and dwell time, and vehicle type composition. The input flow at each vehicle-generation location changes hourly between 2,000 and 12,500 veh/hr. Desired speed distributions range between 15 and 40 mph, varying according to the road’s functional class. Parked vehicles follow a normal dwell time distribution with averages of 60 and 90 seconds for departures and arrivals, respectively.

To emulate traffic conditions, vehicle type compositions also vary hourly and across all vehicle-generation locations. There are six vehicle types in the model: personal passenger vehicles (45-65%), TNCs (15-30%), shuttles (10-20%), taxis (1-10%), limos (1-3%), and buses (0-5%). Personal vehicles, TNC, taxis,
limos, and buses have a parking rate of 100% after entering the study area, meaning all these vehicle types eventually park at the terminal curb. For shuttle vehicles, 50% park in the study area, and the remaining 50% park in a dedicated shuttle access level.

**Validation of the model**

The validation process involved comparing the model outputs with speed and flow data from March 2022. The comparison showed that model-output flows consistently exceeded those in the ground-truth data, while speeds were consistently lower during the afternoon and night. These discrepancies were expected because the model was calibrated using a dataset specific to the busiest day of the year, which differed from the validation data. To address this, the ground-truth data was adjusted as follows:

- Departure morning ground-truth data was not adjusted.
- Between midday and midnight, increased departure ground-truth flows by 15% and decreased departure ground-truth speeds by 40%.
- For the entire day, increased arrival ground-truth flows by 40% and decreased arrival ground-truth speeds by 90%.

Next, the validation process entailed employing a set of statistical and graphical tools. The statistical techniques, including the Kolmogorov-Smirnov (KS), Wilcoxon-Mann-Whitney (WMW), and Anderson-Darling k-Sample (AD) tests, assessed whether the ground-truth and the model-output datasets share the same statistical distribution. In contrast, graphical tools, including Dynamic Time Warping (DTW) and speed-flow diagrams, examined the relationship between speed and flow.

**Model validation methods**

As mentioned, the model validation process encompassed statistical and graphical tools. The first statistical tool was the Kolmogorov-Smirnov (KS) test, a non-parametric goodness-of-fit test used to
determine whether two distributions come from the same hypothesized population (Kendall, 2008). It employs a random sample \( x = (x_1, ..., x_n) \), with an unknown distribution \( F(x) \), and a random sample \( y = (y_1, ..., y_m) \), with an unknown distribution \( G(y) \) (Kendall, 2008), to assess the following null and alternative hypotheses:

- \( H_0: F(x) = G(y) \). The samples come from the same distribution.
- \( H_a: F(x) \neq G(y) \). The samples do not come from the same distribution.

The KS test is widely used due to its simplicity, as it does not demand a normal distribution of the samples and relies on straightforward assumptions: a) samples must be random from the population, b) samples must be independent of each other, and c) the measuring scale must be at least ordinal, but the test is more precise with continuous variables.

The Anderson-Darling (AD) test is a modification of the KS test, giving a heavier weight to the tails and using the following hypotheses (National Institute of Standards and Technology - U.S. Department of Commerce, 2015):

- \( H_0: F(x) = G(x) \). The populations from which the samples came from are identical.
- \( H_a: F(x) \neq G(x) \). The populations from which the samples came from are not identical.

Like the KS test, the AD test does not require a normal sample distribution and its precision increases with continuous variables. Moreover, the sample must be independent from each other and randomly collected.

Finally, the Wilcoxon-Mann-Whitney (WMW) test is a non-parametric test that compares the medians of two samples (Boston University School of Public Health, 2017). The WMW test has four fundamental assumptions (Lund Research Ltd, 2018): a) the observations are independent; b) the data is at least ordinal, but the test can applied to continuous variables; c) the samples were randomly collected; and d) samples share a similar statistical distribution. If the four assumptions are met, one can test the following hypotheses:

- \( H_0: F(x) = G(x) \). The two populations are equal.
• \( H_a: F(x) \neq G(x) \). The two populations are not equal.

Turning to graphical tools, Dynamic Time Warping (DTW) is a technique for comparing time series (Giorgino, 2009). This algorithm estimates the cumulative distance between time series and optimally aligns relationships between variables (Giorgino, 2009). In this way, DTW results assess the distance between the ground-truth and the model-output speed and flow time series. Finally, speed-flow diagrams serve as graphical representations of a fundamental relationship in traffic engineering. They are valuable tools for identifying bottlenecks, assessing traffic density, determining free-flow speeds, and analyzing other critical variables.

**Model validation results**

The analyzed tests assume as null hypotheses that both samples come from the same distribution. Consequently, not rejecting the null hypothesis is crucial to confirm that the model-output and the ground-truth data share the same distribution. Thus, higher p-values (above 0.05) are favorable for the analysis, indicating good results, while those between 0.05 and 0.01 suggest a statistical tendency. Table 3-1 summarizes the results of the three tests.

Table 3-1: Summary of statistical test results for the comparison between the model outputs and the adjusted ground-truth data

<table>
<thead>
<tr>
<th>Access level</th>
<th>Variable</th>
<th>Test p-value*</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure</td>
<td>Flow</td>
<td>0.153</td>
<td>KS</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>0.054</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>0.154</td>
<td>0.178</td>
</tr>
<tr>
<td>Arrival</td>
<td>Speed</td>
<td>0.271</td>
<td>0.158</td>
</tr>
</tbody>
</table>

*Note: KS = Kolmogorov-Smirnov test; AD = Anderson-Darling k-Sample test; WMW = Wilcoxon–Mann–Whitney test

* **Green highlight** = good result; **yellow highlight** = statistical tendency
The results indicate that the model generates outputs that closely match the adjusted ground-truth data distribution, with no significant differences in speed and flow observed on either the departure or arrival ramps. Therefore, the model’s speed and flow outcomes are not significantly different from real-world observations.

Figure 3-5 illustrates the cumulative distribution of speeds and flows in both datasets, with the y-axis showing the empirical cumulative distribution function (ECDF). As observed, both databases follow a comparable trend with minimal differences, likely attributed to randomness in the databases and the differences between the calibration and the validation datasets. The plot similarity further reinforces the conclusion drawn from the numerical tests.

![Empirical cumulative distribution from the model-outputs and adjusted ground-truth speed and flow datasets](image)

After the statistical comparison, Table 3-2 shows the results of the Dynamic Time Wrap (DTW) analysis, which measures the distance between time series datasets.

DTW enables comparison between two types of data. Firstly, single-variable analyses compare time series vectors representing speed and flow changes over time in the model output and ground-truth
datasets. Secondly, two-dimensional analyses study how speed and flow change together over time. Smaller DTW values indicate a closer similarity between the time series.

Table 3-2: Dynamic Time Wrap (DTW) results

<table>
<thead>
<tr>
<th>Adjustment</th>
<th>Link</th>
<th>Single variable</th>
<th>Two-Dimensional</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flow</td>
<td>Speed</td>
</tr>
<tr>
<td>Adjusted ground-truth data</td>
<td>Departures</td>
<td>44.387</td>
<td>1.458</td>
</tr>
<tr>
<td></td>
<td>Arrivals</td>
<td>82.933</td>
<td>0.500</td>
</tr>
<tr>
<td>Actual ground-truth data</td>
<td>Departures</td>
<td>42.162</td>
<td>2.016</td>
</tr>
<tr>
<td></td>
<td>Arrivals</td>
<td>82.526</td>
<td>6.593</td>
</tr>
</tbody>
</table>

The two-dimensional DTW analysis indicates a smaller value for departure link, suggesting that the model provides a more accurate prediction of the relationship between speed and flow at the departure ramp compared to the arrival ramp. However, when examining individual variables, the model performs better in predicting departure flows than arrival flows, but it does a better job simulating arrival speeds than departure speeds.

In the numerical estimation of DTW, there are no absolute right or wrong answers, as each number corresponds to a distance that varies based on the magnitude of the vectors. To provide clearer insights, DTW also visually compares vector differences (see Figure 3-6). Within Figure 3-6, circles highlight the most significant disparities between the model outputs and the adjusted ground-truth data.

The model outputs exhibit some variations between the datasets. Firstly, the model prediction of arrival flows is slightly higher than the ground-truth data. Secondly, the model struggles to predict sudden speed changes in the departure link during morning periods. Thirdly, the model does not show a decrease in speed on the arrival ramp due to increased traffic flow during the afternoon. These differences can be attributed to randomness in the observations and the disparities between the calibration and the validation datasets. Moreover, the model successfully captures the average traffic pattern (speed and flow). Therefore, despite these differences, the model effectively simulates speed and flow over time.
Figure 3-6: Time series comparison between the ground-truth and the model-outputs speeds and flows data. Circles mark the largest differences between datasets.
Finally, Figure 3-8 and Figure 3-7 show the speed-flow diagrams for the departure and arrival ramps. The model accurately predicts the speed-flow relationship during uncongested periods. The green line, representing the best fit for speed-flow during congestion, exhibits a comparable slope in both the model-output (VISSIM) and ground-truth (Real Data) plots.

![Speed vs Flow Diagrams](image.png)

**Figure 3-7: Speed-Flow Diagrams at the Arrival Ramp**

The model’s prediction for the arrival ramp closely aligns with the ground-truth data. In contrast, disparities become evident in the departure ramp due to two primary reasons. Firstly, the ground-truth departure data encompasses congestion at various stages during the analyzed month, while the model represents the average congestion characteristics. Secondly, these differences might stem from disparities between the calibration and validation datasets. Despite this, the departure model-output plot closely mirrors the average shape of the ground-truth departure plot.

Based on the results mentioned above, there is not enough evidence to reject the null hypothesis that the model outputs produce comparable results to the ground-truth data. Thus, the model produces valid outcomes.
Figure 3-8: Speed-Flow Diagrams at the Departure Ramp
Chapter 4
Study Approach

Using a validated microsimulation model of the Seattle-Tacoma International Airport (SEA), this research explores how VMS impacts the performance of curbs at airports and the best approach to manage VMS to enhance their performance. Figure 4-1 visually outlines the methodology applied in this research to attain this goal.

![Figure 4-1: Study Approach Process](chart)

Firstly, sixteen VMS management scenarios were simulated employing the microsimulation tool VISSIM (2023, Service Pack 01). These scenarios encompassed two vehicle compliance rates and four traffic conditions for both departures and arrivals access levels. Additionally, a baseline scenario, where the VMS remains inactive, was simulated to serve as a reference point. Further details about the scenarios can be found in the VMS Curb Management Scenarios subchapter.
Subsequently, simulation outputs were collected, and six performance metrics were calculated, as outlined in the Performance Metrics subchapter. Then, all scenarios were compared against the baseline scenario, aiming to identify the VMS management scenario that maximized benefits. The comparison included absolute and relative changes and Repeated Measures ANOVA. Repeated Measures is a research design that involves administering multiple treatment levels to the same study subjects (Girden, 1992). This technique incorporates a random variable to exclude the effect of the subjects. Thus, the results can be extended beyond the sample. In this experiment, each scenario represents a treatment level, and the study subjects are the multiple simulation runs.

Following this, the study compared the results on traffic, curb performance, and emissions to ascertain the most effective VMS management strategy. Finally, considering the curb capacity, queue length variations, speed, and vehicle flow in the terminal, the ideal conditions for VMS activation and deactivation at SEA were determined. The subsequent subchapters offer further details on the analyzed scenarios and metrics.

**VMS Curb Management Scenarios**

This work examines the impact of VMS on curb performance through sixteen scenarios, all listed in Figure 4-2. The baseline scenario simulates traffic with an inactive VMS (i.e., diversion rate of 0%). The scenarios were developed through various combinations of the two access levels (sending or receiving links), two activation/deactivation approaches (before or after the start of the queue in the receiving and sending link), two traffic conditions in the receiving link (congested or free-flow), and two driver compliance rates (5% or 10%). The sending link is the original destination of the vehicles (before activating the VMS), and the receiving link is where the vehicles deviate to if they comply with the guidance.
Figure 4-2: Analyzed VMS management scenarios

<table>
<thead>
<tr>
<th>VMS Activation</th>
<th>VMS Deactivation</th>
<th>Flow condition at receiving link</th>
<th>Driver Compliance Rate</th>
<th>Scenario Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>Base</td>
</tr>
</tbody>
</table>

- **Before queue starts in the sending link (Early; E)**
  - Congested (C)
    - Before queue ends in the sending link (Early; E)
    - Flow: 5, Compliance Rate: 10, Scenario: EEC_10
  - Free flow (F)
    - Flow: 5, Compliance Rate: 10, Scenario: EEF_10

- **When the queue ends in the sending link (Late; L)**
  - Congested (C)
    - Flow: 5, Compliance Rate: 10, Scenario: ELC_10
  - Free flow (F)
    - Flow: 5, Compliance Rate: 10, Scenario: ELF_10

- **After queue starts in the sending link (Late; L)**
  - Congested (C)
    - Before queue ends in the sending link (Early; E)
    - Flow: 5, Compliance Rate: 10, Scenario: LEC_10
  - Free flow (F)
    - Flow: 5, Compliance Rate: 10, Scenario: LEF_10
  - When the queue ends in the sending link (Late; L)
    - Congested (C)
      - Flow: 5, Compliance Rate: 10, Scenario: LLC_10
    - Free flow (F)
      - Flow: 5, Compliance Rate: 10, Scenario: LLF_10
Driver compliance rates (DCR) are based on the findings of Vasisht et al. (2022) from SEA, only including personal vehicles, taxis, and TNC vehicles. These vehicles would diverge after the VMS is activated, while buses, limos, and shuttles would proceed to their designated access level. Diverged vehicles maintain their dwell time irrespective of the destination; for instance, if a car aiming to pick up a passenger goes to departures instead of arrivals, its dwell time will follow the arrival-link dwell time distribution. All model variables, such as incoming flow, speed, vehicle composition, and curb availability, remained the same for all scenarios.

Each scenario was run for up to four time periods, representing four different traffic conditions: early morning (4:00 a.m. to 9:00 a.m.), morning (9:00 a.m. to 12:00 m.d.), afternoon (1:00 p.m. to 4:00 p.m.), and night (7:00 p.m. to 12 m.n). These periods were selected considering the airport’s historical pattern of exhibiting congestion in at least one of the access levels. If a traffic condition did not exist for a period (e.g., congested receiving link during early morning), the associated scenarios (e.g., EEC_05 during early morning) were removed from the run list. Moreover, each scenario was simulated using ten random seeds, resulting in up to 80 simulation runs per scenario. The results were averaged per scenario and period.

**Performance Metrics**

The outputs of the microsimulation model were evaluated from three perspectives: traffic impacts, curb performance, and emissions. The metrics for each perspective is introduced as follows.
Traffic-related performance metrics

The Airport Curbside and Terminal Area Roadway Operations recommends analyzing an airport’s curb performance using the following metrics: **vehicle delay (VD)**, **queue length (QL)**, and **queue duration (QD)** (National Academies of Sciences Engineering and Medicine, 2010).

VISSIM provides QL and VD as direct outputs in 15-minute intervals. VD was defined as the difference in travel time between congestion and free-flow conditions experienced by all vehicles traveling between the vehicle diversion point and the beginning of the curbs (Figure 3-3). Queues form when vehicle speeds drop to 5 mph or less, and QL is the average distance between the first and the last queueing vehicles.

It’s worth noting that QD processing differs from the other traffic-related metrics. QD represents the time difference between the formation of a queue and its complete discharge, rounded to the nearest 15-minute interval. Given that this metric is not directly available in VISSIM outputs, VISSIM results were collected, post-processed, and aggregated to derive QD. Furthermore, ANOVA-Poisson was chosen for its analysis due to the notable prevalence of zero values in the observations.

Curb performance metrics

Two curb performance metrics developed by Maxner et al. (2023) were adopted for this analysis: curb productivity index (CPI) and curb accessibility (CA). CPI estimates the number of passengers serviced per hour per parking space (Equation 1), and CA presents the ratio of successful vehicle parking attempts (spp) to total parking attempts (tpp) (Equation 2). CPI relates to the number of successfully parked vehicles ($v_l$), the number of picked-up or dropped-off passengers
per vehicle ($p_i$), the simulation time ($t$), and the number of parking spaces ($sp$) (Maxner et al., 2023). Since occupancy data was unavailable, random pick-ups/drop-offs of 1 to 3 passengers were assumed for personal vehicles, TNC, taxis, and limos. Shuttles followed a normal distribution with an average of ten passengers and a standard deviation of two passengers.

\[
CPI = \frac{\sum v_i * p_i}{t/sp} 
\]  
\[
CA = \frac{\sum sp}{\sum tp} 
\]

### Emissions analysis

The emission index, as proposed by Maxner et al. (2023), quantifies the amount of CO$_2$ emissions (lb. CO$_2$/hr) by considering specific emission rates corresponding to different vehicle driving conditions.

Table 4-1 shows the emission rates for each driving state. This metric estimates the emissions for parking and driving separately through Equation 3, where $Eff$ is the emission rate, $t$ is the time a vehicle spends in a given state—driving ($ds$), idling ($l$), or ignition ($l_g$)—and $DS$ is the acceleration- and speed-based driving state. The term $l_g = 1$ if the vehicle is parked for 5 minutes or more, and 0 otherwise. The emission rate covers all vehicles between one mile upstream of the terminal and the last curb space.

\[
EI = \sum Eff_{ds} \times (DS \times t_{ds}) + \sum Eff_l \times t_l + \sum Eff_{lg} \times l_g 
\]
The emission rates and assumptions for personal vehicles, TNCs (Transportation Network Companies), and buses are sourced from Maxner et al. (2023). In contrast, vehicle models between June 2014 and June 2024 were used to estimate taxi and limo fleet vehicle compositions. For taxis, the fleet composition was projected based on King County’s 2021 (2021) taxi breakdown: 14% mini-vans, 38% sedans, 20% small SUVs, and 28% compact cars. Similarly, the limo fleet composition was assumed to be 33% large SUVs, 33% town cars, and 33% small luxury SUVs.
Finally, shuttles and buses were represented by vans with a capacity of fifteen passengers and the Ford E-450 handicap loader bus.

Following determining fleet vehicle compositions for taxis, limos, shuttles, and buses, emission factors were sourced from the U.S. Department of Energy (2022) vehicle fuel economy database. Subsequently, results were extrapolated into gram-per-second emissions, as detailed by Maxner et al. (2023).
Chapter 5

Results and Discussion

This chapter evaluates the analyzed VMS management scenarios compared to a baseline, employing Repeated Measures ANOVA to assess their significance. It begins by examining the impact of VMS on traffic conditions, considering driver compliance rates, vehicle delay, and queue dynamics. Subsequently, curb capacity is assessed using the curb productivity index (CPI) and curb accessibility (CA). In addition, the chapter explores the effects of VMS on emissions. Finally, the optimal VMS management scenario is compared with airport conditions to determine the most effective timing for VMS activation and deactivation at the Seattle-Tacoma International Airport (SEA).

Impacts of VMS on Traffic Metrics

This subchapter explores the effects of VMS on the traffic conditions at airport access ramps. It examines how vehicle delay (VD) varies with VMS use, providing insights into delay mitigation across traffic conditions. The subchapter further explores the QL and QD dynamics in response to VMS.
Vehicle delay (VD)

Figure 5-1 presents vehicle delay (VD) results. Additionally, Figure 5-2 depicts vehicle flows and queue length (congestion) at the terminal’s curbside starting point (see Figure 3-3.B) in the baseline model.

VD varied based on the traffic condition on the receiving link. If the receiving link was uncongested, deviating vehicles reduced the sending link’s congestion without increasing VD in the receiving link, thereby reducing the overall VD at the terminal. For example, VD in the EEF, ELF, and LEF scenarios decreased by 47-78% and 8-22% during the afternoon and night, respectively.

These changes in VD depended on the DCR, with higher DCRs resulting in lower delay. For instance, VD decreased by 47-57% with a DCR of 5% and 61-78% with a DCR of 10%.

Figure 5-1: Vehicle delay (VD) across VMS scenarios and periods at the terminal level

VD varied based on the traffic condition on the receiving link. If the receiving link was uncongested, deviating vehicles reduced the sending link’s congestion without increasing VD in the receiving link, thereby reducing the overall VD at the terminal. For example, VD in the EEF, ELF, and LEF scenarios decreased by 47-78% and 8-22% during the afternoon and night, respectively.

These changes in VD depended on the DCR, with higher DCRs resulting in lower delay. For instance, VD decreased by 47-57% with a DCR of 5% and 61-78% with a DCR of 10%.
Similarly, during early morning, with a long queue (1,500 ft) in the sending link (departures), deviating a small fraction of vehicles (5%) had a minimal impact on VD, while diverging more vehicles (10%) significantly decreased it (9-10%).

To increase the DCR, airports can modify the sign’s location and displayed message. Researchers found that setting the VMS 500-600 feet upstream of the intersection can significantly increase DCR (Peeta et al., 2000). Moreover, modifying the sign’s units of information, graphics, dynamic features, and abbreviations to provide further and reliable travel time information could also increase DCRs (Ardehshiri, 2014; Kimlinger, 2022; Peeta et al., 2000; Yan & Wu, 2014).

Deviating vehicles to a congested link led to two different outcomes. If the queue in the sending link was significantly longer than in the receiving link, deviating vehicles did not decrease the queue in a congested sending link and exacerbated congestion in the receiving link, increasing VD. For example, during the morning, VD increased by 85-102% in all scenarios. However, if congestion is similar in both links, diverging did not decrease queuing and VD. Thus, during the night, VD in the XXC scenarios did not significantly differ from that in the baseline scenario.
Notably, during the afternoon and night, the LLX scenarios (late activation and deactivation) significantly increased VD (324-595%). This phenomenon can be explained by two interacting factors. Firstly, late activation allowed the formation of a longer queue in the sending link. Secondly, late deactivation significantly increased congestion in the receiving link. Consequently, both links got highly congested, highlighting that airports must manage VMS to avoid creating or worsening congestion in the receiving link.

In summary, airports can use VMS to decrease VD before the receiving link reaches its maximum capacity. Once the receiving link reaches congestion, VD will remain unchanged if the congestion is similar in both links or increase if the sending link is more congested than the receiving link. Further details on maximum curb capacity are discussed in subsequent sections.

**Queue length (QL) and queue duration (QD)**

Figure 5-3 and Figure 5-4 illustrate changes in QL (in feet) and QD (in minutes) for the sending and receiving links compared to the baseline.

Using VMS to diverge vehicles significantly reduced QL and QD in the sending link across all scenarios except LLX scenarios. Reductions in QL (100 ft to 1,150 ft) and QD (15 to 144 minutes) were similar across scenarios, and the differences mainly depended on the DCR, with higher rates resulting in shorter queues. For example, during the afternoon and night, QL reductions were 22-23% higher in scenarios with a DCR of 10% compared to those with a DCR of 5%. Furthermore, QD reductions were 33-50% higher in scenarios with 10% DCR compared to those with 5% DCR during morning, afternoon, and night.
Figure 5-3: Queue length (QL) changes across VMS scenarios and time periods at the curb level

Figure 5-4: Queue duration (QD) changes across VMS scenarios and time periods at the curb level
During early morning, using VMS reduced the mean QL in the sending link by 25-130 ft. Yet, as the early morning queue is already too long (1,500 ft; Figure 5-2), these small reductions do not significantly change the mean QL. Similarly, the early morning QD was very high (4 hours; Figure 5-2); therefore, diverging 5% of the vehicles did not significantly reduce QD. In contrast, diverging 10% of the vehicles in some scenarios (EEF and ELF) during early morning significantly delayed queue formation in the sending link (by 15-20 minutes).

Except for the LLC scenarios, the congestion level in the receiving link was the main factor behind the variations in QL and QD there. When the receiving link was congested, deviating vehicles did not increase QL much but substantially increased QD. In particular, QD increased by 9-24 minutes during morning and night. This indicates that QL is less sensitive to changes in the number of vehicles in the queue than QD, possibly due to a non-linear relationship between curb capacity and the number of vehicles queuing, QL and QD.

When traffic conditions were uncongested in the receiving link, diverging vehicles led to three outcomes regarding the QL in the receiving link: unchanged, decreased, or increased. For instance:

1. QL remained unchanged during the early morning because the number of deviated vehicles was insufficient to create congestion.

2. QL decreased during the afternoon (75-100 ft) and most night periods (135-170 ft) because the mean speed in the receiving link increased to 5 mph or more (speed threshold defined in the Traffic-related performance metrics section). Higher speeds also explain the reductions in QD in most XXF scenarios, as they contributed to a faster queue discharge.
3. QL and QD increased in the ELF and LLF scenarios because late deactivation increased the number of vehicles in the receiving link, exceeding curbside capacity and creating congestion.

The LLC scenarios behaved differently than others. Firstly, the late activation increased QL in the sending link by 1,250-1,320 ft, causing the queue to spill back to the point of vehicle diversion (Figure 3-3.C) and creating a bottleneck where all arrival and departure vehicles were forced to queue together. The bottleneck limited the incoming flow to the receiving link, reducing the number of vehicles in the queue thereby decreasing QL and QD.

Overall, activating VMS and diverging vehicles decreased QD and QL in the sending link. If the receiving link is in free-flow condition, VMS did not negatively affect QL and QD. Once the receiving link reaches capacity, diverging new vehicles increases QL and QD.

**Impacts of Variable Message Signs (VMS) on Curb Performance Metrics**

Figure 5-5 and Figure 5-6 present the results for the curb productivity index (CPI) and curb accessibility (CA), respectively. An exploratory ANOVA analysis showed that increasing DCR from 5% to 10% did not make any significant differences in the CPI and CA results.

The timing of VMS activation and deactivation led to three outcomes for curb performance: non-significant changes (XXC scenarios), improvements (XXF scenarios), or deteriorations (late activation and deactivation, i.e., LLF and LLC scenarios).

When the receiving link was congested (EEC, ELC, and LEC scenarios), activating or deactivating VMS did not impact CPI or CA. Once curbs reach capacity, diverged vehicles are forced to queue before reaching parking spaces. Thus, redirecting vehicles increased the receiving link congestion instead of enhancing curb performance.
Figure 5.5: Curb Productivity Index (CPI) results across VMS scenarios and time periods.

Figure 5.6: Curb accessibility (CA) results across VMS scenarios and time periods.

Note: Dashed places mean congestion or free-flow conditions, and thus the associated scenarios did not exist for that time period.
However, one exception to this trend was observed in the ELC_05 scenario during the night, where the departure link served as a sending link. In this scenario, the decreasing departure queue (with a negative slope in Figure 5-2) gets fully and quickly discharged without excessively congesting the arrival (receiving link), thereby improving CPI by 4% and CA by 7%.

Managing VMS to avoid/delay link congestion is critical to increasing curb performance. When the receiving link was uncongested, diverged vehicles could park in an available space, enhancing CA (5-10%) and CPI (3-11%). In particular, the best results were obtained when VMS was activated before the congestion started in either link (EEF scenarios), increasing CPI by 4-10% and CA by 9-11%. Deactivating VMS early enough to avoid congestion in the receiving link showed the second-best results (LEF scenarios), improving CPI by 3-8% and CA by 5-9%.

During the early morning, CA was not significantly impacted by using VMS because the sending link was experiencing severe congestion. Consequently, as explained in the section Impacts of VMS on Traffic Metrics, deviating only a small fraction of vehicles (5% or 10%) did not significantly reduce the number of queuing vehicles, thereby not reducing vehicles with unsuccessful parking attempts.

LLF and LLC scenarios decreased CPI (9-61%) and CA (16-26%). This can be explained by two interacting factors. Firstly, curb performance in the sending link remained unchanged once it got congested. Secondly, as the VMS stayed active longer (late deactivation), more vehicles were deviated, increasing congestion in the receiving link. This held for all but the morning when CA was increased in the LLC scenario. As previously noted, the LLC scenario decreased QD during the morning, leading to a faster queue discharge and fewer vehicles with unsuccessful parking attempts.
Emissions analysis

Figure 5-7 summarizes the emission results. Emissions in the receiving link are similar during early morning and morning. Before noon, the queue spills back beyond the analysis area in the receiving link (between curbs and the vehicle diversion point in Figure 3-3). The emissions are presented only for the analysis area, so when the queue spills back beyond that area, the emission metric value in the sending link remains unchanged, and additional emissions produced from the queue upstream of the diversion point are not accounted for in Figure 5-7.

Table 4 1 displays that the free-flow emission rates are lower than those related to queuing (idling and braking). Consequently, the emissions during the early morning were lower than those during the morning.

Figure 5-7: Emission index aggregated results across VMS scenarios at the curb level
The differences in emissions between the early morning and morning periods depended on the receiving link congestion. During early morning, the receiving link was uncongested, allowing diverged vehicles to flow freely. Conversely, the receiving link was congested during the morning. Thus, diverged vehicles queued in the receiving link.

During the afternoon, emission reductions (9-15%) relate to two opposite situations in the sending and receiving links. Using VMS decreased congestion in the sending link—decreasing queuing emissions—and increased the flow in the receiving link—increasing free-flow emissions. Since the free-flow emission rates are lower than congestion emission rates (see Table 4.1), changes in the sending link were more significant than those in the receiving link, reducing total emissions. In particular, the EEF and LEF scenarios presented the most significant changes (11-12%).

At night, we observed significant differences in the receiving link between the XXC and XXF scenarios. When the receiving link was congested (XXC scenarios), diverged vehicles queued in the receiving link instead of the sending link. Therefore, the emissions related to queuing did not decrease and were merely relocated from one access to the other. Conversely, when the receiving link was uncongested (XXF scenarios), diverged vehicles moved freely in the receiving link. As queuing emission rates are higher than those in free-flow, receiving link emissions were more elevated in XXC than in XXF scenarios.

Once more, the LLC and LLF scenarios behaved differently than the others. As explained in the Impacts of VMS on Traffic Metrics section, these scenarios increased congestion in the sending link. The increased congestion caused the queue to spill back to the point of vehicle diversion, causing a bottleneck where all arrival and departure vehicles were forced to queue together. As the emissions produced outside the analysis area are not accounted for, emissions in the LLC and LLF scenarios are lower than the baseline scenario.
**Optimal Activation and Deactivation of VMS**

As described above, some VMS management scenarios proved to reduce emissions and improve curb performance and traffic conditions. In particular, activating the sign before congestion starts in the sending link and deactivating it before the congestion begins on the receiving link is crucial, as this approach yielded the most significant benefits.

To determine when congestion starts at SEA, vehicular capacity at the curbside starting point in the baseline scenario was examined. Figure 5-2 provides a graphical representation of this analysis, showing the relationship between queue length (blue line) and the vehicular capacity of the ramps (red line), as indicated by the dotted line.

When airport ramps reach capacity, QL grows drastically, indicating the formation of a new queue. Although there are some minor fluctuations in QL, they do not indicate the formation of a new queue but rather small changes in the length of an existing queue. The dotted lines reveal that queue formation consistently occurs at specific flow values. Once the ramp reaches these predetermined flow levels, queue formation is triggered. This typically happens at traffic flow rates of 650-700 vehicles per hour for the arrival access level. Similarly, significant increases in departure QL are observed at flow rates of 975-1,100 vehicles per hour.

The capacity of the airport’s ramps and curb lanes are linked. When the curb lanes are fully occupied, vehicles wait in the thru lane until a parking space becomes available, as depicted in Figure 5-8. This behavior, documented during a site visit in March 2023, creates a bottleneck at the terminal’s curbside starting point. Consequently, all vehicles must wait before proceeding, hampering the airport’s overall capacity to maintain a continuous vehicle flow.
The speed-flow diagram (Figure 5-9) shows the abovementioned flows in coral color. The scattered areas lying above those coral parts indicate congestion.

To avoid congestion and undesired VMS effects, we recommend using the minimum flow value of the abovementioned ranges as the threshold for activating/deactivating VMS. Thus, the airport should activate VMS to diverge vehicles from departures close to the 975 veh/hr flow mark and deactivate it when arrivals approach 650 veh/hr. Similarly, they should activate VMS to re-
route vehicles from arrivals close to the 650 veh/hr flow mark and deactivate it when the departure ramp approaches 975 veh/hr. These thresholds will differ for different airports but can be easily obtained from the historical data collected through sensors or other traffic condition measurement means.
Chapter 6

Conclusions

This research delved into how implementing variable message signs (VMS) at airports impact curb performance, including curb productivity index (CPI), curb accessibility (CA), queue length (QL), queue duration (QD), vehicle delay (VD), and emissions. This chapter explores the main contributions of this master’s thesis, encompassing the effects of VMS on the abovementioned metrics, identifying the optimal VMS management strategy, and practical recommendations for VMS deployment. Finally, this chapter concludes by presenting the research’s limitations and suggesting avenues for future studies.

Contributions

This research presents valuable insights into the transportation field and practical recommendations for the deployment of VMS. The findings reveal that airports can maximize VMS benefits by timely activating and deactivating VMS, even when only a small fraction of vehicles (5%) followed the displayed instructions. In this way, VMS has substantial effects on traffic, emissions, and curb performance:

- **Traffic performance**: Using VMS to re-route vehicles to non-congested ramps reduced VD (8-78%). The effects on QL and QD varied significantly for the sending and receiving links, depending on how many drivers followed the displayed instructions, with higher driver compliance rates resulting in shorter queues. The sending link experienced significant reductions in QL (100 ft to 1,150 ft) and QD (15 to 144 minutes) across most VMS management strategies. Yet the
impact on the receiving link depended on congestion: significant increases in QD (9 to 24 min) when the link was congested, but no significant changes during free flow.

- **Emission rates**: VMS strategies significantly reduced CO2 emissions, ranging from 8% to 23% in most scenarios.

- **Curb performance**: The impacts of using VMS to diverge vehicles varied across scenarios. When the receiving link was congested, activating or deactivating VMS did not significantly impact CPI or CA. Conversely, diverging vehicles enhanced CA (5-10%) and CPI (3-11%) when the receiving link was uncongested.

Based on these findings, the optimal activation and deactivation strategy for VMS is:

- **Optimal VMS management strategy**: The optimal strategy is activating VMS before congestion starts on the sending link and deactivating it before congestion begins on the receiving link. This approach yielded the most significant improvements in CPI (8-10%), CA (9-10%), VD (29-78%), and emissions (12-14%).

- **Detrimental strategies**: Activating VMS after the queue was formed did not improve conditions in the sending link, and its late deactivation actually congested the receiving link. Consequently, most metrics were worsened under this VMS management approach, including increments in VD (96-594%) and drops in CPI (6-61%), and CA (17-26%).

In light of these findings, practical recommendations for VMS deployment are proposed:
• It is recommended to activate the sign before the congestion starts in the sending link and deactivate it before the congestion begins on the receiving link. Airports can easily identify those activation/deactivation moments by monitoring the traffic patterns and installing sensors to measure the speed and flow at critical points.

• In the specific case of the Seattle-Tacoma International Airport, the airport should activate VMS to diverge vehicles from departures close to the 975 veh/hr flow mark and deactivate it when arrivals approach 650 veh/hr. Similarly, they should activate VMS to re-route vehicles from arrivals close to the 650 veh/hr flow mark and deactivate it when the departure ramp approaches 975 veh/hr.

• Managing VMS heuristically and by intuition is discouraged, as it may not consistently improve curb performance and could even exacerbate congestion. In particular, VMS had insignificant impacts on curb performance when the receiving link was congested.

This study provides a framework for researchers and airport planning teams to assess the impacts of VMS on their traffic congestion and curb performance. Moreover, while the specific values and statistics in this study relate to the SEA airport, as the analysis was conducted using a repeated measures approach and a wide range of input values and scenarios, the findings provide valuable insights into how airports could exploit and manage VMS technologies.

**Limitations and Suggestions for Future Studies**

While providing a robust and comprehensive methodology and analysis, like any other study this research had certain limitations that warrant further consideration in future studies:
1. **Specific case study:** This analysis focused on SEA airport. While the developed framework can be applied to any airport and some of the findings can be applied to airports with similar infrastructure to SEA, they may not apply to airports with different infrastructure. Future research can use the proposed framework to analyze the features different from SEA, such as varying numbers of terminals, access levels, curb spaces, traffic compositions, and VMS locations.

2. **Impact analysis:** This master’s thesis analysis focused on six metrics covering traffic impacts, curb performance and emissions. Some other impacts such as traffic density, safety, conflicts, curb utilization rates, etc., were not considered in this study.

In addition, future work could explore integrating the predictive VMS control algorithm presented in Nazir et al. (2022) within the proposed framework. The model predictive control developed by Nazir et al. (2022) uses forecasts of vehicle demand based on the passenger volume to modify VMS deployed messages. Future work could compare the performance of the predictive MPC against the sixteen VMS scenarios presented in this work.
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SEA (Seattle-Tacoma International Airport), 2023. Picture of the variable message signs at the Airport Expressway. Seattle-Tacoma International Airport Planning Team.


