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Evaluating the Impacts of Variable Message Signs on Airport Curbside Performance Using Microsimulation

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Abstract

Inefficient curb space allocation increases congestion and emissions at airports. Variable message signs (VMS) can alleviate this issue, guiding vehicles from congested to underutilized curbs. However, VMS effectiveness hinges on the right activation and deactivation timing. Using a microsimulation model of the Seattle-Tacoma International Airport, we analyzed the impacts of implementing VMS and determined the best time to turn the sign on and off. We simulated sixteen VMS management scenarios and compared the results against those of a baseline where there was no VMS. We found that strategic and timely management of the VMS is crucial to achieving improvements in congestion and curb performance. Specifically, activating VMS before congestion started on the sending link and deactivating it before congestion began on the receiving link substantially improved curb productivity and accessibility, vehicle delay, and CO_2 emissions. On the other hand, if not managed correctly, VMS may lead to little to no improvements, or even negative impacts on traffic conditions and curb performance. For instance, late activation or deactivation can worsen curb accessibility and vehicle delay. Our framework provides valuable insights into how airports could successfully manage VMS technologies.

Keywords

airport ground access, curbside management, microsimulation, variable message sign

Curbs facilitate vehicle access and egress for individuals in densely congested environments (*1*). Given the ongoing urban growth and rapid expansion of transportation network companies (TNC) (*1*, *2*), authorities face the complex task of allocating scarce curb space resources to meet an increasing demand. An inefficient allocation of curb space decreases parking accessibility and productivity and increases congestion, travel times, and emissions (*1*, *3*–*6*).

There is a range of research concerning curb management in urban areas, focusing on short- and long-term parking for personal, TNC, transit, and freight vehicles. In particular, parking behavior (*1*, *7*, *8*), parking policies (*3*, *6*, *9*), capacity requirements (*4*, *9*, *10*), curb allocation (*4*, *11*, *12*), passenger pick-up and drop-off (*2*, *13*, *14*), cruising for parking (*15*), and pricing (*16*) are recurring topics in the literature.

Airport curbs are among the most congested that could benefit from effective curb management. Yet, since their infrastructure, dwell time, vehicle maneuvers, and demand variability differ between airport and urban curbs (*17*, *18*), the findings from the urban curb management research may not apply to airport curbs. Consequently, there is a separate body of curb management literature focused on airports.

Qualitative research on airport curb management provides insights into the level of service and examples of

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policies (*18–21*). In particular, mode choice literature allows for understanding passengers' landside transportation choices and describes the impacts of alternative, nonmotorized, and transit modes on airport accessibility (*22–28*). Moreover, researchers have evaluated curb policies, including geofencing, double parking, alternative parking, enforcing maximum dwell times, and prioritizing electric, autonomous, TNC, and transit vehicles (*8*, *17*, *21*, *24*).

To meet the increasing demand, airports may also expand curb infrastructure. The National Academies of Sciences Engineering and Medicine provides methods such as widening curbside lanes, increasing curb length, and constructing additional parking (*21*). Similarly, Parizi and Braaksma developed a computer program to determine the optimal number and location of curbside positions and effective curb length (*29*). Moreover, Kleywegt and Liu compared different curb layouts, finding the optimal configuration—number of parking spots, parking angle, and double parking—to increase capacity for different vehicle speeds and dwell times (*30*).

Despite its demonstrated effectiveness, increasing infrastructure requires significant investments. Thus, airports constantly seek low-cost options—such as technological innovations—for managing their curbs (*20*). Airports experience an unbalanced demand as passengers arrive simultaneously at specific entrances at certain hours, leaving some curbs underutilized while others experience congestion (*21*). Prior research has found that effectively relocating airport-curb demand can mitigate congestion (*31*, *32*). Therefore, one way to address airport congestion is to divert the exceeding demand to underutilized curbs using variable message signs (VMS).

A VMS provides real-time information by modifying its displayed message (*33*). Some researchers have studied the effects of VMS on routing decisions (*34*, *35*), speed (*36–38*), and traffic safety (*35–38*). Researchers have also explored the implications of VMS on parking garages and on-street parking using driving simulators (*39*, *40*), simulations (*41*), and mathematical frameworks (*39*, *42–44*). These studies demonstrated that using VMS does not improve parking performance when supply exceeds demand but decreases circulation time and turnover rates when supply is less than demand (*39*, *42–44*).

The VMS strategy has also been deployed in airports to improve congestion by deviating traffic between curbs when one is congested. Vasisht et al. showed the effectiveness of the VMS at the Seattle-Tacoma International Airport (SEA), finding that VMS decreased congestion and increased vehicle speeds (*45*). Nazir et al. presented a macroscopic dynamic model of SEA's VMS operations and found that VMS improved the ramp speed up to three times, saving 80 vehicle-hours and reducing idle time, fuel waste, and emissions (*5*).

Despite this, VMS effectiveness faces two primary challenges. First, drivers may ignore the guidance (*41*). SEA, for example, showed only a 5.5%–9.1% driver compliance rate (DCR) when drivers were instructed to divert from departures to arrivals and 1.9%–4.2% in the opposite scenario (*45*). Second, if VMS is not activated and deactivated at the right moment, it will not operate at its full potential. Typically, airports use VMS heuristically and by intuition rather than through a systematic evidence-based approach (*5*, *45*). If they infer that one of the ramps is more congested than the other, they ask drivers to use the other ramp. However, this approach does not fully harness the VMS capabilities and might even exacerbate congestion and reduce curb performance.

This research investigates the optimal sign activation and deactivation strategies that could improve curb performance while mitigating congestion and emissions. Identifying optimal management strategies can help airports move away from managing VMS heuristically, instead adopting a systematic, evidence-based approach. Using SEA as a case study, we employed a validated agent-based microsimulation model to assess the impacts of various VMS management scenarios. The scenarios were built considering different DCRs and traffic states and were tested for four time periods: early morning, morning, afternoon, and night. The results of each scenario were compared against those of a baseline where there is no VMS.

This paper contributes to the literature by studying how to maximize VMS benefits for curb management at airports. We quantify VMS trade-offs—in relation to curb productivity and accessibility, queue length and duration, delay, and emissions—to determine the optimal activation and deactivation strategy. Moreover, this analysis helps identify which strategies provide significant benefits and which lead to either negligible or negative effects, thereby avoiding ineffective VMS use.

Study Approach

Figure 1 illustrates the methodological framework used in this study, structured as a sequential four-step process, where each step serves as the input for the next. Each row represents one step, and the three columns summarize the step name, a brief description of the task performed, and the outcome generated. The outcome from each step serves as the input for the next, creating a clear and logical progression through the framework.

First, we developed sixteen distinct scenarios to evaluate different approaches to managing VMS at airports. Our designed scenarios cover different activation/deactivation approaches, traffic conditions on sending and

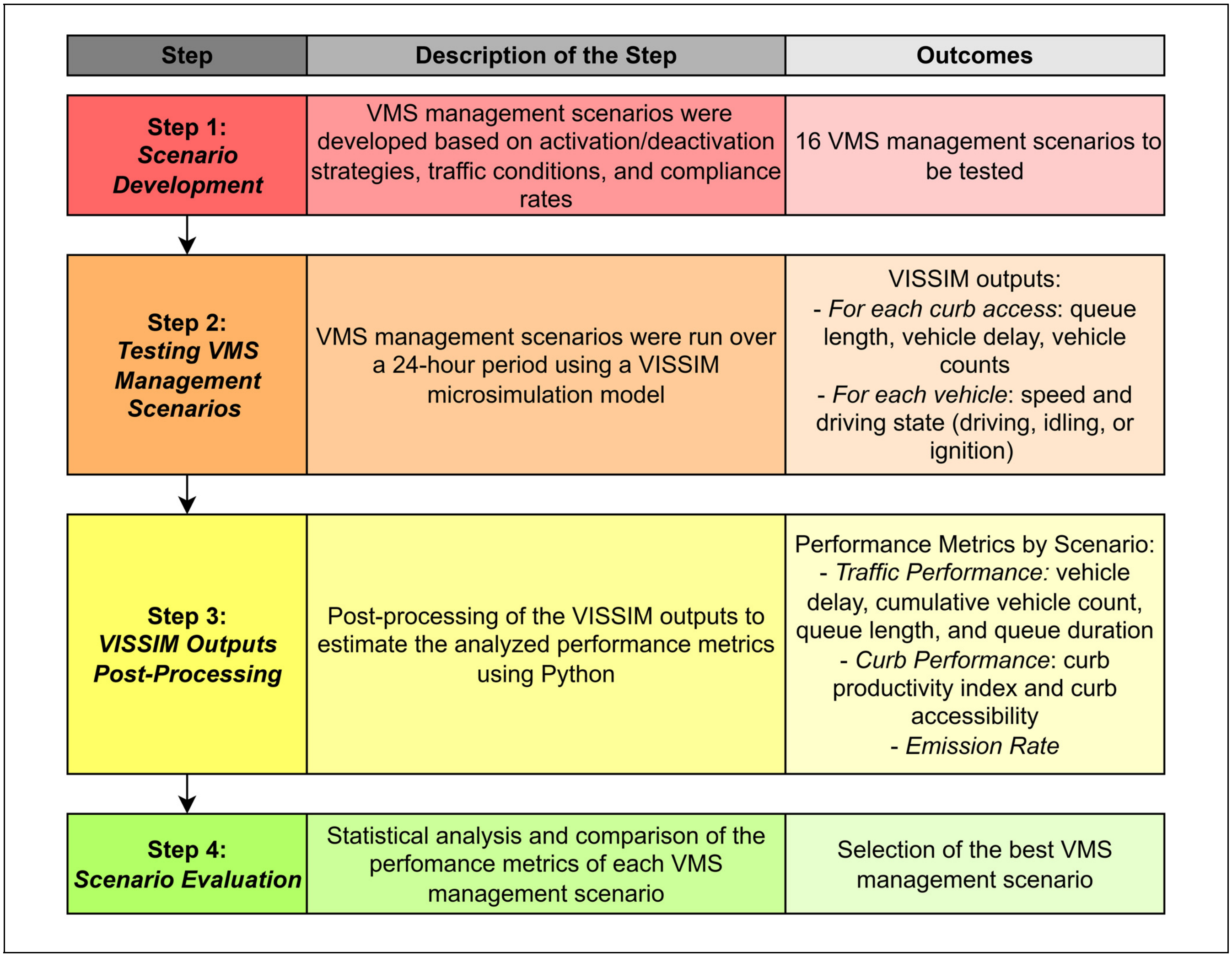

Figure 1. Four-step methodological framework for VMS impact assessment.
Note: VMS = variable message sign.

receiving links (i.e., access links from/to which vehicles are diverted), time of day, and DCRs. Either of the ramps (arrivals or departures) may function as the sending or receiving link, depending on which is congested at a given time and what the suggested diversion would be, which in turn is based on historical traffic patterns at SEA. Further details on the construction of these scenarios are provided in the section "VMS Curb Management Scenarios."

In the second step, we employed VISSIM—an agent-based traffic flow microsimulation tool—to model the developed scenarios. Simulation models allow the analysis of future or hypothetical scenarios, yielding reliable and detailed results. They offer a cost-effective alternative to pilot projects. For example, Ugirumurera et al. used a microsimulation model to evaluate the effects of six curbside management scenarios at the Dallas-Fort Worth International Airport (*24*), and Harris et al. analyzed the effects of four management policies at the Pearson International Airport in Toronto (*17*). The simulation generated a range of outputs, including 15-min aggregated values for queue lengths, vehicle delays, and vehicle counts at each ramp, as well as second-by-second speed and driving state data for each vehicle.

In the third step, the simulation outputs were postprocessed (in Python) to compute the relevant performance metrics. These metrics capture traffic conditions, curbside efficiency, and airport-related emissions, and are detailed in the section "Performance Metrics."

Finally, the performance of each VMS scenario was compared with a baseline scenario without VMS, as well as other management scenarios. This comparison relied on both absolute and relative differences, as well as Repeated Measures ANOVA, as described in the section "Performance Metrics." Through this analysis, the study identified the VMS management scenarios that delivered

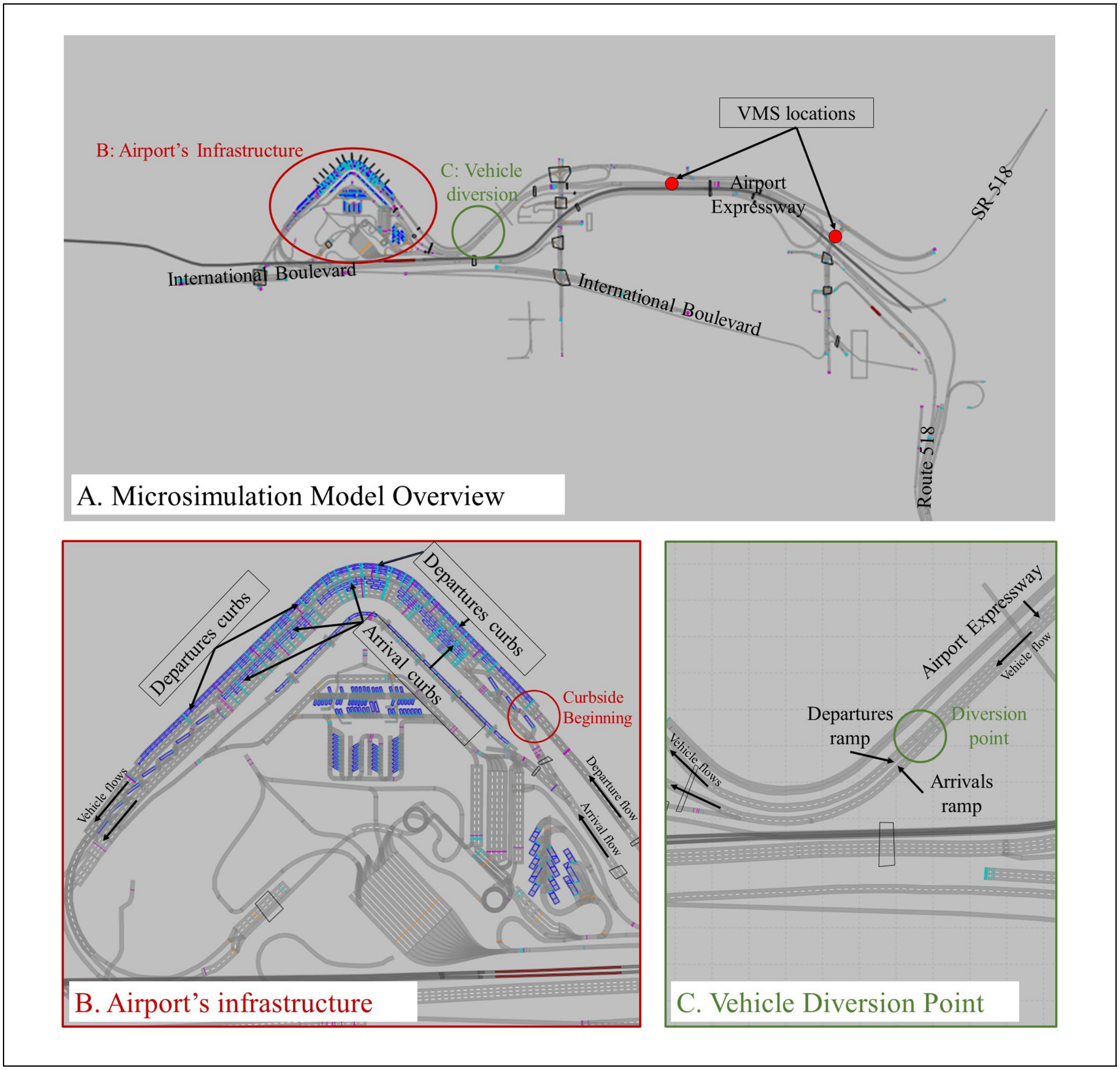

Figure 2. Overview of the microsimulation network at SEA, including terminal and access infrastructure: (*a*) microsimulation model overview, (*b*) airport's infrastructure, and (*c*) vehicle diversion point.
Note: SEA = Seattle-Tacoma International Airport; VMS = variable message sign.

the most favorable outcomes based on traffic, curbside operation or emission goals.

Case Study

With 45.9 million passengers, SEA was the eighth busiest US airport in 2023. SEA has a broad network of 33 airlines and connects Seattle with 92 domestic and 28 international destinations (*46*). This study employs a microsimulation model of this airport provided by SEA's aviation planning team. It models 39.05 mi of highway, including the airport's main terminal and the surrounding highways.

Figure 2 provides an overview of the SEA microsimulation model. The figure is divided into three parts. Figure 2*a* shows the full network, including the Airport Expressway, International Boulevard, and the locations of the two VMSs. Figure 2*b* zooms into the airport terminal area, highlighting the layout of the arrival and departure curbs. Figure 2*c* focuses on the vehicle diversion point, where drivers decide whether to proceed to the arrivals or departures ramp.

The model was built and calibrated using the ground-truth data from August 2022, the busiest month of the year. Calibration of the model was performed by a consulting firm hired by SEA, and the data for it came from existing speed-flow cameras located at the airport's curbs, ramps, and highway access points, as well as field data (collected by the consultant) on key input parameters such as vehicle flow, speed, dwell times, turning movements, and vehicle type composition. Before using the model for our analysis, we validated it using data from August 2023, collected through the same camera infrastructure, along with field data (collected by the authors). For further details on the calibration and validation process, interested readers may refer to Diaz Gutierrez (*47*).

The study area comprises the airport's main terminal and two access levels (arrivals and departures). Vehicles approach the terminal using the Airport Expressway, which splits into the arrivals and departures ramps. The arrival ramp consists of two lanes over a stretch of 1,800 ft and terminates at the arrival curbside, which features three parking lanes and three travel lanes, each approximately 1,000 ft long. Similarly, the departure ramp comprises two lanes for 1,500 ft and leads to the departure curbside, which includes two parking lanes and two travel lanes, each about 1,600 ft long.

Two VMSs are installed on the Airport Expressway, located between Route 518 and the Vehicle Diversion Point, as shown in Figure 2*a*. Of these, the VMS closest to the terminal is used to redirect approaching vehicles from congested to uncongested curbs, and the second one is used for other communication purposes. For further details on SEA's infrastructure, interested readers may refer to Diaz Gutierrez (*47*).

Model inputs included vehicle flow, speeds, curb availability, dwell time, and vehicle type compositions. The input flows changed hourly between 2,000 and 12,500 veh/hr, with traffic distributed across 38 entry points. Desired speed distributions ranged between 15 and 30 mph.

Moreover, the model assumes that vehicles park in 20 ft parking spaces following a normal dwell time distribution with averages of 60 and 90 s for departing and arriving vehicles, respectively. These values reflect operational differences between departure and arrival curbs. Departing vehicles tend to have shorter stops, as passengers aim to catch flights, while arriving vehicles typically wait at a specific location until their passengers exit the terminal. These set dwell times are preserved for the respective vehicles, even when being rerouted via VMS to a different curb. For instance, a vehicle originally heading to the arrivals curb retains the dwell time distribution of an arrival vehicle, even if it is redirected to the departures curb.

There were six vehicle types in the model: personal vehicles (45%–65%), TNC vehicles (15%–30%), shuttles (10%–20%), taxis (1%–10%), limos (1%–3%), and buses (0%–5%). All personal vehicles and limos park at the analyzed curbs. Buses have their dedicated curbs that are located separately from the ones analyzed in this study. Shuttles, taxis, and TNCs are designated to park in the Central Garage; however, some of them still pick up and drop off passengers at the analyzed curbs. So, the model includes a small fraction of them.

VMS Curb Management Scenarios

We developed 16 VMS scenarios and a baseline wherein there is no VMS. The scenarios were built by systematically permutating key factors, including two VMS activation approaches (before or after the start of the queue in the sending link), two VMS deactivation approaches (before or after the queue ends in the sending link), two traffic flow conditions in the receiving link (congested or free-flow), and two DCRs (5% or 10%). The sending link is the original destination of the vehicles, and the receiving link is where the vehicles deviate if they follow the VMS guidance. Either of the ramps (arrivals or departures) can play the role of sending or receiving link depending on congestion conditions. For instance, when the arrivals ramp is congested, vehicles are diverted to the departures ramp, making arrivals the sending link and departures the receiving link. These allocations are informed by historical traffic conditions at SEA.

Figure 3 illustrates the systematic process to develop the scenarios, resulting in 16 VMS management scenarios. The scenario names are coded using a combination of letters that reflect the selected conditions: E or L for the timing of VMS activation/deactivation (Early or Late), F or C for the receiving link traffic condition (Free-flow or Congested), and the compliance rate as a numeric suffix.

Nazir et al. (*45*) reported a 5.5%–9.1% DCR for departing vehicles instructed to divert to arrivals, and a lower 1.9%–4.2% rate for arriving vehicles instructed to divert to departures. These results suggest that vehicles dropping off passengers are slightly more flexible in accepting curb reassignment, possibly because reaching the terminal quickly is more important than arriving at a specific airline entrance. In contrast, arriving drivers often aim to meet passengers at specific locations, making them somewhat less willing to use alternate curbs. While these differences are meaningful, they remain relatively modest. Therefore, for simplicity, we have adopted

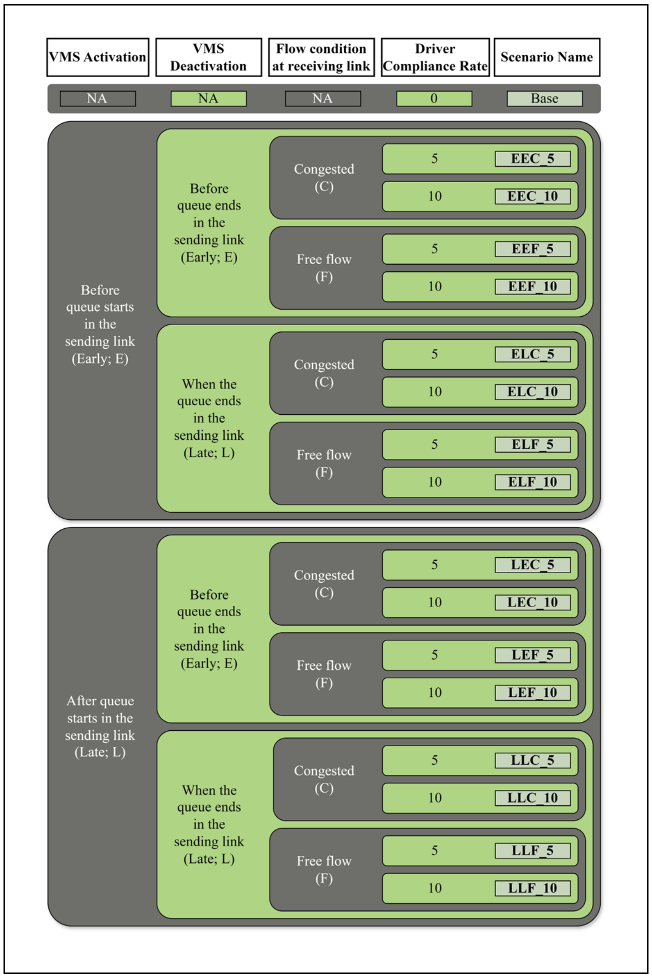

Figure 3. Overview of the VMS management scenarios developed based on different activation/deactivation strategies, traffic conditions, and driver compliance rates.
Note: VMS = variable message sign.

DCR values of 5% and 10% for both departing and arriving vehicles to account for different levels of flexibility and compliance behaviors.

We modified the model such that diverted vehicles maintain their associated dwell time regardless of their destination; that is, if a vehicle aiming to pick up a passenger goes to departures, its dwell time will follow the arrival dwell time distribution. Other 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 periods: early morning (4:00–9:00 a.m.), morning (9:00–12:00 midday), afternoon (1:00–4:00 p.m.), and night (7:00–12:00 midnight). These periods were selected based on ground-truth data, considering the typical congestion patterns at SEA. If a particular traffic condition did not exist during a given time period, the associated scenarios were excluded from the simulation. For instance, during the early morning period, the arrival ramp consistently operates in free-flow conditions, meaning it cannot serve as a congested receiving link. Therefore, scenarios requiring a congested receiving link, such as EEC_05 and EEC_10 during early morning, were not included in the analysis. Moreover, each scenario was simulated using 10 random seeds, resulting in up to 80 simulation runs per scenario. The results were averaged per scenario and time period.

Performance Metrics

We evaluated the results from the three following perspectives: traffic impacts, curb performance, and emissions. We compared the scenario's results against those of a baseline, using absolute and relative changes and Repeated Measures ANOVA. Repeated Measures is a research design that involves administering multiple treatment levels to the same subjects (*48*), incorporating a random variable to exclude the effect of the subject. In our experiment, each scenario represents a treatment level, and the study subjects are the 80 simulation runs. We designed the study subjects based on the time period, analyzed ramp, and random seed to exclude the influence of these variables from the analysis.

Traffic Impacts. The ACRP Report 40 recommends analyzing the airport's curb performance using the following metrics: vehicle delay (VD), queue length (QL), and queue duration (QD) (*21*). VISSIM provides QL and VD as direct outputs. We defined VD as the difference in travel time between congested and free-flow conditions experienced by vehicles. It was measured between the vehicle diversion point and the start of the first curb space (Figure 2). 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. QD is the time difference between when the queue forms and when it is fully discharged. We used ANOVA-Poisson analysis for QD estimation because of the high proportion of zero values in the observations.

Curb Performance. We have adopted two curb performance metrics developed by Maxner et al. for our analysis: curb productivity index (CPI) and curb accessibility (CA) (*12*). In the following equations, Equation 1 estimates CPI as the number of passengers serviced per hour per parking space, and Equation 2 presents CA as the ratio of successful vehicle parking attempts (spp) to total parking attempts (tpp):

$$CPI = \left(\sum v_i * p_i\right)/t/sp \quad (1)$$

$$CA = \sum spp/\sum tpp \quad (2)$$

Table 1. CO_2 Emission (lb. CO_2/hr) Estimates for Different Types of Vehicles by Driving Status and Speed

Driving status	Speed (mph)	Vehicle types					
		Personal vehicles	TNC	Buses	Taxis	Limos	Shuttles
Ignition off	0	0	0	0	0	0	0
Ignition after parking (I_g)	0	7.133	6.179	43.383	1.544	8.653	31.1
Idling (parked or stopped) (I)	0	1.737	1.504	10.562	1.544	2.107	7.572
Fast acceleration	0–10	3.473	3.008	21.124	3.088	4.213	15.143
	10–20	4.342	3.761	26.405	3.86	5.266	18.929
	20–30	5.21	4.513	31.686	4.632	6.32	22.715
	30 +	6.078	5.265	36.967	5.404	7.373	26.501
Moderate acceleration	0–10	2.605	2.256	15.843	2.316	3.16	11.358
	10–20	3.473	3.008	21.124	3.088	4.213	15.143
	20–30	3.473	3.008	21.124	3.088	4.213	15.143
	30 +	4.342	3.761	26.405	3.86	5.266	18.929
Slow acceleration	0–10	2.605	2.256	15.843	2.316	3.16	11.358
	10–20	2.605	2.256	15.843	2.316	3.16	11.358
	20–30	2.605	2.256	15.843	2.316	3.16	11.358
	30 +	3.473	3.008	21.124	3.088	4.213	15.143
Free-flow at design speed	All	2.605	2.256	15.843	2.316	3.16	11.358
Deceleration/Braking	All	1.737	1.504	10.562	1.544	2.107	7.572

Note: TNC = Transportation Network Company vehicles.

A parking attempt starts when a vehicle's status changes from "none" to "driving to parking space" in the simulation. It is successful if the vehicle's status changes to "parked," and failed if it changes to "parking request declined." CPI relates to the number of successfully parked vehicles (v_i), the number of picked up or dropped off passengers per vehicle (p_i), the simulation time (t), and the number of parking spaces (sp). For occupancy, we assumed random pick-ups/drop-offs of one to three passengers for personal vehicles, TNCs, taxis, and limos, and a normal distribution (with an average of ten and a standard deviation of two passengers) for shuttles.

Emissions. We adopted the emission index proposed by Maxner et al. to calculate the amount of CO_2 emissions (*12*). Their index estimates the emissions for different vehicle states separately using

$$EI = \sum Eff_{ds} \times (DS \times t_{ds}) + \sum Eff_I \times t_I + \sum Eff_{Ig} \times I_g \quad (3)$$

where Eff is the emission rate, t is the time a vehicle spends in a given state—driving (ds), idling (I), or ignition (I_g)—and DS is the acceleration- and speed-based driving state. The term $I_g = 1$ if the vehicle is parked for 5 min or more, and 0 otherwise. In our emission calculation, we covered all vehicles in the analysis area, which is between the last curb space and the diversion point (Figure 2*c*).

For personal vehicles, TNCs, and buses, we used Maxner et al.'s emission rates and assumptions (*12*). For taxis and limos, we assumed 2014–2024 vehicle models. For taxis, we assumed 14% mini-vans, 38% sedans, 20% small SUVs, and 28% compact cars based on the fleet information from King County (*49*), and for limos, we considered even distribution (33% each) for large SUVs, town cars, and small luxury SUVs.

We calculated each vehicle type emission factor using the vehicle fuel economy database provided by the U.S. Department of Energy (*50*) and extrapolated the values into gram-per-second emissions. Table 1 presents the extrapolated emission values for different vehicle types and driving states, including ignition, acceleration, free-flow, and deceleration/braking. The acceleration state is further categorized into fast acceleration ($>6\,m/s^2$), moderate acceleration ($1.75–6\,m/s^2$), and slow acceleration ($<1.75\,m/s^2$). Within each driving state, emissions are further broken down by speed level.

Emission rates for personal vehicles, TNCs, and buses were obtained from Maxner et al. (2023).

Results and Discussion

In the following, we compare the analyzed VMS management scenario based on the described performance metrics. Analyzed periods were selected based on ground-truth data. If a traffic condition was absent during a specific period, the associated scenarios are not shown in the plots.

Traffic Impacts

Figure 4 compares the VD results for each of the analyzed VMS management scenarios against those of the baseline (grey bar). The results are broken down by time of day (early morning, morning, afternoon, and night) and further separated by location within the

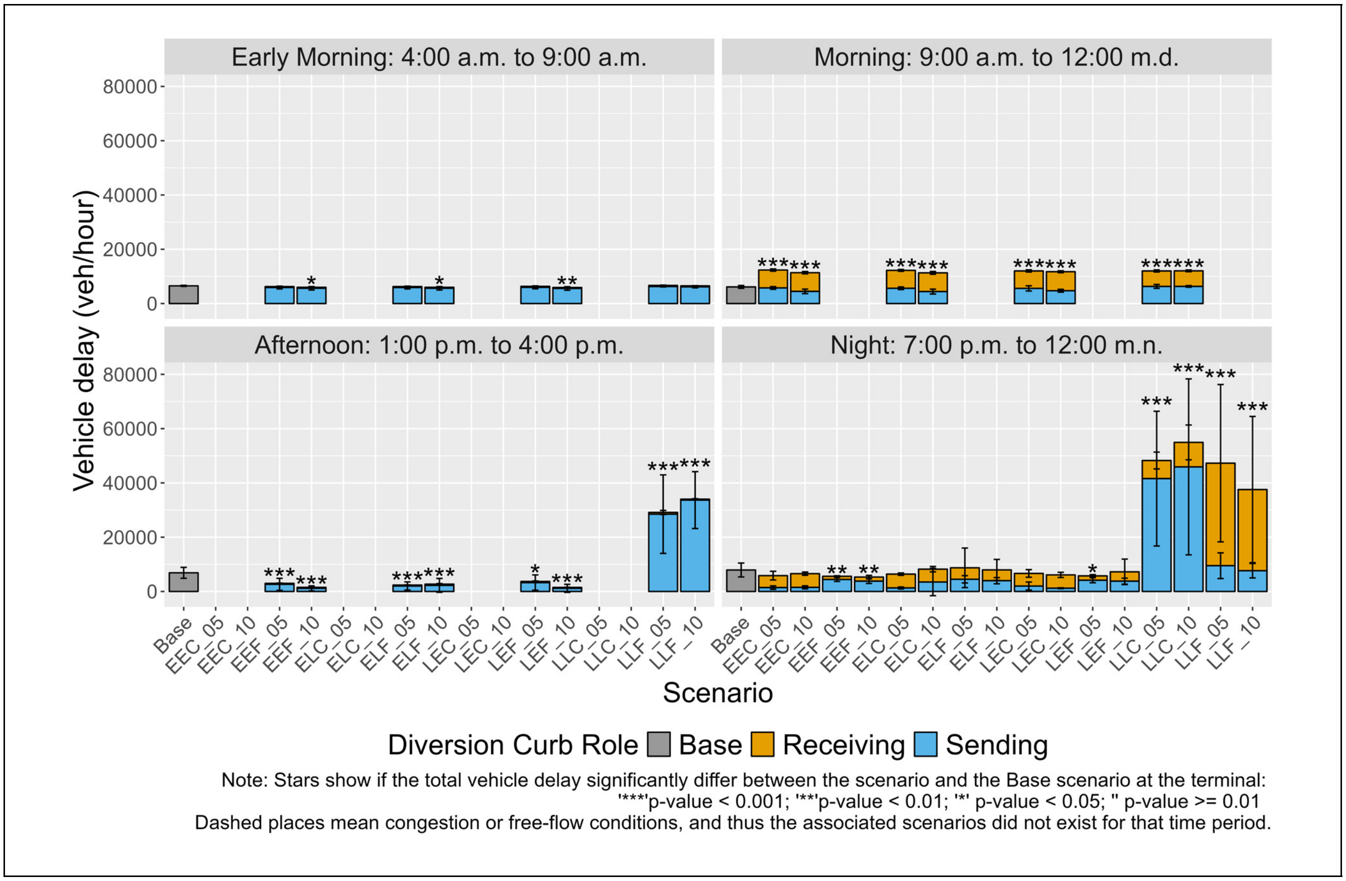

Figure 4. Estimated VD for each VMS management scenario by time of day and curb role (sending vs. receiving).
Note: VD = vehicle delay; VMS = variable message sign.

airport network, specifically the sending and receiving links. The delays of both links are stacked, as they collectively represent the total delay experienced at the airport terminal. Asterisks above the bars indicate statistically significant differences between each scenario and the baseline.

VD varied based on the receiving traffic condition. If the receiving link was uncongested (XXF scenarios, X is a placeholder for letters corresponding to our scenario name conventions in Figure 3), deviating vehicles reduced the sending link's congestion without increasing VD in the receiving link, thereby reducing the terminal's VD. For example, VD in the EEF, ELF, and LEF scenarios decreased by 47%–78% and 8%–22% respectively during afternoon and night.

The changes in VD depended on the DCR, with higher DCRs resulting in lower VD. During afternoon, VD decreased by 47%–57% when DCR = 5% and by 61%–78% when DCR = 10%. Similarly, during early morning, with a long queue (1,500 ft) in the sending link, deviating a small fraction of vehicles (5%) had a minimal impact on VD, while diverting more vehicles (10%) significantly decreased it (9%–10%).

To decrease VD, airports can potentially increase DCRs through changing the VMS location and message. The placement and layout of VMS are critical (*36*, *37*, *51–53*). Positioning it closer to the diversion point is especially important, as the influence on driver routing decisions diminishes with distance. The content of the message also significantly affects driver behavior (*34*, *54–56*). Therefore, airports should prioritize messages that enhance driver exposure, clearly communicate travel time savings, emphasize reliability, and appeal to individual driving habits and prior experiences. Finally, the wording and visual design of messages play a key role. Research shows that factors such as message length, phrasing, light, use of colors, flashing elements, symbols, and pictograms all contribute to improved compliance (*51–53*).

Deviating vehicles to a congested link led to two outcomes. If congestion is similar in both links, diverging did not decrease VD (XXC scenarios during night). However, if the queue in the sending link was significantly longer than in the receiving link, deviating vehicles did not significantly decrease congestion in the sending link and exacerbated the receiving link's

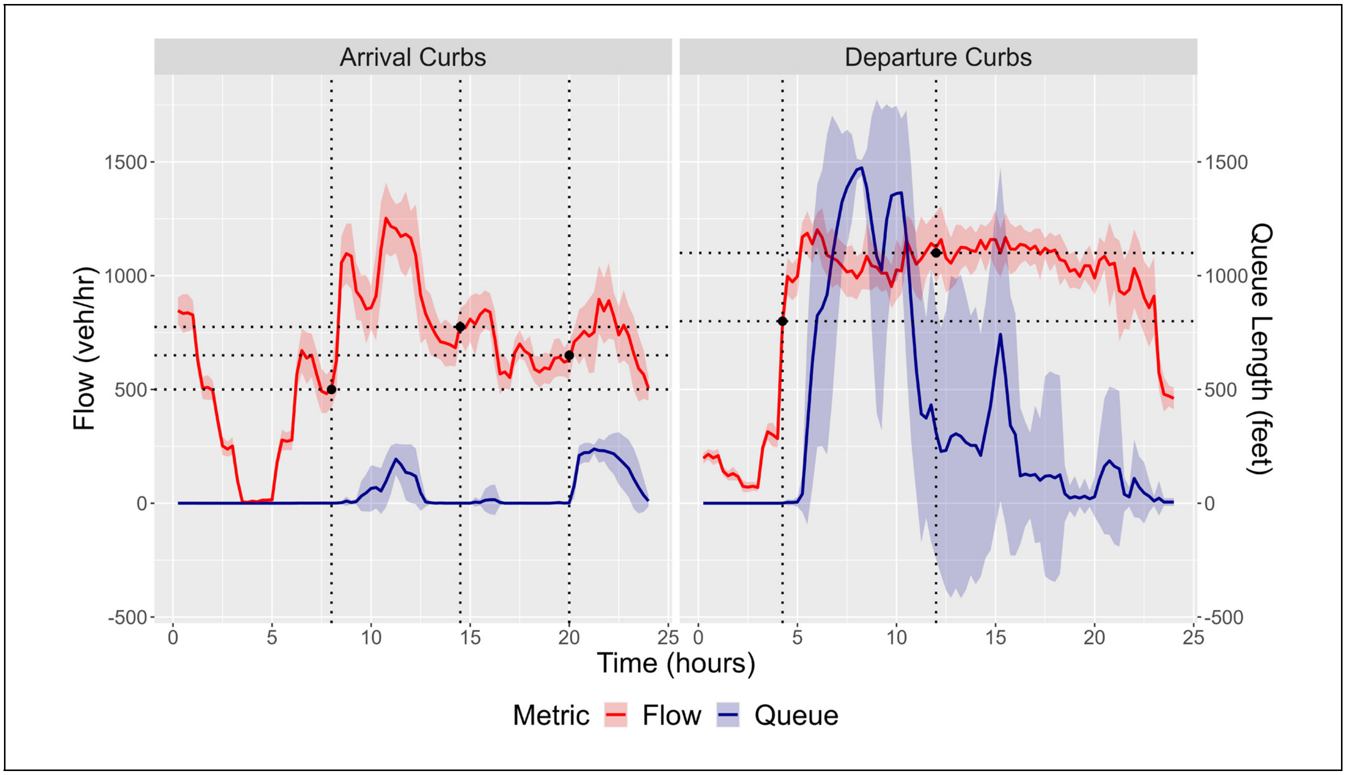

Figure 5. Baseline time series of the airport's traffic flow and queue length by time of day and curb access.

congestion. For example, during morning, VD increased (85%–102%) in all scenarios as the mean QL was 1,500 ft for departures and 250 ft for arrivals. This happens because the arrival and departure curbs have different maximum flows.

Figure 5 illustrates this pattern by showing how traffic flow (in red) and QL (in blue) fluctuate throughout the day in the baseline scenario. To clearly distinguish traffic conditions at each ramp, the figure is divided into two panels, that is, one for arrivals and one for departures.

Notably, during afternoon and night, the LLX scenarios significantly increased VD (324%–595%). This can be explained by two interacting factors: a) late activation resulted in forming a longer queue in the sending link, and b) congestion in the receiving link was also increased because of the new vehicles. This highlights the importance of managing VMS to avoid creating or worsening congestion in the receiving link.

Thus, airports can decrease VD by using VMS 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 will increase when the sending link is more congested than the receiving link. Figures 6 and 7 illustrate how QL and QD changed on the receiving and sending links after implementing each VMS management scenario. The changes represent the difference in QL and QD compared with the baseline scenario, with asterisks next to a bar indicating a statistically significant difference. Results are presented for different times of day: early morning, morning, afternoon, and night.

Using VMS significantly reduced QL and QD in the sending link across all scenarios, except for the LLX scenarios. Reductions in QL (100–1,150 ft) and QD (15–144 min) were similar across scenarios, and the differences mainly depended on the DCR, with higher rates resulting in shorter queues. For example, during afternoon and night, QL reductions were 22%–23% higher with DCR = 10% compared with DCR = 5%. Furthermore, QD reductions were 33%–50% larger with DCR = 10% compared with DCR = 5% (during morning, afternoon, and night).

During early morning, using VMS reduced the mean QL in the sending link (25–130ft). Yet, as the early morning queue is already too long (1,500ft; Figure 5), these small reductions did not significantly change the QL. Similarly, the early morning QD was very high (4hrs; Figure 5); 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 (15–20 min) in the sending link.

Except for the LLC scenarios, the congestion level in the receiving link was the main factor behind QL and

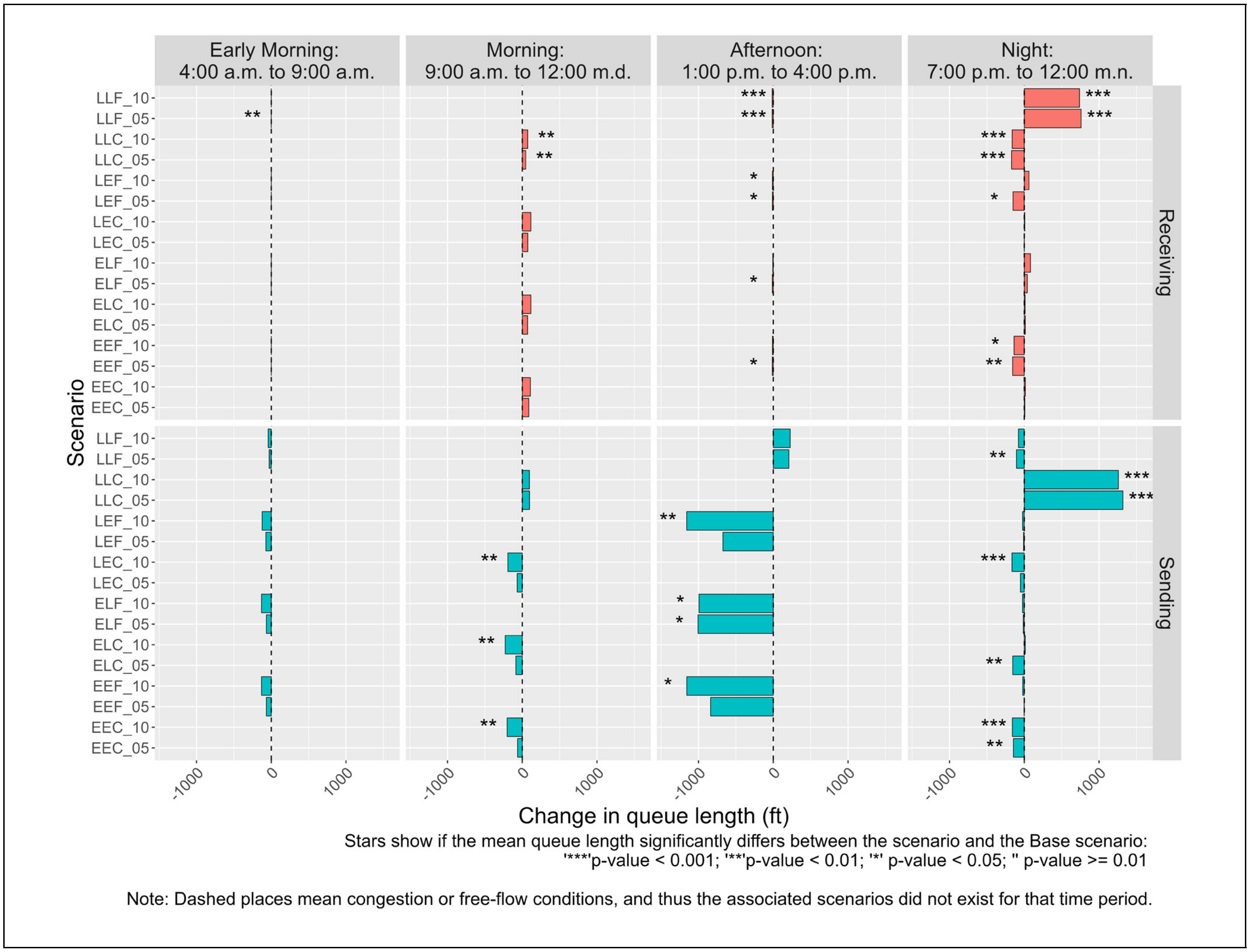

Figure 6. Changes in queue length across VMS management scenarios by time of day and curb role (sending vs. receiving), relative to the baseline.
Note: VMS = variable message sign.

QD variations. When the receiving link was congested, deviating vehicles did not increase QL much but substantially increased QD. In particular, QD increased 10–24 min during morning and night. This indicates that QL is less sensitive to changes in the number of vehicles in the queue than QD, possibly because of a nonlinear relationship between curb capacity, and QL and QD.

During uncongested traffic conditions, diverging vehicles led to three QL outcomes in the receiving link: unchanged, decreased, or increased. It remained unchanged during early morning because the number of deviated vehicles was not too big to create congestion. QL decreased during the afternoon (75–100ft) and most night periods (135–170ft) because the mean speed in the receiving link increased to 5 + mph. (Higher speeds also explain the reductions in QD in most XXF scenarios, as they contributed to a faster queue discharge.) Finally, 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. First, the late activation increased QL in the sending link (1,250–1,320ft), causing the queue to spill back to the vehicle diversion point (Figure 2*c*) and creating a bottleneck where all vehicles were forced to queue together. The bottleneck limited the incoming flow to the receiving link, reducing the number of vehicles in the queue, and thereby decreasing QL and QD.

Curb Performance

Figures 8 and 9 present the estimated CPI and CA for each VMS management scenario at the terminal level, that is, the receiving and sending links combined. Metrics are compared against the baseline scenario (shown in

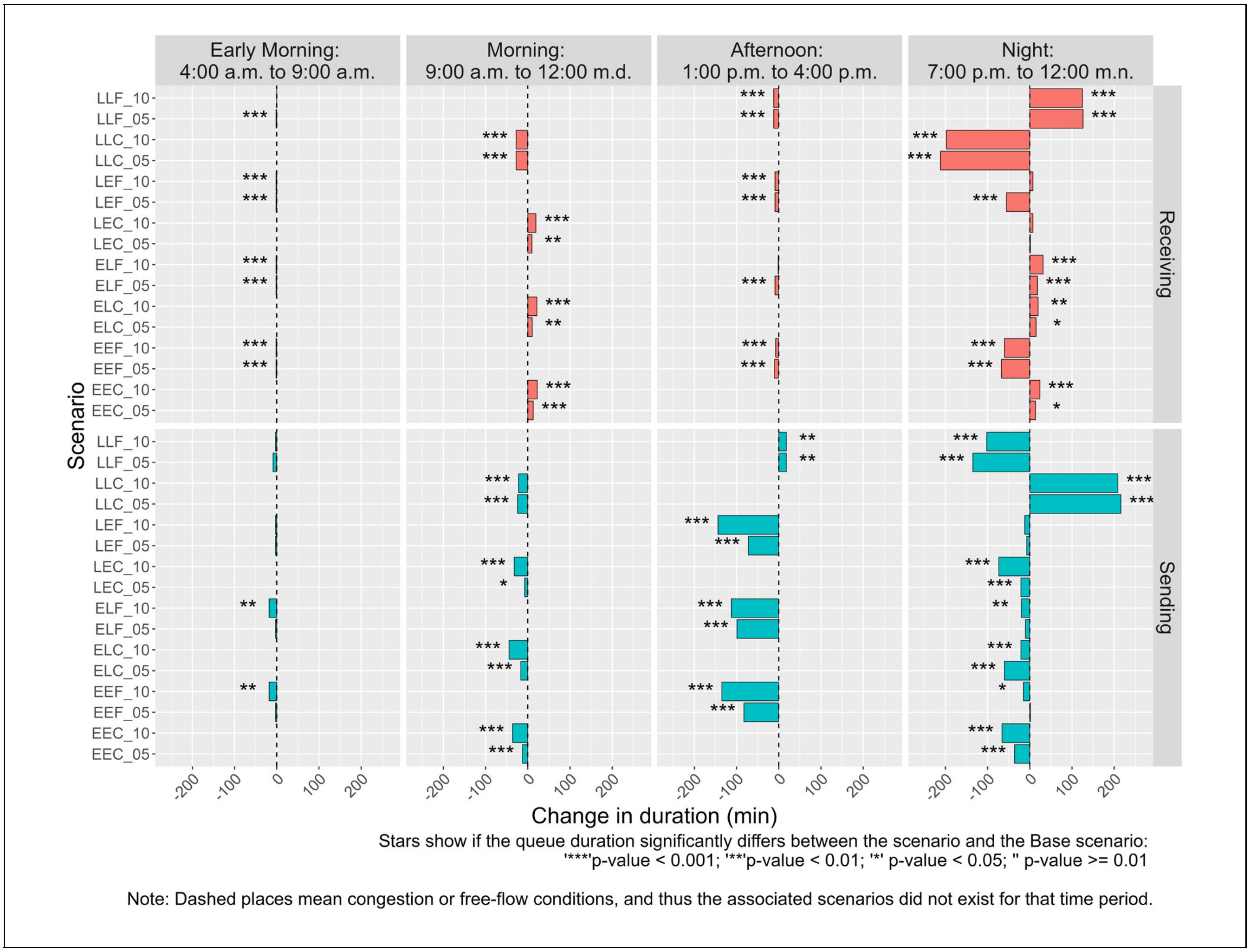

Figure 7. Changes in queue duration across VMS management scenarios by time of day and curb role (sending vs. receiving), relative to the baseline.
Note: VMS = variable message sign.

grey) across different times of day. Asterisks above the bars indicate statistically significant differences between each scenario and the baseline.

The timing of VMS activation and deactivation led to three outcomes: nonsignificant changes (XXC scenarios), improvements (XXF scenarios), or deteriorations (late activation and deactivation; i.e., LLF and LLC scenarios).

When the receiving link was congested (XXC scenarios), activating or deactivating VMS did not affect CPI nor CA. Once the curb reaches capacity, diverted vehicles are forced to queue. Thus, redirecting vehicles only increased the receiving link congestion and did not enhance curb performance. An exception to this was the ELC_05 scenario at night, where the decreasing departure queue (negative slope in Figure 5) gets fully discharged without congesting the arrival link, thereby improving CPI (4%) and CA (7%).

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

During early morning, CA was not significantly affected by using VMS. The sending link was experiencing severe congestion then, and deviating only a small fraction of vehicles did not significantly reduce the number of queuing vehicles, thereby still many vehicles could not park.

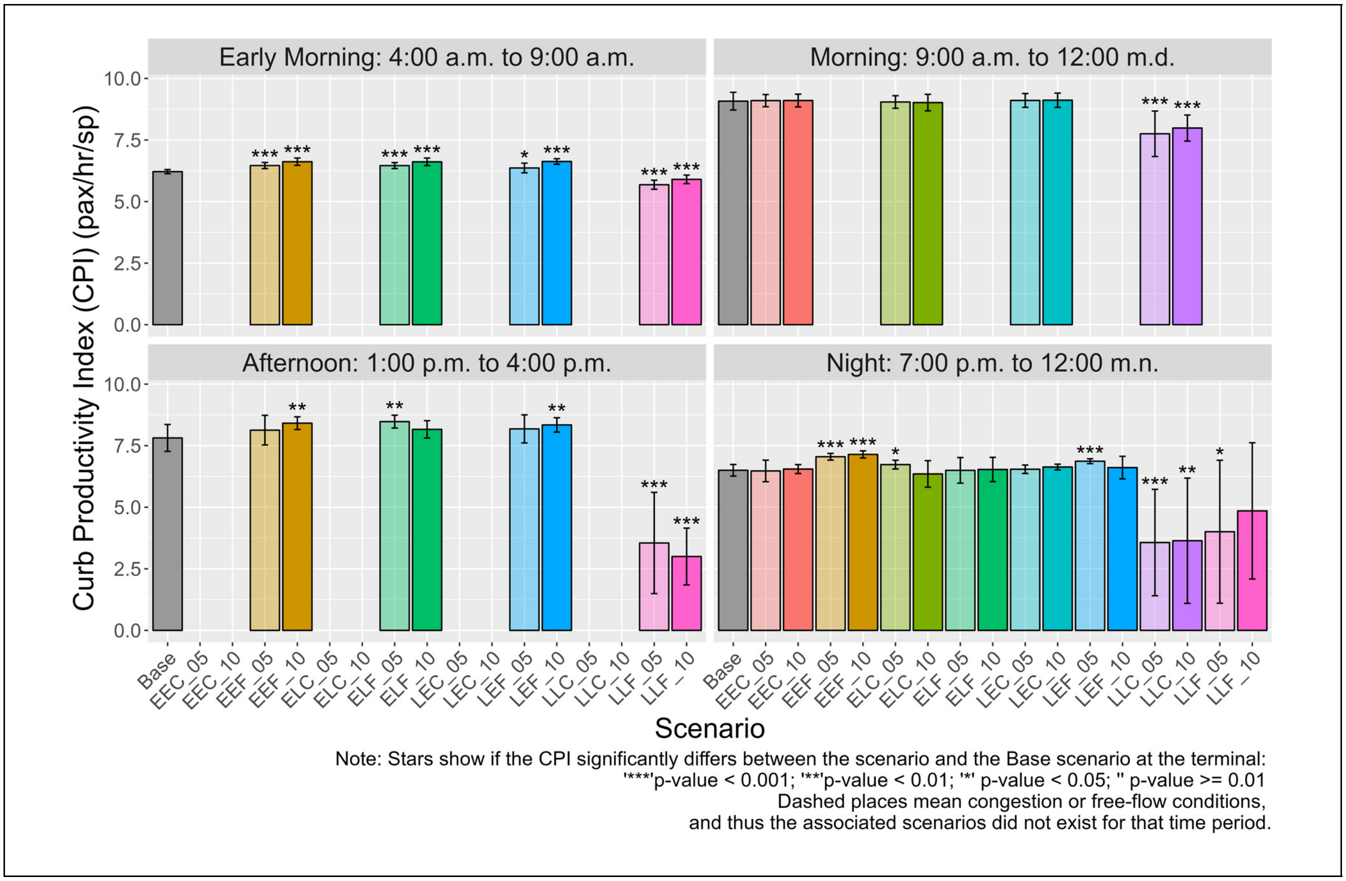

Figure 8. Estimated curb productivity for each VMS management scenario by time of day at the airport's terminal.
Note: VMS = variable message sign.

LLF and LLC scenarios decreased CPI (9%–61%) and CA (16%–26%). This can be explained by two interacting factors. First, once the sending link became congested, its curb performance remained unchanged. Second, as the VMS stayed on, more vehicles were deviated, increasing the receiving link's congestion. This held for all but the morning period when CA was increased in the LLC scenario. In that scenario QD decreased, leading to a faster queue discharge and fewer vehicles with unsuccessful parking attempts.

Emissions

Figure 10 compares the emission results for each of the analyzed VMS management scenarios against those of the baseline (grey bar). The results are broken down by time of day (early morning, morning, afternoon, and night) and further separated by location within the airport network, specifically the sending and receiving links. The emissions of both links are stacked, as they collectively represent the emissions at the airport terminal. Asterisks above the bars indicate statistically significant differences between each scenario and the baseline.

Before noon, the queue in the sending link spills back past the diversion point, and since the emissions are calculated only for the analysis area, the emission index value in the sending link is the same for morning and early morning, and additional emissions produced from the queue upstream of the diversion point are not accounted for.

The differences between the early morning and morning periods depended on the receiving link. During early morning, the receiving link was uncongested, allowing diverted vehicles to flow freely. However, the receiving link became congested during morning, and therefore, diverted vehicles queued at the receiving link. Free-flow emission rates are lower than those related to queuing (idling and braking). Consequently, emissions during early morning were lower than morning.

During afternoon, emission reductions (9%–15%) resulted from two opposite situations in the sending and receiving links. Using VMS decreased congestion and thus queuing emissions in the sending link while increasing the flow and thus free-flow emissions in the receiving link. Since the free-flow emission rates are lower than queuing emission rates, total emissions were decreased.

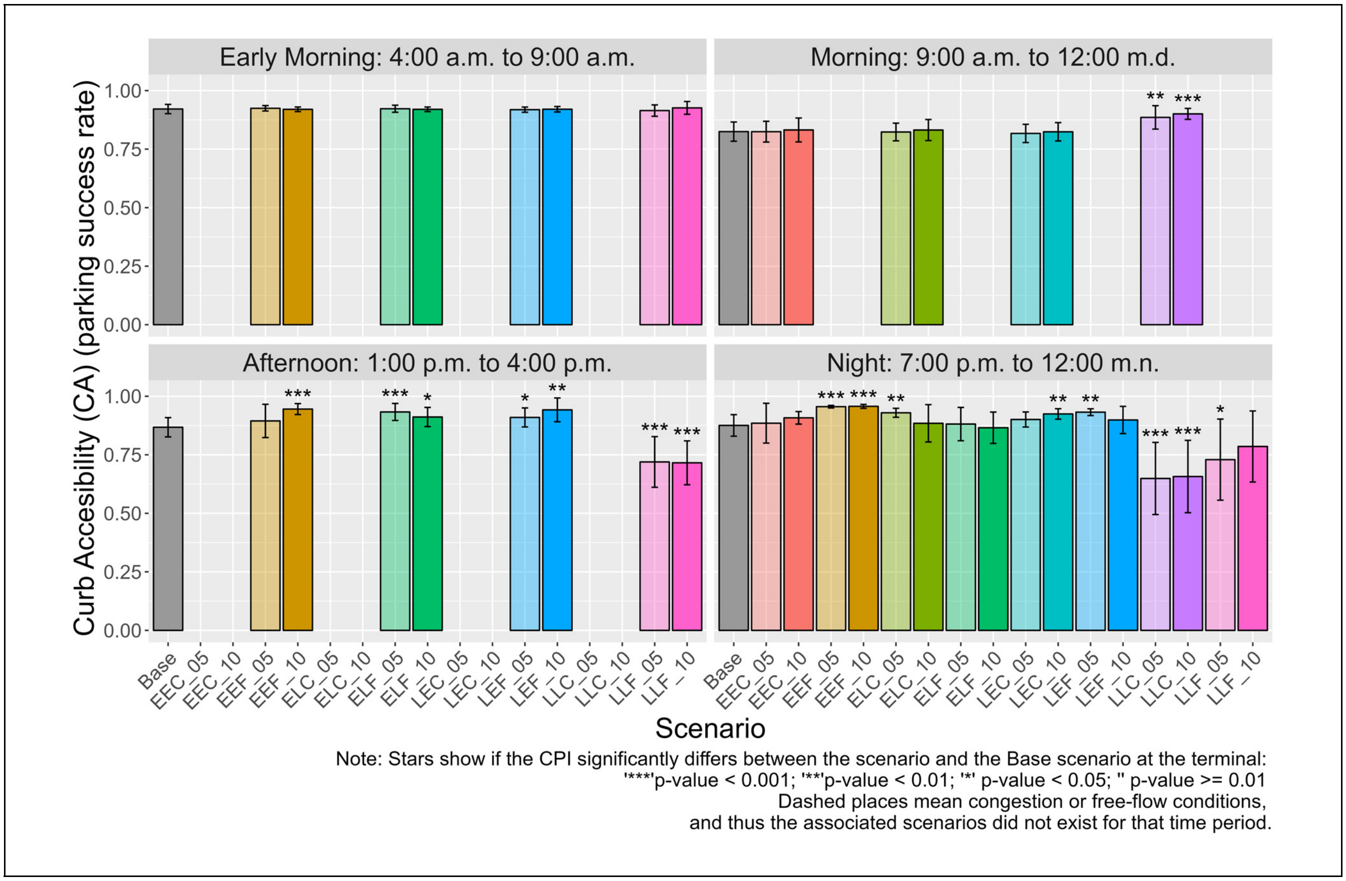

Figure 9. Estimated curb accessibility for each VMS management scenario by time of day at the airport's terminal.
Note: VMS = variable message sign.

In particular, the EEF and LEF scenarios presented the most significant reductions (11%–12%).

During the night, we observed significant differences in the receiving link between scenarios. When the receiving link was congested (XXC scenarios), diverted vehicles queued in the receiving link instead of the sending link. Therefore, the queuing emissions did not decrease and merely relocated from one link to the other. Conversely, when the receiving link was uncongested (XXF scenarios), diverted vehicles moved freely, creating less emission.

Once more, the LLC and LLF scenarios behaved differently. These scenarios increased congestion in the receiving link, causing the queue to spill back past the diversion point. However, since the emissions produced outside the analysis area are not accounted for, emissions in the LLC and LLF scenarios are shown lower than the baseline.

When to Activate/Deactivate VMS?

To maximize VMS benefits, it is crucial to activate the sign before congestion starts in the sending link and deactivate it before the congestion begins in the receiving link. To determine when congestion starts at SEA, we studied the curb capacity. Figure 11 illustrates the full-day speed-flow diagram for the analyzed curbs under the baseline scenario. It is divided into two panels, one for arrival curbs and one for departure curbs. Moreover, three colors are used to represent different traffic states (free-flow, congestion formation, and congestion), helping the reader identify the traffic conditions (flow and speed) under which congestion begins.

When airport curbs reach capacity, QL (blue line in Figure 5) grows drastically, indicating queue formation. 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. At SEA, queue formation happens when traffic flow is 500–650 veh/hr at the arrival link and 975–1,100 veh/hr at the departure link (see vertical dotted lines in Figure 5).

The speed-flow diagram for the baseline scenario (Figure 11) shows the abovementioned flows in grey color. The scattered area above the grey section indicates congestion. To avoid congestion and undesired VMS effects, we recommend using the minimum flow value of

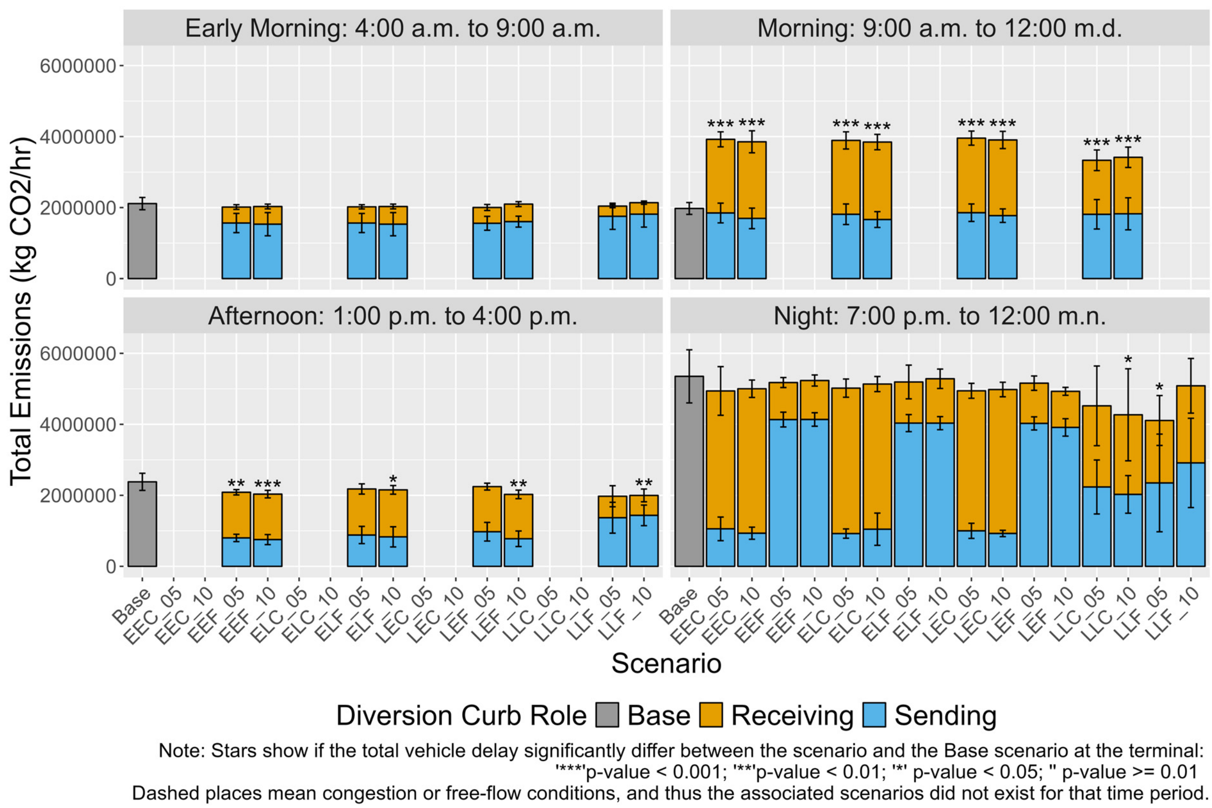

Figure 10. Estimated CO_2 emissions for each VMS management scenario by time of day and curb role (sending vs. receiving).
Note: VMS = variable message sign.

the abovementioned ranges as the threshold for activating/deactivating VMS. Following the optimal VMS management strategy outlined earlier (activate before one ramp becomes congested and deactivate before the other ramp also does), SEA should divert vehicles:

- From departures to arrivals: before the flow on the departures ramp reaches 975 veh/hr and continue doing so as long as the flow on the arrivals ramp remains below 650 veh/hr.
- From arrivals to departures: before the flow on the arrivals ramp reaches 650 veh/hr and continue doing so as long as the flow on the departures ramp is below 975 veh/hr.

These thresholds can be identified using each airport's historical data, collected through sensors, cameras, or other traffic monitoring tools, and applying the same framework described here. Particularly, SEA has speed-flow cameras installed on the curbs, ramps, and highway access points that can be used to detect these thresholds and to manage their sign(s) accordingly.

Conclusion

This research explored how VMS affects curb performance at airports, using SEA as a case study. The results showed that airports can maximize VMS benefits in alleviating congestion and increasing curb performance by timely activating and deactivating VMS. We also found that implementing VMS led to significant emission reductions (9%–15%).

However, the timing of the VMS activation/deactivation played a crucial role in maximizing VMS benefits. For example, activating VMS when the receiving link was congested did not significantly improve congestion, emissions, or curb performance, and late activation and/or late deactivation of VMS even resulted in worsened situations. Conversely, activating VMS before congestion starts in the sending link delays queue formation, and deactivating it before congestion begins on the receiving link allows more vehicles to flow freely, yielding the most significant improvements. Thus, using VMS outside the recommended management strategy may lead to insignificant changes, or even a decrease, in performance.

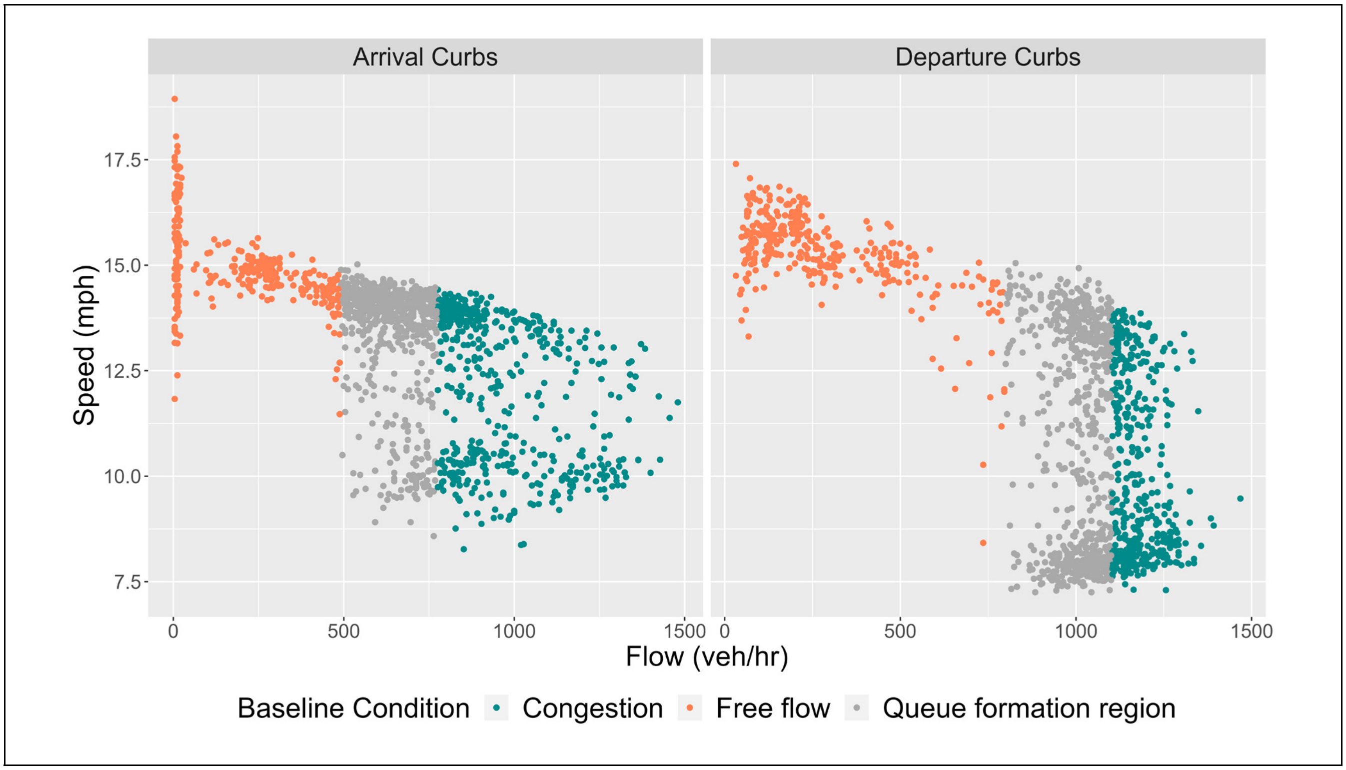

Figure 11. Baseline speed-flow diagram by curb access.

While most scenarios affected curb performance and emissions, their impacts on traffic conditions were much smaller, although significant. Rerouting vehicles to non-congested ramps reduced delay (8%–78%). The effects on QL and QD varied significantly for the sending and receiving links. The sending link experienced significant reductions in QL (100–1,150ft) and QD (15–144 minutes) across all scenarios, yet the impact on the receiving link depended on congestion: there were significant increases in QD (9.8–24min) when the link was congested, but not much on free-flow.

While the specific values and statistics in this study are based on SEA and may not apply directly to other airports, the findings offer broader relevance for airports with similar and different layouts or demand profiles.

For airports with layout and demand characteristics similar to SEA, the findings could be directly applied. The analysis was conducted using a repeated-measures method that incorporated a wide range of input values, demand profiles, and operational scenarios. This design helps isolate the impact of the VMS intervention, making the results robust and transferable to comparable settings.

For airports with different layouts or demand patterns, this research still provides two key benefits. First, it demonstrates that VMS can serve as a low-cost and adaptable tool for managing curbside congestion. Second, the proposed framework and performance metrics offer a foundation that can be used to test different VMS deployment strategies for airports. In particular, airports with more complex configurations (multiple terminals or access points) can use our framework to assess the effectiveness of their designed VMS operation. As such, the methodology presented here can support data-driven curbside management across a wide range of airport environments.

While this study provides a robust and comprehensive methodology, it is important to acknowledge several limitations that may affect the generalizability of the results. First, the analysis is focused specifically on SEA, and the model incorporates several features unique to this site. These include a single-terminal layout, a dual curbside-ramp system, and the SEA-specific geometry and demand patterns derived from the airport's highest-demand day. While the overall framework is transferable and some findings may apply to airports with similar demand and infrastructure, the results may not generalize to airports with significantly different layouts or traffic conditions. Second, the study centers on six performance metrics related to traffic impacts, curbside operations, and emissions. Other metrics, such as such as pedestrian volume and flow, frequency of conflict points, safety incident rates, curb occupancy rates, and traffic density, were not considered. Incorporating these elements in the analysis could provide a more holistic understanding of the trade-offs between different management and operation strategies. Third, although the VISSIM model was calibrated and validated using extensive ground-truth data, like any other model it still relies on some assumptions. The simulation covers 24 h corresponding to the day of the highest demand at SEA and includes all vehicle types (e.g., private vehicles, TNCs, shuttles, buses, limos), with input parameters modeled as distributions based on observed data. However, pedestrian movements were not modeled, and the surrounding road network outside the airport was excluded. The model represents the highest-demand day without accounting for atypical events, such as incidents, weather disruptions, or flight delays. In addition, demand variation across seasons or days of the week was not considered.

Future work by the authors is planned to integrate the findings of this study with a VMS control algorithm to enable automated VMS management. Such an algorithm would forecast vehicle flows based on projected passenger volumes and real-time traffic conditions. It would then dynamically adjust the VMS rerouting messages according to the optimal management scenarios identified in this research. This integration could significantly enhance the effectiveness, responsiveness, and the overall performance of airport curbside management.

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Author Contributions

The authors confirm their contribution to the paper as follows: study conception and design: J. Diaz-Gutierrez, A. Ranjbari; data processing: J. Diaz-Gutierrez, T. Maxner; analysis and interpretation of results: J. Diaz-Gutierrez, A. Ranjbari; draft manuscript preparation: J. Diaz-Gutierrez, A. Ranjbari, T. Maxner, N. Longo, N. Nazir. All authors reviewed the results and approved the final version of the manuscript.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT and Grammarly to check grammar, improve language, and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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References

1. Girón-Valderrama, G. C., J. L. Machado-León, and A. Goodchild. Commercial Vehicle Parking in Downtown Seattle: Insights on the Battle for the Curb. *Transportation Research Record*, Vol. 2673, No. 10, 2019, pp. 770–780. https://doi.org/10.1177/0361198119849062.
2. Ranjbari, A., J. L. Machado-León, G. Dalla Chiara, D. MacKenzie, and A. Goodchild. Testing Curbside Management Strategies to Mitigate the Impacts of Ridesourcing Services on Traffic. *Transportation Research Record*, Vol. 2675, No. 2, 2020, pp. 219–232. https://doi.org/10.1177/0361198120957314.
3. Butrina, P., S. Le Vine, A. Henao, J. Sperling, and S. E. Young. Municipal Adaptation to Changing Curbside Demands: Exploratory Findings from Semi-Structured Interviews with Ten U.S. Cities. *Transport Policy*, Vol. 92, 2020, pp. 1–7. https://doi.org/10.1016/j.tranpol.2020.03.005.
4. Nazir, N., C. Dowling, S. Choudhury, S. Zoepf, and K. Ma. *Optimal, Centralized Dynamic Curbside Parking Space Zoning*, Presented at the 2022 IEEE 25th International Conference on Intelligent Transportation Systems, 2022. https://doi.org/10.1109/ITSC55140.2022.9922247
5. Nazir, N., S. Vasisht, S. Choudhury, S. Zoepf, and C. P. Dowling. Mitigating Landside Congestion at Airports Through Predictive Control of Diversionary Messages. *arXiv*, 2022. https://doi.org/10.48550/ARXIV.2209.13837.
6. Zalewski, A., S. Buckley, and R. Weinberger. *Regulating Curb Space: Developing a Framework to Understand and Improve Curbside Management*. Presented at the 91th Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.

7. Schmid, J., X. (Cara) Wang, and A. Conway. Commercial Vehicle Parking Duration in New York City and Its Implications for Planning. *Transportation Research Part A: Policy and Practice*, Vol. 116, 2018, pp. 580–590. https://doi.org/10.1016/j.tra.2018.06.018.
8. Machado-León, J. L., D. MacKenzie, and A. Goodchild. An Empirical Analysis of Passenger Vehicle Dwell Time and Curb Management Strategies for Ride-Hailing Pick-Up/Drop-Off Operations. *Transportation*, 2023. https://doi.org/10.1007/s11116-023-10380-6.
9. Jaller, M., J. Holguín-Veras, and S. D. Hodge. Parking in the City: Challenges for Freight Traffic. *Transportation Research Record*, Vol. 2379, No. 1, 2013, pp. 46–56. https://doi.org/10.3141/2379-06.
10. Arnott, R., E. Inci, and J. Rowse. Downtown Curbside Parking Capacity. *Journal of Urban Economics*, Vol. 86, 2015, pp. 83–97. https://doi.org/10.1016/j.jue.2014.12.005.
11. Yu, M., and A. Bayram. Management of the Curb Space Allocation in Urban Transportation System. *Wiley Online Library*, Vol. 28, No. 5, 2021. https://doi.org/10.1111/itor.12941.
12. Maxner, T., A. Ranjbari, C. P. Dowling, and Ş. Güneş. Simulation-Based Analysis of Different Curb Space Type Allocations on Curb Performance. *Transportmetrica B: Transport Dynamics*, Vol. 11, No. 1, 2023, pp. 1384–1405. https://doi.org/10.1080/21680566.2023.2212324.
13. Fehr and Peers. *Curbs for the Future: Cincinnati Curb Study*. Cincinnati, OH, 2019. https://www.fehrandpeers.com/blog/cincinnati-curb-study/
14. Fehr and Peers. *Curbs for the Future: San Francisco Curb Study*. San Francisco, 2018. https://www.fehrandpeers.com/blog/san-francisco-curb-study/
15. Geroliminis, N. Cruising-for-Parking in Congested Cities with an MFD Representation. *Economics of Transportation*, Vol. 4, No. 3, 2015, pp. 156–165. https://doi.org/10.1016/j.ecotra.2015.04.001.
16. Arnott, R., and J. Rowse. Curbside Parking Time Limits. *Transportation Research Part A: Policy and Practice*, Vol. 55, 2013, pp. 89–110. https://doi.org/10.1016/j.tra.2013.07.009.
17. Harris, T. M., M. Nourinejad, and M. J. Roorda. A Mesoscopic Simulation Model for Airport Curbside Management. *Journal of Advanced Transportation*, Vol. 2017, 2017, pp. 1–19. https://doi.org/10.1155/2017/4950425.
18. Galagedera, S. D. B., H. R. Pasindu, and J. Bandara. Airport Curbside and Parking Area Operations at BIA–Analysis of User Behavior. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, Vol. 47, No. 4, 2014, pp. 43–51.
19. Ison, S., R. Merkert, and C. Mulley. Policy Approaches to Public Transport at Airports—Some Diverging Evidence from the UK and Australia. *Transport Policy*, Vol. 35, 2014, pp. 265–274. https://doi.org/10.1016/j.tranpol.2014.06.005.
20. Hamzawi, S. G. Lack of Airport Capacity: Exploration of Alternative Solutions. *Transportation Research Part A: Policy and Practice*, Vol. 26, No. 1, 1992, pp. 47–58. https://doi.org/10.1016/0965-8564(92)90044-8.
21. National Academies of Sciences Engineering and Medicine. *Airport Curbside and Terminal Area Roadway Operations*. The National Academies Press, Washington, DC, 2010.
22. Tam, M. L., W. H. K. Lam, and H. P. Lo. Incorporating Passenger Perceived Service Quality in Airport Ground Access Mode Choice Model. *Transportmetrica*, Vol. 6, No. 1, 2010, pp. 3–17. https://doi.org/10.1080/18128600902929583.
23. Tam, M.-L., W. H. K. Lam, and H.-P. Lo. The Impact of Travel Time Reliability and Perceived Service Quality on Airport Ground Access Mode Choice. *Journal of Choice Modelling*, Vol. 4, No. 2, 2011, pp. 49–69. https://doi.org/10.1016/S1755-5345(13)70057-5.
24. Ugirumurera, J., J. Severino, K. Ficenec, Y. Ge, Q. Wang, L. Williams, J. Chae, M. Lunacek, and C. Phillips. A Modeling Framework for Designing and Evaluating Curbside Traffic Management Policies at Dallas-Fort Worth International Airport. *Transportation Research Part A: Policy and Practice*, Vol. 153, 2021, pp. 130–150. https://doi.org/10.1016/j.tra.2021.07.013.
25. Budd, T., T. Ryley, and S. Ison. Airport Ground Access and Private Car Use: A Segmentation Analysis. *Journal of Transport Geography*, Vol. 36, 2014, pp. 106–115. https://doi.org/10.1016/j.jtrangeo.2014.03.012.
26. Kamga, C., A. Conway, A. Singhal, and A. Yazici. Using Advanced Technologies to Manage Airport Taxicab Operations. *Journal of Urban Technology*, Vol. 19, No. 4, 2012, pp. 23–43. https://doi.org/10.1080/10630732.2012.717461.
27. Hermawan, K., and A. C. Regan. Impacts on Vehicle Occupancy and Airport Curb Congestion of Transportation Network Companies at Airports. *Transportation Research Record*, Vol. 2672, No. 23, 2018, pp. 52–58. https://doi.org/10.1177/0361198118783845.
28. Budd, T., S. Ison, and T. Ryley. Airport Surface Access in the UK: A Management Perspective. *Research in Transportation Business & Management*, Vol. 1, No. 1, 2011, pp. 109–117. https://doi.org/10.1016/j.rtbm.2011.05.003.
29. Parizi, M., and J. Braaksma. Optimum Design of Airport Enplaning Curbside Areas. *Journal of Transportation Engineering*, Vol. 120, No. 4, 1994. https://doi.org/10.1061/(ASCE)0733-947X(1994)120:4(536).
30. Kleywegt, A. J., and X. Liu. Throughput Capacity Comparison for Airport Pickup and Dropoff Facilities. *Transportation Research Record*, Vol. 2676, No. 2, 2021, pp. 148–164. https://doi.org/10.1177/03611981211037544.
31. Al-Deek, H., S. R. C. C. Venkata, J. Flick, and A. Khattak. Dynamic Message Sign Deployment and Diversion Behavior of Travelers on Central Florida Toll Roads. *Transportation Research Record*, Vol. 2129, No. 1, 2009, pp. 24–34. https://doi.org/10.3141/2129-04.
32. Duncan, G., and H. Johnson. Development and Application of a Dynamic Simulation Model for Airport Curbsides. In *The 2020 Vision of Air Transportation: Emerging Issues and Innovative Solutions*, 2012. https://doi.org/10.1061/40530(303)12.
33. Kimlinger, M. *Variable Message Signal Operations Manual*. Oregon Department of Transportation, Salem, 2022.
34. Ardeshiri, A. *Exploring Route Choice Behavior Using Driving Simulator Data under Dynamic Message Sign Guidance*. PhD dissertation. Morgan State University, Baltimore, 2014.
35. Haghani, A., M. Hamedi, R. Fish, and A. Nouruzi. *Evaluation of Dynamic Message Signs and Their Potential Impact*

on Traffic Flow. Maryland State Highway Administration Office of Policy & Research, College Park, 2013.
36. Banerjee, S., M. Jeihani, N. K. Khadem, and D. D. Brown. *Speed Pattern Analysis Based on Units of Information in the Proximity of Dynamic Message Signs: A Driving Simulator Study*. Presented at the 98th Annual Meeting of the Transportation Research Board, Washington, D.C., 2019.
37. Kolisetty, V. G. B., T. Iryo, Y. Asakura, and K. Kuroda. Effect of Variable Message Signs on Driver Speed Behavior on a Section of Expressway under Adverse Fog Conditions—A Driving Simulator Approach. *Journal of Advanced Transportation*, Vol. 40, No. 1, 2006, pp. 47–74. https://doi.org/10.1002/atr.5670400104.
38. Selby, R. *Impact of Dynamic Message Signs on Driver Behavior Under Reduced Visibility Conditions*. MS thesis. University of Central Florida, Orlando, 2016.
39. Ahangari, S., C. Chavis, M. Jeihani, and Z. R. Moghaddam. Quantifying the Effect of On-Street Parking Information on Congestion Mitigation Using a Driving Simulator. *Transportation Research Record*, Vol. 2672, No. 8, 2018, pp. 920–929. https://doi.org/10.1177/0361198118773893.
40. Holton, A. E., and D. L. Fisher. Advanced Parking Management Systems: Models of Drivers' Parking Strategies. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, No. 42, 1998. https://doi.org/10.1177/154193129804201713
41. Sun, D. J., X.-Y. Ni, and L.-H. Zhang. A Discriminated Release Strategy for Parking Variable Message Sign Display Problem Using Agent-Based Simulation. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 17, No. 1, 2016, pp. 38–47. https://doi.org/10.1109/TITS.2015.2445929.
42. Caicedo, F. Real-Time Parking Information Management to Reduce Search Time, Vehicle Displacement and Emissions. *Transportation Research Part D: Transport and Environment*, Vol. 15, No. 4, 2010, pp. 228–234. https://doi.org/10.1016/j.trd.2010.02.008.
43. Mei, Z., and Y. Tian. Optimized Combination Model and Algorithm of Parking Guidance Information Configuration. *EURASIP Journal on Wireless Communications and Networking*, Vol. 2011, No. 104, 2011. https://doi.org/10.1186/1687-1499-2011-104.
44. Mei, Z., Y. Tian, and D. Li. Analysis of Parking Reliability Guidance of Urban Parking Variable Message Sign System. *Mathematical Problems in Engineering*, Vol. 2012, 2012. https://doi.org/10.1155/2012/128379.
45. Vasisht, S., S. Choudhury, N. Nazir, S. Zoepf, and C. Dowling. Estimating Driver Response Rates to Variable Message Signage at Seattle-Tacoma International Airport. *Findings*, 2022. https://doi.org/10.32866/001c.38134.
46. Port of Seattle. SEA Airport Statistics. *Fact Sheets*. https://www.portseattle.org/page/airport-statistics. Accessed May 22, 2023.
47. Diaz Gutierrez, J. *Enhancing Airport Curbside Efficiency with Variable Message Sign Strategies*. MS thesis. The Pennsylvania State University, University Park, 2024.
48. Girden, E. R. *ANOVA: Repeated Measures*. SAGE, Newbury Park, CA, 1992.
49. King County. *2021 King County for-Hire Transportation Annual Report*. King County, WA, 2021.
50. U.S. DOE (Department of Energy). Compare Side-by-Side [Online]. *U.S. Department of Energy, Administered by Oak Ridge National Laboratory*. https://www.fueleconomy.gov/feg/Find.do?action = sbsSelect%26id = 38834%26id = 41931%26id = 42341. Accessed May 24, 2023.
51. Erke, A., F. Sagberg, and R. Hagman. Effects of Route Guidance Variable Message Signs (VMS) on Driver Behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 10, No. 6, 2007, pp. 447–457. https://doi.org/10.1016/J.TRF.2007.03.003.
52. Dudek, C. L., and G. L. Ullman. Flashing Messages, Flashing Lines, and Alternating One Line on Changeable Message Signs. *Transportation Research Record*, Vol. 1803, No. 1, 2002, pp. 94–101. https://doi.org/10.3141/1803-13.
53. Ullman, B. R., N. D. Trout, and C. L. Dudek. *Use of Graphics and Symbols on Dynamic Message Signs: Technical Report*. Texas Department of Transportation Research and Technology Implementation Office, Austin, 2008.
54. Harder, K. A., J. Bloomfield, and B. J. Chihak. *The Effectiveness and Safety of Traffic and Non-Traffic Related Messages Presented on Changeable Message Signs (CMS)*. Minnesota Department of Transportation, Minneapolis, MN, 2003.
55. Peeta, S., J. L. Ramos, and R. Pasupathy. Content of Variable Message Signs and On-Line Driver Behavior. *Transportation Research Record*, Vol. 1725, No. 1, 2000, pp. 102–108. https://doi.org/10.3141/1725-14.
56. Yan, X., and J. Wu. Effectiveness of Variable Message Signs on Driving Behavior Based on a Driving Simulation Experiment. *Discrete Dynamics in Nature and Society*, 2014. https://doi.org/10.1155/2014/206805.