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Research Article

Evaluation of Ramp Metering Impacts on Travel Time Reliability and Traffic Operations through Simulation

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Ramp metering has been found to improve traffic conditions on the freeway mainline by breaking the platoons of ramp vehicles minimizing turbulence at the merge locations. The majority of the ramp metering evaluation studies have examined traffic performance under specific demand conditions, whereas travel time reliability and variability aspects have not been adequately addressed. This paper focuses on evaluating two well-known ramp metering algorithms in terms of travel time reliability as well as other performance measures such as queue lengths, throughput, and congestion duration, looking at a wide range of traffic demands throughout a calendar year. The evaluation was done through simulating an 8-mile corridor in Kansas City, KS. The results showed localized improvements due to ramp metering at the northern section of the facility, in terms of travel time reliability, throughput, and congestion duration. It was also shown that ramp metering may cause a new (possibly "hidden") bottleneck to occur downstream, thus diluting its overall benefits when looking at an entire freeway facility. It is further noted that although ALINEA performed better than HERO on the mainline, traffic operations on the on-ramps significantly deteriorated using isolated control.

1. Introduction

Over the last half century, traffic demand on freeways and ramps has increased substantially. As a result of this increase, roadway users experience recurring congestion, excessive delays, and crashes [1], which affect travel time reliability. To meet the public's needs, several of congestion mitigation policies and strategies, both in the demand and in the supply side, are being implemented by transportation officials [2]. These primarily concern

(i) Increasing the existing roadway capacity,
(ii) Introducing traffic management strategies to better manage existing capacity,
(iii) Charging specific roadways (congestion pricing),
(iv) Providing information to users to affect their travel choices.

One widely used traffic management strategy is ramp metering. Ramp metering works by breaking up platoons of vehicles entering from the on-ramps and delay localized congestion, leading to increase of travel speed and throughput and reduction of emissions and vehicle crashes [1]. Although ramp metering has been effective in reducing congestion and improving safety, its impacts on travel time reliability have not been extensively studied. As such, the primary objective of this paper is to evaluate the impact of selected ramp metering algorithms on travel time reliability using a freeway facility along I-35 SB in Kansas City, KS, through simulation. The evaluation also includes measurements of throughput, queue lengths, and congestion duration at specific locations along the facility.

2. Literature Review

Ramp metering is the operation of controlling the entering traffic into a freeway by using traffic signals on the ramps. It was initiated modelled as a pretimed signal controller and it evolved to operate as a traffic-responsive signal controller using real-time traffic measurements. Ramp metering algorithms can be grouped to localized (regulate a single on-ramp) and system-wide or coordinated (regulate a facility with multiple on-ramps) systems [1].

2.1. Ramp Metering Algorithms. Local ramp metering strategies regulate a single on-ramp as an independent system. Early traffic-responsive algorithms were based on feedforward philosophy like Demand Capacity (DC) and Percent-Occupancy (OCC) algorithms. Recent algorithms started using the popular feedback philosophy like ALINEA [3]. The main difference between feedforward (open-loop) and feedback (closed-loop) is that the output of the system is not used in the next iteration in feedforward systems, while it is used in feedback systems. At feedback systems the detectors are usually installed downstream of the on-ramp where the merge occurs [3].

The ALINEA algorithm [4] uses the output of the previous cycle as input for its current. The outputs that are used are previous cycle time metering rate $r(k-1)$ and downstream occupancy $o_{out}(k-1)$. ALINEA uses the following to calculate the ramp metering rate:

$$r(k) = r(k-1) + K_R\left[\hat{o} - o_{out}(k)\right] \tag{1}$$

where $r(k)$ is the current cycle ramp metering rate in seconds, $r(k-1)$ is the previous cycle ramp metering rate in seconds, K_R is a regulator parameter (smoothing factor), $\hat{o}$ is the desired downstream occupancy, and o_{out} is the measured occupancy (percentage).

ALINEA is a very popular algorithm and many versions have been developed to improve its efficiency. Some of ALINEA's extensions are FL-ALINEA, UP-ALINEA, UF-ALINEA, AD-ALINEA, X-ALINEA/Q, and PI-ALINEA [5]. Each extension has its own unique algorithm and is derived either for certain circumstances in the system or as a new method to control the ramp metering. For example, FL-ALINEA [6] uses flow measurements instead of occupancy measurements, since flow is directly related to the fundamental traffic flow variables. UP-ALINEA [6] was developed to account for the lack of measurement detectors downstream of the ramp in which upstream traffic measurements can be used to run ALINEA algorithm. In this case, the desired downstream occupancy o_{out} used in (1) is estimated from upstream measurements.

One of ALINEA's drawbacks is that by limiting the number of vehicles entering from the on-ramp, the on-ramp might exhibit excessive queues which in turn might affect the adjacent surface streets. X-ALINEA/Q addresses this problem using an override system [6]. In this system the algorithm calculates two metering rates: one from any ALINEA algorithm, $r(k)$ and one from queue length measurements, $\acute{r}(k)$, and the maximum one is used. Lastly, the Proportional-Integral PI-ALINEA was developed to resolve the issue of distant downstream bottleneck activations.

Coordinated ramp metering algorithms are becoming increasingly popular as their main goal is to manage multiple ramps along a facility that experience recurring congestion. Coordinated ramp metering algorithms such as METALINE, SZM, HERO, and SWARM assign metering rates to each metered on-ramp while considering the benefit of the facility as a whole.

METALINE is the integral coordinated system version of ALINEA [7]. It turns the ALINEA equation into a vector according to the following:

$$\begin{aligned} r(k) = r(k-1) &- K_{LQI}^{1}\left[\rho(k) - \rho(k-1)\right] \\ &- K_{LQI}^{2}\left[\hat{\rho}(k) - \hat{\rho}_d\right] \end{aligned} \tag{2}$$

where ρ is the vector of densities and K_{LQI}^{1} and K_{LQI}^{2} are gain matrices, which are based on the desired traffic performance, and other parameters as defined previously. METALINE was implemented in Boulevard Périphérique in Paris, France, as an incident controlling algorithm.

The Stratified Zone Metering (SZM) algorithm introduces the definition of overlapping zones [8]. In this algorithm a zone is defined as a section of freeway bounded by two mainline detectors. Each zone can be decomposed into several groups of zones, called layers; each layer uses a different set of mainline detectors. The typical length of a zone in SZM ranges from 0.5 mile to 3 miles. SZM has been implemented along I-494 in Minnesota. The following describes the principle of the algorithm:

$$\mathrm{A} + \mathrm{U} + \mathrm{M} + \mathrm{F} = \mathrm{X} + \mathrm{B} + \mathrm{S} \tag{3}$$

where

A is the upstream mainline volume (measured)

U is the sum of unmetered entrance ramp volumes (measured)

M is the sum of metered ramp volumes (predefined)

F is the sum of metered freeway to freeway ramp volumes (predefined)

X is the sum of exit ramp volumes (measured)

B is the downstream bottleneck capacity (constant–usually 2200 veh/h/ln)

S is the spare capacity on the mainline which is the space available within the zone (computed)

Heuristic Ramp-metering CoOrdination (HERO) is a linked algorithm that uses master-slave structure to manage on-ramp metering rates [9]. HERO assigns the Master role to the downstream on-ramp where the bottleneck occurs. This bottleneck occurs because ALINEA implements queue control when there is insufficient ramp storage. HERO assigns the upstream on-ramps as slaves and uses their ramp storage for the master ramp. HERO coordinates and controls the upstream on-ramp (Slave) metering rate by assigning minimum queue length, $\mathrm{w}_{\mathrm{min}}$. The upstream on-ramp metering rates are calculated based on

$$q_o^{LC}(k_C) = -K_w\left[w_{min,o} - w_o(k_C)\right] + d_o(k_C - 1) \tag{4}$$

$$q_o(k_C) = \max\left\{\min\left\{q_o^{r}(k_C), q_o^{LC}(k_C)\right\}, q_o^{w}(k_C)\right\} \tag{5}$$

where $q_o(k_C) = r(k)$, K_w is a control parameter set as $1/T_c$ or less for smoother control action, and T_c is the control sample time. When HERO is activated, both upstream and downstream ramp rates are regulated so that the upstream and downstream relative queue lengths stay close to each other. The minimum queue length which is assigned to the upstream on-ramp is updated every T_c until the Master ramp relative queue falls below the activation threshold.

The system-wide adaptive ramp metering (SWARM) algorithm comprises of two independent algorithms where the more restrictive of the two is used to control the ramp metering rate. The first algorithm is called SWARM1 and it is based on forecasting density using linear regression and Kalman filtering and system-wide apportioning [10, 11]. The second algorithm is called SWARM2, and it is a local traffic responsive system, which turns measured densities into metering rates using linear conversion. SWARM has been implemented extensively in California and in Portland, Oregon [12].

2.2. Measuring Reliability and Operational Performance. Travel time reliability quantifies the variation of travel time of a given trip, for a selected time period (e.g., peak period), and over a selected horizon (e.g., a year) [13]. Travel time variations typically result from recurring variations in demand, severe weather, incidents, work zones, and special events. Measuring travel time over a long horizon (e.g., one year) results in obtaining travel time distribution. Several definitions of travel time reliability exist. HCM6 [13] distinguishes between time-based and index-based reliability measures.

Time-based reliability measures include

(i) Planning time, the travel time a traveller would need to budget to ensure on-time arrival 95% of the time;

(ii) Buffer time, the extra travel time a traveler would need to budget, compared with the average travel time, to ensure an on-time arrival 95% of the time;

(iii) Misery time, the average of the highest 5% of travel times (approximating a 97.5 percentile travel time), representing a near-worst-case condition;

(iv) On-time percentage, a measure of success based on the percentage of trips that are made within a target travel time;

(v) Percentage of trips exceeding a target maximum travel time, a measure of failure;

(vi) Standard deviation, the statistical measure of how much travel times vary from the average; and

(vii) Semistandard deviation, a statistical measure of travel time variance from the free-flow speed.

Index-based reliability measures include:

(i) Travel time index (TTI), the average travel time on a facility divided by the travel time at free-flow speed;

(ii) Planning time index (PTI), the 95^{th} percentile travel time divided by the free-flow travel time;

(iii) 80^{th} percentile TTI, the 80^{th} percentile travel time divided by the free-flow travel time;

(iv) 50^{th} percentile TTI, the 50^{th} percentile travel time divided by the free-flow travel time;

(v) Buffer index (BI), the buffer time divided by the free-flow travel time;

(vi) Misery index (MI), the misery time divided by the free-flow travel time, and a useful descriptor of near-worst-case conditions on rural facilities; and

(vii) Reliability rating (RR), the percentage of vehicle miles traveled experiencing a TTI less than 1.33 for freeways and 2.50 for urban streets; these thresholds approximate the points beyond which travel times become much more unreliable.

Bhouri et al. [14] evaluated the travel time reliability along the A6W motorway in Paris, after implementing the ALINEA ramp metering algorithm and the CORDIN (coordinated control) strategy, using field data. The results of their evaluation showed that both ramp metering algorithms significantly improved travel time variability compared to the no control case, by 24-37% depending on the reliability measure used. They also concluded that the coordinated ramp metering performed better than ALINEA.

ALINEA has been implemented on A6W Motorway in Paris, France under the scope of the European research project EURAMP [15]. Initial field evaluations of ALINEA included five on-ramps for approximately 20 km of roadway [14]. The implementation of ALINEA showed a reduction in total time spent by 9.8% and an increase in mean speed by 4.3%. In terms of travel time reliability, ALINEA improved the motorway's MI by 31%, the BI by 37%, and the PTI by 28%.

In addition to the reliability measures, performance measures related to traffic operations along the facility can also be used to evaluate the impact of ramp metering under specific demand scenarios. One of the most studied performance measures is throughput, which measures the number of vehicles that is flowing through the bottlenecks during a specific time period. Simulation experiments have shown that ramp metering can increase the throughput, up to the time to breakdown [16]. Banks [17] also stated that metering "is more likely to be effective if it is used to eliminate or control very specific causes of flow breakdown, such as arrival of dense platoons of ramp vehicles at the merge point." In that sense, the overall throughput up to the time to breakdown may be increased.

Simulation experiments have also shown that ramp metering increases average speeds, and reduces the duration of congestion [16]. Simulation evaluations of METALINE and ALINEA using the macroscopic simulator META showed that, in the presence of unexpected incidents, METALINE was superior in dissolving congestion faster [7]. When both were compared in normal conditions (recurrent congestion) they had approximately the same performance.

The effectiveness of Minnesota's Zone algorithm became obvious after the evaluation study conducted in 2000, where the ramp meters were turned off in the Minneapolis area.

Figure 1: I-35 map and proposed metered junctions (provided by KDOT and KC Scout).

Analysis of the data indicated that when the ramp meters were temporarily turned off; traffic volumes, travel time, travel time reliability, safety, emissions, and fuel consumption measurements were worse than when the meters were on [1].

Field evaluations of the SWARM algorithm showed that compared to pretimed metering, the total delay on the freeway increased with SWARM, as a result of higher metering rates at most on-ramps. It was also concluded that travel times at on-ramps decreased, as a result of the trade-off between the freeway and on-ramp delays [12].

Several ramp metering algorithms have also been evaluated through simulation. HERO, ALINEA and PI-ALINEA were compared by using a macroscopic simulation software named METANET [9]. Multiple scenarios were tested and the results showed that HERO had lower total time spent by each vehicle and higher total waiting time on the on-ramp compared to ALINEA and PI-ALINEA.

3. Field Data Collection and Simulation Modelling

3.1. Data Preparation. The facility analysed in this research is an 8-mile long section of I-35 SB in Kansas City, Kansas, from Cambridge Dr. (in the North) to 75th Street (in the South). This section includes 11 interchanges, while the Kansas Department of Transportation (KDOT) is interested in implementing ramp metering at four on-ramps (67th Street, 18th Street, Southwest Blvd., and 7th Street) (Figure 1). Traffic volume and speed data at the mainline, on-ramps, and off-ramps were obtained from the KC Scout Portal (http://www.kcscout.net/KcDataPortal). Only weekdays (excluding holidays) were considered for this analysis and the data were obtained for 12 months (April 1st 2016 to March 31st 2017). The peak period was found to start at 3:15pm and end at 6:15pm; therefore, the simulation analysis period was defined to be from 2:50pm to 6:35pm, to ensure that the simulation starts and ends at uncongested conditions. Data involving traffic incidents (minor, major, stalled vehicle, etc.) along the facility, as well as days with adverse weather were excluded, as these cannot be modelled in simulation software. The data for traffic incidents were obtained from the KC Scout Portal. If an incident occurred, the data from the affected sensors (at the incident location and within two miles upstream of the incident) were removed from the analysis, while the remaining data were retained. The adverse weather conditions were obtained from (https://www.wunderground.com) and account for days with snow, fog, and precipitation of more than 0.20 inches.

The remaining days were used for developing the variability of the annual traffic demand for the facility. All detector data were divided by day of the week, and month of the year, so for example, data were grouped for every Monday in April. Then, the volumes for each 5-minute interval were averaged across the same weekdays of the month. The result was the average volume in 5-minute intervals that represent all Mondays in April. After averaging the volumes in all detectors, 60 demand scenarios were developed (5 weekdays times 12 months). Each scenario runs using four random seed numbers (four iterations) and the results were averaged. However, some detectors were faulty and did not provide data in some locations or days. Also, due to the elimination of data with incidents or adverse weather, fewer data were analysed. To account for the missing data, volumes from the next or previous months were used.

Figure 2 shows the 60 demand profiles at three locations along the facility. Figure 2(a) shows the demand profile at the beginning of the facility (Cambridge Cr), Figure 2(b) shows the demand profile approximately at the middle of the facility (Lamar Ave), while Figure 2(c) shows the demand profile at the most downstream bottleneck (67th St).

3.2. Model Calibration and Simulation. The entire facility was modelled in VISSIM 9.0 [18]. For the calibration process, speeds and flows primarily at the bottleneck locations were used as performance measures to ensure that the simulated model realistically depicts traffic operations at the facility. The selected calibration day was April 22nd 2016. The car-following (Wiedemann 99) and lane changing parameters in VISSIM were adjusted accordingly to produce similar speeds and flows within a 10% error margin for an initial run. The software default and selected car-following parameters, as well as the calibrated lane changing parameters, are shown in Tables 1 and 2.

Next, 150 random seeds were run and the ten random seeds that produced heat maps close to the actual speeds heat map (inspected visually), were finally selected [19]. In addition, speed-flow diagrams for the mainline detectors at bottleneck locations along the facility were evaluated for calibration (Figure 3). From this figure it is shown that the speed-flow curves are in good agreement.

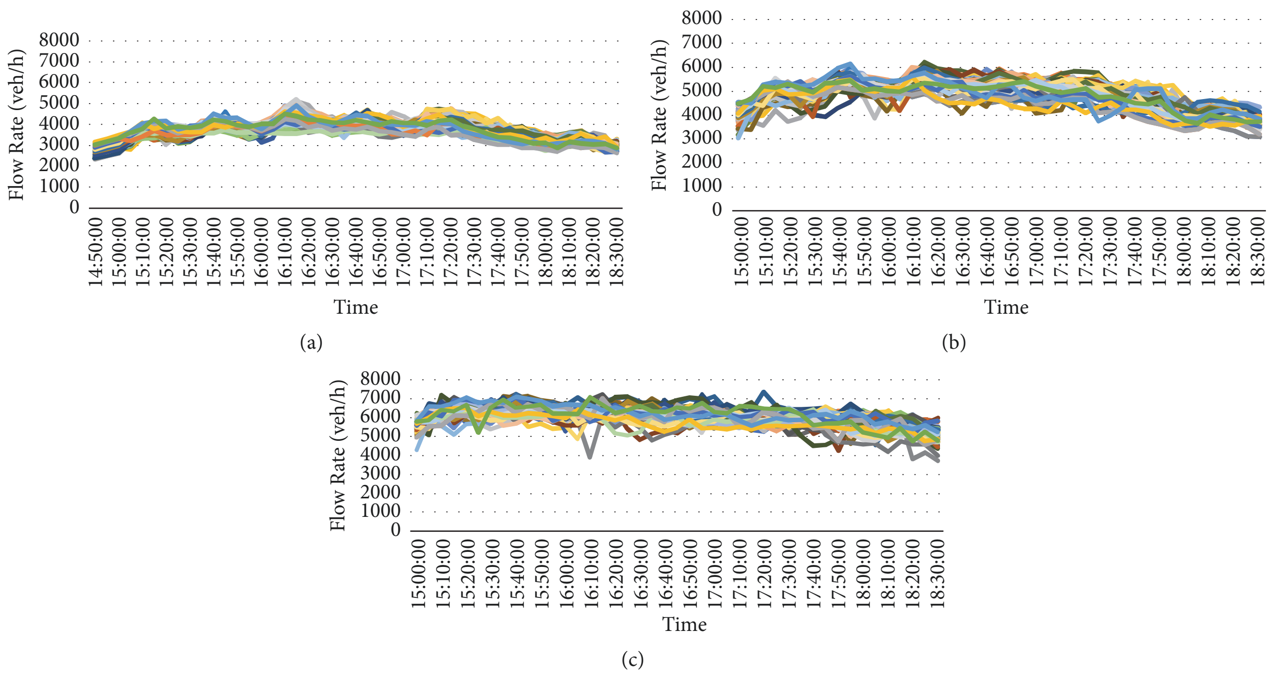


Figure 2: Demand profiles at (a) Cambridge Cr. (b) Lamar Ave. (c) 67th St.

Table 1: Calibrated Wiedemann 99 model parameters.

Parameter	Default	Freeway	Diverge	Merge	Weave
CC0	4.92	5.60	7.50	7.80	9.00
CC1	0.90	1.05	1.15	1.30	1.45
CC2	13.12	13.10	12.00	12.00	12.60
CC3	-8.00	-8.00	-8.00	-8.00	-8.00
CC4	-0.35	-0.30	-0.35	-0.35	-0.35
CC5	0.35	0.30	0.35	0.35	0.35
CC6	11.44	11.44	11.44	11.44	11.44
CC7	0.82	0.82	0.82	0.82	0.82
CC8	11.48	10.48	10.48	12.48	12.48
CC9	4.92	4.92	4.92	4.92	4.92

3.3. Ramp Metering Strategies. For the purposes of this research, two different ramp metering strategies were evaluated through simulation and compared against the “no control” case. These are the popular isolated ramp metering strategy, ALINEA, and its coordinated version called HERO.

ALINEA uses the downstream detector critical occupancy to maximize the mainline throughput according to equation (1) [4]. This algorithm was used at the four locations to be metered by KDOT. Based on the literature, the smoothing factor, K_R, was considered to be 70 [4]. The critical occupancy downstream of each metered ramp was determined from simulation data to be 13% for all sites. Also, the time step to calculate the cycle length was set to be 20 seconds at the 7th St, 18th St, and 67th St ramp meters and 30 seconds at the Southwest Blvd ramp meter. The time step was calculated as the travel time a vehicle needs to reach from the ramp meter to the downstream detector. Ramp metering was activated at 3:00pm and when the occupancy rate was above 11% for two consecutive time steps and terminated at 6:00pm. The ramp metering flow for all meters was set to range between 720 veh/h/ln and 200 veh/h/ln, which is equivalent to a ramp metering cycle length of 5 seconds to 18 seconds per vehicle, respectively. The algorithm would run as a one-car-per-green strategy. For queue flush, a ramp cycle length of 5 seconds was implemented when the queue length reached 75% of the queue capacity of an on-ramp.

HERO is a system-wide algorithm that uses the ALINEA algorithm in addition to an on-ramp master slave configuration. HERO was implemented on 18th St and Southwest Blvd with 18th St acting as the master ramp, and Southwest Blvd and 7th St with Southwest Blvd acting as the master ramp. The master on-ramp starts using the slave queue storage when its queue reaches 50%, and the storage size that is used on the slave on-ramp is 50%. The queue activation percentage

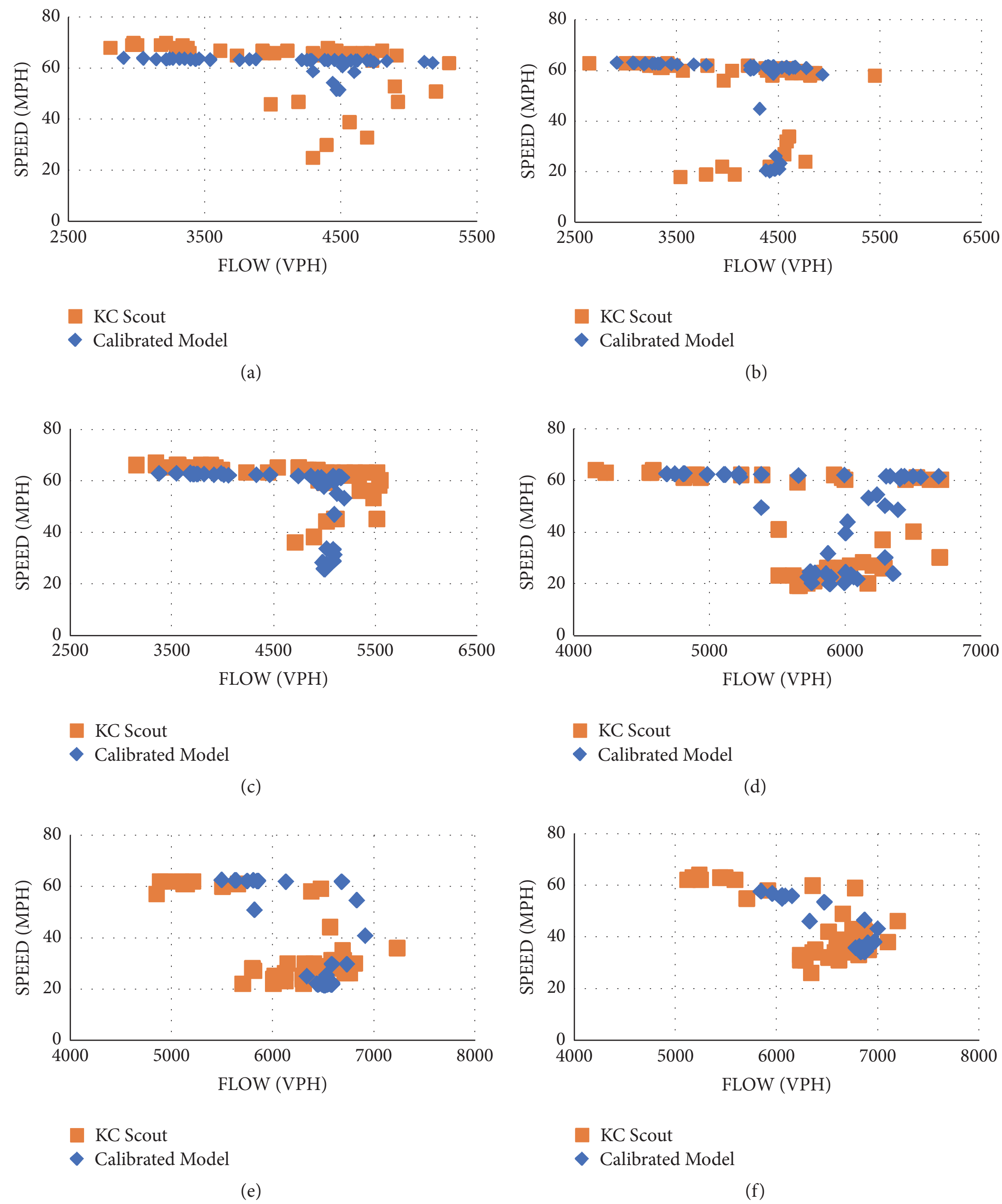


Figure 3: Speed-flow diagrams at (a) 7th St. (b) Southwest Blvd. (c) 18th St. (d) Johnson Dr. (e) 67th St. and (f) 67th St. merge detectors.

(50%) on the master ramp and the queue creation on the slave ramp are user-defined. Any percentage an operator wants could be implemented. The logic behind using 50% activation and queue creation is that the ramps are located relatively far away from each other. Therefore, for the slave on-ramp queue creation to take effect, the master on-ramp queue still has time before it reaches capacity. In addition, in real life there are traffic signals on the arterials connecting to the on-ramp, so if a signal turns green it will supply the on-ramp with a large number of vehicles in a small amount of time. This demand must have enough storage on the on-ramp to avoid overflowing on the arterial network. The algorithm would run as a one-car-per-green strategy.

Given that the 67th St on-ramp is located further downstream from the remaining ramps, it was assumed that this ramp would operate independently; thus the ALINEA algorithm was implemented there.

4. Evaluation Results

The three simulated scenarios of no control, ALINEA, and HERO were evaluated in terms of the travel time, throughput,

Table 2: Calibrated lane change parameters.

	Default	Freeway	Diverge	Merge	Weave
General Behavior	Free Lane selection	Free Lane selection	Free Lane selection	Free Lane selection	Free Lane selection
Max. Deceleration (ft./s^2):					
Own	-13.12	-13.12	-13.12	-13.12	-13.12
Trailing Vehicle	-9.84	-9.84	-9.84	-9.84	-12.00
-1 ft./s^2 per distance (ft.):					
Own	100	300	200	300	400
Trailing Vehicle	100	200	200	200	400
Accepted deceleration:					
Own	-3.28	-3.00	-3.00	-4.50	-4.50
Trailing Vehicle	-3.28	-2.25	-3.00	-3.00	-4.50
Waiting before diffusion (s)	60	60	60	60	60
Min. headway (front/rear)	1.64	1.64	1.64	1.64	1.64
Safety distance reduction factor	0.60	0.60	0.7	0.45	0.4
Max. deceleration for cooperative braking (ft./s^2)	-9.84	-9.84	-16.00	-18.00	-18.00
Advanced Merging	√	√	√	√	√
Cooperative lane change:	√	√	√	√	√
Max. speed difference	1.84	16.00	16.00	16.00	16.00
Max. collision time	10.00	10.00	10.00	10.00	10.00

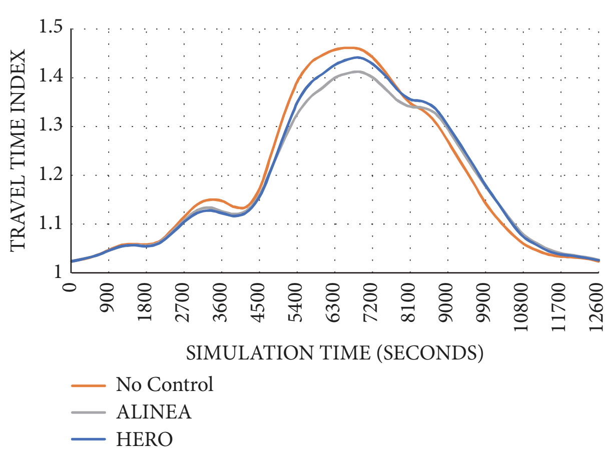


Figure 4: Facility TTI for the three control scenarios or no control, ALINEA, and HERO ramp control. The no control scenario has higher TTI compared to the two ramp control scenarios.

congestion duration, and queue lengths at the on-ramps. In addition, several travel time reliability measures were also used to evaluate the reliability along the study corridor. All performance measures were collected in 5-min intervals for the entire simulation duration. The average of every 5-minute interval in the 60 demand scenarios was used for the analysis and comparison.

4.1. Travel Time and Travel Time Reliability. Facility travel time measures the travel time (TT) of vehicles that travelled the entire facility from Cambridge Circle junction to 75th St junction. The free flow TT of the entire facility was measured to be 465 seconds. Figure 4 presents the Travel Time Index (TTI) with respect to time of day from 3:00pm (0 sec) to 6:30pm (12,600 sec) for the three control scenarios.

According to Figure 4, HERO has lower TTI than the no control scenario from 2700 second (3:45pm) to 7800 second (5:10pm) and ALINEA has lower TTI than the no control scenario from 2700 second (3:45pm) to 8400 second (5:20pm). However, towards the end of the simulation the no control TTI becomes lower than HERO and ALINEA. This might be because the ramp meters initially hold vehicles on the on-ramps, which leads to lower TTI on the mainline, but later on, when the ramp queue storage reaches capacity and starts discharging vehicles at high rates, the mainline traffic conditions deteriorate and the freeway TTI increases.

Travel time reliability analysis was conducted for all 240 demand scenarios. The cumulative distributions of the entire facility TT for the three scenarios are shown in Figure 5, where it can be seen that ALINEA and HERO travel times are slightly less than the no control scenario. The mean, median, 85th percentile (TT_{85}), 95th percentile (TT_{95}) travel times, buffer time, and buffer index of all three control scenarios are presented in Table 3, along with percent differences compared to the no control scenario.

According to Table 3, ALINEA and HERO resulted in lower mean, median, and 85th percentile travel times compared to the no control scenario. However, HERO had slightly higher 95th percentile travel time, as well as buffer time and buffer index, compared to the no control scenario, indicating that the coordinated ramp metering algorithm has worse performance than the isolated one.

Table 3: Mean, median, 85^{th} percentile, 95^{th} percentile travel time, buffer time, and buffer index for the no control, ALINEA, and HERO ramp control for the facility.

	No control	ALINEA	HERO	ALINEA (%)	HERO (%)
TT_{mean}	553 sec	549 sec	552 sec	-0.8%	-0.3%
TT_{median}	499 sec	497 sec	497 sec	-0.4%	-0.4%
TT_{85}	655sec	639 sec	648 sec	-2.5%	-1.1%
TT_{95}	795 sec	789 sec	805 sec	-0.8%	1.3%
Buffer Time	242 sec	240 sec	254 sec	-0.8%	5.0%
Buffer Index	43.7%	43.7%	46.0%	0.0%	0.05%

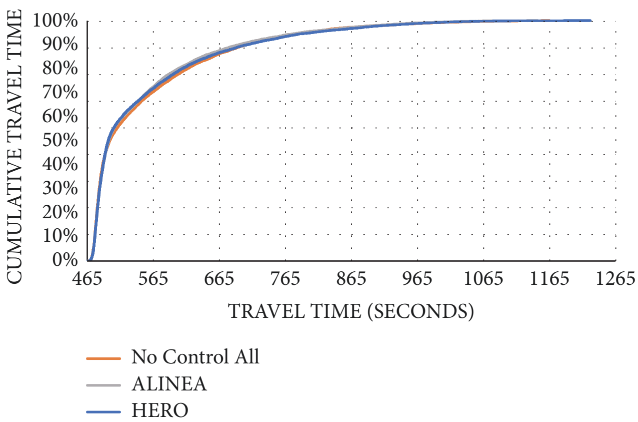


Figure 5: Cumulative travel time distribution of the facility under no control, ALINEA, and HERO ramp control.

To further investigate the performance of the two algorithms, the entire facility was divided in two sections: section 1: from Cambridge Circle junction to Metcalf Ave off-ramp (upper half), and section 2: from Metcalf Ave off-ramp to 75^{th} St junction (lower half). The main reason for dividing the facility into two sections is that these two sections seem to operate independently. There are two bottlenecks located at Southwest Blvd and 18^{th} St (both on section 1) that are interacting, but only one bottleneck (Southwest Blvd on-ramp) is scheduled to be metered. The third bottleneck is located at 67^{th} St (section 2), which is also going to be metered, and it does not spill back to section 1. As such, it was logical to divide the facility and analyse each section separately.

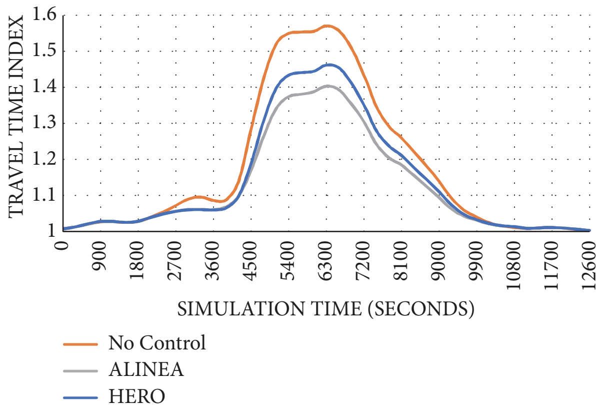
Figure 6 shows the TTI distribution for the two sections, for the entire simulation period. As it can be seen for section 1 (Figure 6(a)), HERO and ALINEA have lower TTIs than the no control scenario, for most of the simulation period. Also, ALINEA has lower TTIs than HERO. This may be because the queue flushing system that ALINEA uses is less adaptable to large queues compared to HERO's queue control, which suggests that ALINEA favours more the mainline than the ramps.

On section 2 (Figure 6(b)) the analysis shows a different pattern. HERO and ALINEA have slightly lower TTIs than the no control scenario before 4:00 p.m. (3,600 seconds). However, after that, the TTI of both ALINEA and HERO increases, and becomes greater than the TTI of the no control scenario. This might be attributed to the lower travel times and higher speeds in the upstream section (section 1). As shown earlier, the ramp meters at section 1 lessen the effect of the bottlenecks at that location, which causes vehicles to travel faster downstream and reach the bottleneck at 67^{th} St. Table 4 summarizes the travel time-related indices for both sections separately, where it is clearly seen that the benefits of ramp metering are evident at section 1 only and that improved traffic conditions upstream resulted in deterioration of traffic conditions at the most downstream bottleneck.

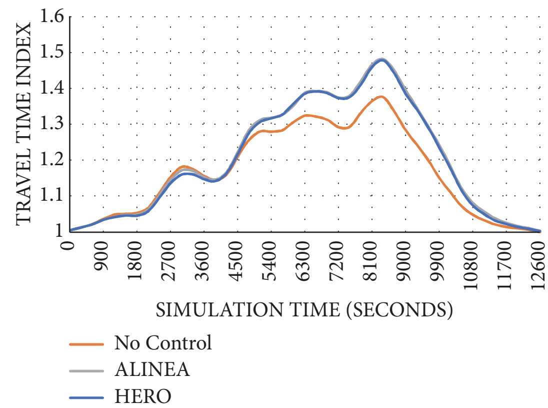
4.2. Queue Length and Waiting Time at On-Ramps. Although ramp metering is generally beneficial to the mainline, long queues may form at the on-ramps. The queue length and the ramp vehicles wait times depend on the ramp metering algorithm. ALINEA uses a queue flushing strategy by setting the metering rate to maximum flow. HERO uses a queue control strategy that adapts for the current queue length present at each time step, and sets a metering rate to optimize the ramp storage and prevent the queue from spilling back to the arterials. The average and maximum queue lengths and waiting times from the simulation are shown in Table 5. Spillback percentage is the percentage of 5-minute intervals that experience queue length longer than the ramp queue capacity.

The average queue lengths and wait times at 7^{th} St and Southwest Blvd are longer in HERO than in ALINEA, whereas at 18^{th} St the opposite is true. This is because in HERO, the 7^{th} St and Southwest Blvd on-ramps act as slave ramps and create queues when the 18^{th} St ramp (master) queue length exceeds the queue activation threshold, while in ALINEA the on-ramps act in isolation. Therefore, HERO primarily benefits the master on-ramp. The queue spillback on the arterials (as well as the maximum queue lengths and wait times) was more severe in the ALINEA control compared to the HERO control scenario. Queue lengths and spillback percentages were not available at 67^{th} St, as a detector was not in place there; however, since ALINEA operates at that location under both ALINEA and HERO scenarios, it is speculated that the queue lengths, wait times, and spillback percentages are similar. However, further simulation testing needs to be done to verify our assumption.

4.3. Throughput. Throughput is measured as the number of vehicles passing through a segment during a specific time intervals just before the breakdown event (i.e., transition to



(a)



(b)

Figure 6: Travel time index for the entire simulation duration for (a) section 1 and (b) section 2.

Table 4: Mean, median, 85th percentile, 95th percentile travel time, buffer time, and buffer index for the no control, ALINEA, and HERO ramp control per section.

	No control	ALINEA	HERO	ALINEA (%)	HERO (%)
			Section 1		
TT_{mean}	303 sec	290 sec	294 sec	-4.3%	-2.9%
TT_{median}	257 sec	257 sec	257 sec	0.0%	0.0%
TT_{85}	359 sec	320 sec	332 sec	-11.0%	-7.7%
TT_{95}	447 sec	384 sec	408 sec	-13.9%	-8.8%
Buffer Time	156 sec	106 sec	126 sec	-32.0%	-19.2%
Buffer Index	53.5%	38.2%	44.6%	-28.6%	-16.6%
			Section 2		
TT_{mean}	249 sec	257 sec	256 sec	3.1%	2.7%
TT_{median}	221 sec	222 sec	222 sec	0.3%	0.3%
TT_{85}	290 sec	315 sec	310 sec	8.8%	7.2%
TT_{95}	390 sec	420 sec	426 sec	7.2%	9.4%
Buffer Time	140 sec	163 sec	170 sec	16.4%	21.4%
Buffer Index	56.2%	63.2%	66.3%	12.5%	18.0%

congested conditions) occurs. The three control scenarios were evaluated based on their throughput at the ramp meter locations. Given the large variability of demands in all scenarios generated, throughput was measured only for the seed numbers that experience high, medium, and low congestion levels, chosen based on visually inspecting the speed heat maps. High congestion levels corresponded to congestion duration that ranged between 1 to 1.5 hours. Medium congestion level corresponded to congestion duration between 30 and 45 minutes, while low congestion level accounted for less than 30 minutes of congestion. The per-lane throughput at all metered sites, as well as the change in throughput between the no control and the metered scenarios, is presented in Table 6.

Both Southwest Blvd and 18th St on-ramps benefited the most from the introduction of ramp metering across all congestion levels. The 7th St junction had higher throughput only during the high congestion level scenario, as it was mostly free-flowing during the medium and low congestion scenarios. At 67th St the throughput was relatively unaffected during high congestion (1% decrease with ALINEA and 2% increase with HERO), while improved throughput was observed during the medium congestion scenario. Lastly, as indicated earlier, 67th St appears to become more congested during both ramp metering scenarios, as more traffic manages to arrive from upstream. As such, when traffic is low, traffic is free-flowing at 67th St during the no control scenario and, therefore, throughput is higher than the metered (more congested) scenarios.

4.4. Congestion Duration. Congestion duration is defined as the duration that the mainline corridor speed is below 75% of the free flow speed for at least 15 minutes [13, 20] after the breakdown event. Free flow speed for the entire facility was measured to be 64 mph; therefore, the speed threshold for the breakdown events is assumed to be 48 mph. Congestion duration was evaluated only during the heavily congested scenarios (congestion duration for the no control scenario was between 1 and 1.5 hours). The results of the congestion

TABLE 5: Queue length and waiting time results for ALINEA and HERO ramp control.

Ramp Location	Avg. Queue	Max. Queue	Spillback %	Avg. Wait Time	Max Wait Time
			ALINEA		
7^{th} St.	48 ft	238 ft	0.0%	6.6 sec	61.2 sec
Southwest Blvd.	413 ft	1712 ft	12.8%	71.3 sec	372.3 sec
18^{th} St.	195 ft	440 ft	2.1%	38.5 sec	82 sec
67^{th} St.	N/A	N/A	N/A	53.5 sec	148 sec
			HERO		
7^{th} St.	99 ft	230 ft	0.0%	18.6 sec	61.2 sec
Southwest Blvd.	430 ft	930 ft	0.0%	79.8 sec	200.8 sec
18^{th} St.	160 ft	380 ft	0.1%	31.6 sec	73.5 sec
67^{th} St.	N/A	N/A	N/A	53 sec	155 sec

TABLE 6: Throughput and percentage change of throughput for the three control scenarios.

Control Scenario	7^{th} St.	Southwest Blvd.	18^{th} St.	67^{th} St.
		High Congestion Level Throughput (veh/h/ln)		
No control	1,536	1,592	1,648	1,794
ALINEA	1,604 (4.4%)	1,624 (2.0%)	1,724 (4.6%)	1,776 (-1.0%)
HERO	1,612 (4.9%)	1,640 (3.0%)	1,728 (4.9%)	1,830 (2.0%)
		Medium Congestion Level Throughput (veh/h/ln)		
No control	1,600	1,508	1,648	2,104
ALINEA	1,600 (0%)	1,632 (8.2)%	1,696 (2.9%)	2,180 (3.6%)
HERO	1,600 (0%)	1,700 (12.7)%	1,660 (0.07%)	2,160 (2.7%)
		Low Congestion Level Throughput (veh/h/ln)		
No control	1,600	1,536	1,596	2,336
ALINEA	1,600 (0%)	1,604 (4.4%)	1,688 (5.8%)	2,048 (-12.3%)
HERO	1,600 (0%)	1,604 (4.4%)	1,608 (0.8%)	2,280 (-2.4%)

TABLE 7: Congestion duration for the three control scenarios.

	7^{th} St.	Southwest Blvd.	18^{th} St.	67^{th} St.
No Control	50 minutes	80 minutes	105 minutes	155 minutes
ALINEA	0 minutes	0 minutes	60 minutes	155 minutes
HERO	0 minutes	50 minutes	80 minutes	150 minutes

duration analysis for the three control scenarios are presented in Table 7.

It appears that ramp metering had a positive effect on congestion duration. The 7^{th} St, Southwest Blvd, and 18^{th} St bottlenecks exhibited significant reduction is congestion duration. However, 67^{th} St did not experience significant change in congestion duration, because the mainline at that junction experiences higher demand incoming from the upstream facility with higher speeds. ALINEA also outperformed HERO as it resulted in reduced congestion duration at all merge junctions except 67^{th} St where HERO was slightly better.

5. Summary and Conclusions

In this paper, two well-known ramp metering algorithms, a local (ALINEA) and a system-wide (HERO), were evaluated considering several performance measures, including travel time reliability, queue lengths, throughput, and congestion duration. Travel time reliability was measured through the cumulative probability of travel times, travel time index, buffer time, and buffer index. In the context of this study, travel time reliability was found to be important for assessing the impact of ramp metering for a variety of demands. The evaluation was done through simulating in VISSIM an 8-mile long freeway facility in Kansas City, KS.

The simulation results showed that travel time reliability for the entire facility did not exhibit significant improvement when a ramp metering strategy was implemented. However, the upper half of the facility underwent drastic improvement in travel time and travel time reliability, while the lower half of the facility experienced worse travel times and travel time reliability after implementing ramp metering strategies. The ramp meter on 67^{th} St created a brief good impact on travel times, but it was overshadowed by the excessive vehicle demand incoming from the upper half of the facility. This suggests that although ramp metering might have positive effects on traffic operations and reliability, it might cause a new (possibly "hidden") bottleneck to occur downstream, thus diluting its overall benefits when looking at an entire freeway facility. In addition, it was also found that ALINEA generated better travel times than HERO; however, the difference was small. The benefits illustrated by the two algorithms in this research greatly depend on the selection of the parameters used in ALINEA and HERO. It is possible that selection of different parameters would likely yield different results in terms of reliability and performance.

Throughput and congestion duration were also improved when ramp metering was implemented during heavy, medium, and low congestion levels in all junctions, except the most downstream one (67^{th} St.) where throughput during the low congestion scenario was decreased and congestion duration did not significantly change. ALINEA was more effective in reducing congestion duration compared to HERO, at 7^{th} St, Southwest Blvd, and 18^{th} St junctions.

Queue length and waiting time on the on-ramps during ramp metering were also evaluated in this study. ALINEA uses a queue flush system, which discharges the queue at maximum metering rate when the on-ramp queue reaches 75% of the queue capacity. HERO uses a queue control system, which adjusts the metering rate by setting the current queue not to exceed the queue capacity. It was found that the HERO algorithm prevented queue spillbacks on the adjacent arterials, whereas these spillbacks were not avoided in ALINEA. Therefore, although ALINEA seemed to outperform HERO in terms of the remaining performance measures, HERO resulted in a better balance in serving the mainline and the on-ramps without deteriorating the performance at the adjacent arterial network.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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