Research Article

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Assessment of ALINEA method performance at different loop detector locations using field data and micro-simulation modeling via AIMSUN

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Abstract: A ramp metering (RM) or ramp signal is an effective method for traffic management, especially at merging sections in urban expressways. This research aims to assess the Asservissement Linéaire d'Entrée Autoroutière (ALINEA) method performance at different loop detector locations using field data and micro-simulation modeling via advanced interactive microscopic simulator for urban and non-urban networks (AIMSUN). The operation of RM was executed using the ALINEA method. The field data were collected from two locations in Manchester in the UK for calibration and validation in AIMSUN. Occupancy values at different loop detector locations were evaluated. The results indicated that the current simulation model could represent reality to acceptable limits. Increasing the number of detector locations at the merging entrance will decrease the occupancy value. The results showed that the effect of loop detector location is a significant factor in determining the critical occupancy of the merging section. Also, the downstream location is more appropriate for determining the congestion or critical status. The AIMSUN software showed significant consistency in representing field data of merging sections. The minimum value of GEH (Geoffrey E. Havers) that equal to 0.5 has been used to statistically and graphically demonstrate this behavior.

Keywords: ALINEA, AIMSUN, ramp-metering, expressway, traffic, loop detector

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1 Introduction

About 40% of all urban traffic congestion is caused by bottlenecks in the traffic system [1]. On motorways, geometric changes such as merging and diverging, weaving sections, and lane decreases have a strong correlation with the triggering of recurrent bottlenecks. The strong "merging" demand seen as cars look for suitable lanes to carry out their route selections is one of the fundamental traffic characteristics of such bottleneck locations. However, as traffic volume increases, traffic flow may become tighter (with fewer gaps) due to drivers' desire to shorten their trip times. In high-volume situations, such conflicts between the demand for merging and the availability of spaces for merging can have major mobility (such as traffic breakdown and stop-and-go waves) and safety (such as rear-end and side-swiping crashes) repercussions [2]. By regulating the speed and flow, active (advance) traffic management (ATM) techniques such as ramp metering (RM) and variable speed restrictions have been widely used to improve traffic flow along these stretches. By reducing and smoothing out high ramp demand, RM increases merging efficiency. Ramp management, is a technique for limiting the number of vehicles utilizing a traffic signal to enter a motorway. They are set up to enable a single vehicle or a small platoon of vehicles (often two or three) in each green phase and have a substantially shorter cycle time. The amount and speed of on-freeway traffic determine the metering rate. The objective of freeways is to boost throughput and speed to keep the freeway operating as efficiently as possible. To lessen the effect of the ramp traffic on the mainline flow, the RMs are typically used to manage traffic at the on-ramp to access the highway [3]. RM is frequently employed for expressway traffic control to maximize traffic efficiency, where traffic lights govern the on-ramp flow. Despite RM's advantage in decreasing traffic congestion, it is constrained by spilled lines at on-ramps and overcrowded bottlenecks. Another area for improvement in RM is that it prioritizes main traffic over on-ramp traffic, which calls into question the equity standard that all on-ramp traffic entering the highway experience identical delays [4]. Various research studies have been conducted to assess the advantages of RM. Generally, it was discovered that RM is a successful highway management approach to address the recurrent congestion problems and enhance freeway safety at the freeway merge point [5]. RMs are installed to control the rate of vehicles moving into the mainline traffic, thus, it prevents the critical volume of a freeway from being controlled. It is considered the most effective tool currently available for motorway congestion, with its effectiveness already proven by field implementation results [6]. Without RM, high ramp flows merging into the motorway mainline increase the chance of flow breakdown and significantly reduce capacity as a result [7,8]. Istanbul/Turkey is considered one of the most worldwide metropolitan areas with substantial transportation networks with different transport modes [9]. These traffic lights can be either fixed timed or vehicle actuated, which can be entire traffic actual semi-traffic traffic actuated [10]. There is no assurance that they are the best for a particular freeway, while they take time to be fine-tuned and often adversely affect traffic flow, resulting in driver frustration [11].

RM categories are often based on the action scope or control philosophy [12]. Existing ramp metering may come under local management or coordinated control depending on the scope of the activity. Using data from the respective highway segment's traffic measurements, local metering control calculates the metering rate. Demand-capacity is one popular local metering technique [13].

The regional transportation agency's demands and objectives are considered while choosing the best ramp metering system [3]. The aforementioned intended outcomes may be attained thanks to RM, which enhances mobility, dependability, efficiency, safety, and even lessens environmental effects. Additionally, it has been demonstrated in the literature to be cost-effective. With the rapid advancement of technology (such as linked autonomous cars and surveying drones) and new demanding situations (such as crowded industrial locations and emergency vehicles), more research will be required to improve the quality, efficacy, and efficiency of RM [14]. Traffic-related input factors, like traffic flow density, vehicle speed, journey durations, and collision and accident data, to mention a few, are used by control algorithms to govern RM systems. There have previously been several accessible algorithms described [14]. Considering that RM is primarily implemented on existing roads (especially freeways), which must be upgraded or modified for specific capacity performances for a variety of reasons related to urbanization and the growth of the vehicle population [14], RM represents a sound technique from an economic perspective. RM is an effective method that, with no negative economic impact, may improve a traffic volume management plan on the highway, allowing for general traffic flow while preventing illness on secondary roads [14].

The topic in this work can be defined as simulating ramp metering (RM) using different loop detectors on downstream and verifying the ALENA algorithm using AIMSUN software. The key feature of this study is the use of AIMSUN software for assessing the ALENA algorithm for ramp metering management.

1.1 Critical occupancy

The proportion of time that a traffic loop detector placed in the road pavement is occupied by cars might be used to determine occupancy. Its primary value is the simplicity with which occupancy may be measured using a loop detector. Additionally, occupancy, like density, may be used to represent the traffic conditions (i.e., normal or congested) [15].

The most useful lane occupancy is the proportion of time, during a given period, the vehicle spends at a particular point in the lane. Corridor occupancy is a non-dimensionless temporal measurement. The phrase "A certain point in the lane" applies to a "certain time." The same lane occupancy (for the same period) will be tested along any length of the lane that vehicles cannot enter or exit. The length makes the vehicle's travel time over this length short compared to the time interval used to calculate occupancy. Highways use lane occupancy (average highway occupancy) in control systems. The information acquired from control systems is used to determine lane occupancy [16].

Three inferences can be made: First, selecting a threshold occupancy between 19 and 20% is crucial to both the averaging process and the emerging pattern. The link is also well characterized for both high (>30%) and low (20%) occupancy levels. Without a doubt, the uncongested regime has nearly linear shape, but the congested regime at occupancy levels above 30% has a straight or slightly convex shape. Third, there is evidence that the relationship is continuous [17], even though it is less evident in the intermediate (20–30%) occupancy range.

The threshold at which traffic becomes clogged up may be described as critical occupancy. The critical occupancy represents the flow rate at capacity. Different scholars have proposed various critical occupancy levels. According to data from the Queen Elizabeth Way in Ontario, a crucial occupancy at loop detectors upstream of the merging section, for instance, was discovered to be between 19 and 21%. The Minnesota Department of Transportation used only 18%

to distinguish between congested and average situations. Based on modeling findings, it was determined that the essential occupancy of Pacific Motorway in Australia varied from 17 to 20%, and data from loop detectors in the USA were used to highlight the presence of bottlenecks using temporal occupancy. Traffic is not considered crowded when occupancy is less than 20%, in the transitional period when occupancy is between 20 and 25%, and in the congested phase when occupancy is greater than 25% [18].

In the traffic models of the two systems, the critical occupancy is used to separate the free flow and crowded flow conditions. Observations are assumed to have occupancy values below critical work. It is in a free-flow system, with the occupancy values believed to be greater than the critical occupancy in a crowded flow regime. Determining the critical occupancy value from field observations is a significant achievement. There is no universally recommended procedure for determining critical occupancy from traffic data. Often, the value of critical occupancy depends on flow, as demonstrated by numerous study locations [19].

The constructed model included the RM algorithms Asservissement Linéaire d'Entrée Autoroutière (ALINEA), demand capacity (D-C), and an-alternative congested control approach (ANCONA). The calibration procedure recommended a critical occupancy value of 23% for the ALINEA and D-C algorithms. The ANCONA algorithm was recommended to activate the RM system at a speed of 60–65 km/h. Several flow rates were employed to demonstrate the efficacy of these algorithms and the flows at which RM controls might be helpful in cutting down on overall time spent (TTS). It was discovered that the advantages of using RM controls increased as the ramp flow decreased. The results show that the ANCONA algorithm offered a reduced trip time compared to other algorithms for the flow ranges and circumstances studied. However, further research is needed to determine how well RM controls perform in various settings [18].

The identical site chosen for the ALINEA algorithm's optimal critical occupancy has been found using the D-C method (i.e., 300 m downstream from the nose). Critical occupancy values between 21% and 27% have been examined with a 1% increase. The results of this method imply that the calculated value of 23% was the same as what was discovered during the calibration of the ALINEA algorithm. In comparison to "without control," the D-C algorithm application increased highway throughput by 1.6% [20].

The critical occupancy and ideal position of traffic detectors are the chosen parameters for calibrating the ALINEA and D-C algorithms, and they are acquired by running the simulation model for all possible combinations of the ranges for these parameters that have been chosen. For the critical occupancy, values between 17 and 30% with a 1% increment were employed, whereas for the ANCONA algorithm, values for the location of the downstream detectors varied between 0 and 1,000 m from the nose with a 50 m increment [18].

1.2 RM technique

The merging section represents the combination of two traffic movements (from the freeway and on-ramp) into one movement. Merging vehicles' average speeds varied by 5–10 km/h from those recorded in the right lane [21]. At the end of the on-ramp, the average speed of merging vehicles surpassed the average speed of through vehicles on the right lane [22]. The minimum acceptable time (or crucial) gap for a car merging into the through-lane traffic is often between 0.75 and 1.0 s [23]. The smallest acceptable space narrows occur as a vehicle approaches the end of the acceleration lane. Another element that must be considered is the onramp's geometric ramp characteristics. Vehicles on tapered entrance ramps are reported to be accelerated more than parallel ramp designs and exhibit aggressive merging movements [24]. Additionally, if a forced merge attempt is launched within the "merge influence region," the driver in the outer through lane may no longer be able to safely adjust his headway to the merging vehicle, increasing the likelihood of traffic problems. To make room for the merging traffic from the on-ramp, drivers tend to shift the vehicle speed or lane position suddenly. On the contrary, the ability to plan and carry out a speed reduction and lane change effort was demonstrated by drivers who were in the "pre-merge influence region," which enhances collaboration and lessens confrontations with the on-ramp vehicles. Cars from the on-ramp merge into the drivers' headway gap and cut the current headway to the lead vehicle in half; the typical vehicle following behavior will be hampered. This forces the driver to slow down to allow more time to pass the new lead vehicle [23]. Researchers have proposed that as traffic flow near a bottleneck rises, particularly on-ramps, the likelihood of breakdown also rises. Increased lane changing due to increased mainline and on-ramp flow resulted in forced lane changes (FLCs), which caused backups in the acceleration and shoulder lanes downstream of the merge [25]. Pre-breakdown capacity refers to the capacity before a breakdown event. Congested capacity refers to queue discharge flow. The queue discharge is 10–30% less than the pre-breakdown capacity [26]. Studies on pre-breakdown capacity focused on the occurrence of the breakdown. Additionally, the maximum pre-breakdown flow occurs 5–15 min before the breakdown. The maximum discharge flow occurs 5- or 15-min flow during oversaturated conditions. The speeds on the freeway segment fall below a crucial number of 55 mph; the breakdown phenomenon is defined as the change from free flow to synchronized flow. In addition, its density is more than the difference between C and D levels of service. Three breakdown identification techniques are presented based on the volume-occupancy correlation, speed drop, and occupancy rise. It has been demonstrated that poorer merge capacities occur with greater ramp-to-freeway demand ratio levels. According to HCM (2010), merging turbulence has little impact on merge capacity. The merging bottleneck capacity ranges between 1,920 and 2,080 veh/h/ln at three-lane motorway segments where the ramp flow ratio (ramp flow over upstream freeway flow) ranges from 1.0 to 0.1 [25]. The HCM (2010) suggested that capacity values are significantly greater than those obtained in empirical research. Freeway on-ramp merging zones are typical bottlenecks of the freeway network due to their lower capacity and the high risk of accidents and disputes brought on by frequent lane changes, complex geometric design, and a range of driving habits in these locations.

NHTSA reports that 94% of all recorded traffic accidents are primary drivers faulted. Errors in the recognition, decision-making, and performance processes are among the primary driver-related causes [27]. The distribution of merging locations is influenced by various variables, including the flow of traffic on the main road, the significant road time headway, the flow of traffic on the ramp, and the behavioral traits of the drivers [28]. On-ramp vehicles search for an acceptable gap to merge onto the main road in the acceleration lane.

Similar to how density revealed that the threshold [15] between normal and congested traffic might be characterized as critical occupancy, occupancy can be used to describe the traffic conditions (i.e., standard or congestion). The critical occupancy represents the flow rate at capacity. Different scholars have proposed various critical occupancy values. For instance, Ontario's Queen Elizabeth Way data revealed that the critical occupancy at loop detectors upstream of the merge section was 19% and 21% [17]. According to modeling data, the Pacific Motorway in Australia's essential occupancy ranged from 17 to 20%. Data from loop detectors in the USA were used by Zhang and Levinson [29] to determine the occurrence of bottlenecks using time occupancy. Traffic is not considered to be congested when occupancy is less than 20%, in the transitional phase when occupancy is between 20% and 25%, and in the congested phase when occupancy is greater than 25% [15,17]. To accomplish this, occupancy data must be gathered from a mainline cross-section that is a maximum of a few hundred meters downstream of the metered on-ramp. However, due to lane drops, bridges, tunnels, upgrades, curves, speed-limit areas, or uncontrolled on-ramps, bottlenecks with a smaller capacity than the merging region occasionally exist further downstream. This advice uses measurements from those bottlenecks [30]. Therefore, the length of the detection zone affects occupancy as detected by detectors. The zone of influence (detector length) of each type of detector varies, and the length of the zone of influence is essentially multiplied by the length of the vehicle to determine occupancy. As a result, depending on the size and type of the detectors, the measured occupancy may vary for different detection zones, even for identical roadway and traffic conditions. This indicates that length must be taken into account [31].

Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS). Microsimulation is utilized for evaluation before or concurrently with the on-street operation. The study of dynamic traffic control, incident management plans, real-time route guiding tactics, adaptive intersection signal controls, ramp, and mainline metering, etc., are only a few of the numerous goals this covers [32]. Ramp metering's key components are presented, along with several methods (such as fixed timing and local control) and some of the most often used computer algorithms (such as ALINEA). Trubia et al. [14] used augmentations, HEBLER, and variable speed limit control for ramp metering algorithms to test the cooperative traffic microsimulation implementation. Simulation results have verified the functioning assignment of the suggested cooperation framework. Gregurić et al. [33] developed ALENA/Q algorithms for RM verification and testing using the CTM simulation software to detect unstable traffic cases. Simulation results have verified the employed algorithms, which consider unstable traffic cases. Li et al. [34] used ALENA and HERO algorithms for RM in VISSAM simulation software, and the results show a mainline balance with RM without impact on arterial network performance. The algorithms declared RM performance evaluation [35].

1.3 RM algorithms

RM systems have significantly improved safety and mobility, reducing collisions by 15–25% and increasing average speeds by 9–25% [2]. Many algorithms are used in RM to reduce the traffic congestion generated from the ramp in the merge section area with upstream. Table 1 shows the difference between the algorithms used in RM.

The AIMSUN (advanced interactive microscopic simulator for urban and non-urban networks) is a traffic microsimulation model and is used in this study. AIMSUN is an

Table 1: Algorithms used for controlling RM

Country (Ref.)	Types of Algorithms	Parameters	Site of Detector			Data Collection Techniques	Strengths	Limitation
			Upstream	Downstream	Multi-Detectors			
[38]	Demand Capacity D-C	occupancy	√	√		detectors	Measured from flow upstream and occupancy downstream	The minimum metering rate is used when it's the downstream occupancy exceeds a critical value (O cr)
[39]	Demand Capacity INRETS	capacity			√(3) detectors		Measured from flow upstream and occupancy downstream	For utilization where there's free following condition and when there is heavily of congestion, a DC algorithm
[40]	ALINEA algorithm	occupancy		√			Measured from occupancy downstream	Critical occupancy, which corresponds to the maximum flow, yields more reliable results than relying only on the capacity value
[41]	RWS algorithm	Occupancy downstream and speed upstream	√				Measured from flow upstream	Similar to the way the D-C algorithm works
[42]	Percent occupancy algorithm	capacity	√				Measured from flow and occupancy for upstream	Acquired from the demand capacity (D-C) algorithm
[38]	D-C	occupancy	√				Measured from flow upstream and occupancy downstream	Only the minimum metering rate (qrmin) will be released from the RM signals when the downstream occupancy exceeds a critical value (O cr)
[39]	Demand Capacity INRETS	occupancy			√(3 detectors)		Measured from flow upstream and occupancy downstream	DC algorithm for under severe congestion and free-following conditions
[38]	RWS algorithm	occupancy	√				Measured from flow upstream	Similar to the way the D-C algorithm works
[42]	Percent occupancy algorithm	capacity	√				Measured from flow and occupancy for upstream	Acquired from the demand capacity (D-C) algorithm
[43]	MALINEA	occupancy	√				Measured from occupancy upstream and downstream	In the upstream merge section, ALINEA was unable to reduce congestion. Choosing the optimum position for the downstream detectors' station is difficult
[42]	FL-ALINEA	occupancy		√			Measured flow and occupancy for downstream	The flow measurement (q out) obtained from downstream detectors and the occupancy measurement

(Continued)

Table 1: *Continued*

Country (Ref.)	Types of Algorithms	Parameters	Site of Detector			Data Collection Techniques	Strengths	Limitation
			Upstream	Downstream	Multi-Detectors			
[44]	Speed-Occupancy algorithm	Occupancy and speed	√Metering Rates: 1. Occupancy measurement (qri (k)) 2. Speed measurement (qr2(k))				Measured from speed and occupancy for upstream	Traffic conditions could be reflected by both speed and occupancy parameters
[45]	ANCONA algorithm	Speed					Measured from speed for upstream	Because it was downstream from the active bottleneck location, it was unable to detect when traffic congestion occurred
[46]	Local ALENA	occupancy		√Two detectors			Measured occupancy from downstream	maximize the mainline throughput by maintaining a desired occupancy on the downstream mainline freeway
[3]	Hero ALENA	occupancy	√	√			Measured occupancy from upstream and downstream	occupancy should be estimated from downstream detector flow drop when the mainline is close to capacity

established international leader in mobility planning and transportation management technology. The services of AIMSUN are used by consulting firms, government organizations, and academic institutions for various purposes, such as developing cloud-based regional planning frameworks, implementing real-time traffic management, or modeling the effects of autonomous automobiles. Working constantly at the cutting edge of new technology to maximize intelligent, sustainable transportation, regardless of the project's magnitude. The scenario analysis module, which creates and simulates traffic management strategies, and the OD tool, which creates and manipulates origin–destination matrices describing the mobility patterns required by the dynamic analysis of traffic conditions, are two particular tools included in AIMSUN/ISM. The EMME/2 transport planning program has a flexible interface, which has been used to build the matrix calculation processes [36].

AIMSUN has three levels (macroscopic, micro, and meso) that deal with different networks for traffic urban and non-urban traffic. The software has a hybrid simulator, so it allows a large area of modeling and fast speed fulfillment [37].

The AIMSUN microscopic simulator was created as a component of many initiatives supported by European ITS programs [11]. After its original creation, the simulator substantially evolved and was utilized in various large-scale projects in North America, Australia/New Zealand, South America, and Europe, including Barcelona, London, Amsterdam, Stockholm, and others, as well as Auckland and Brisbane (Montreal, Minneapolis). These initiatives and independent evaluators like the Robert Bosch GmbH group have helped evaluate and certify the AIMSUN model [11].

1.4 ALINEA

ALINEA is the most widely used and effective local RM control strategy in the most frequent circumstances. The addressed bottleneck is mainly the merging area and, thus, quite close to the metered on-ramp. Several local RM control solutions have been proposed in the literature. ALINEA, the first local RM method created using feedback control theory, aims to increase highway throughput in the area where ramps merge [47]. Under both recurrent and nonrecurrent congestion conditions, ALINEA performs well. Enhancing bottleneck and zone by using ALINEA instead of the original local occupancy control methods is possible. Compared to ALINEA, it is discovered that the updated bottleneck and zone algorithms, which use ALINEA as the local control algorithm, are more effective in easing traffic congestion. Under all conditions, the updated bottleneck algorithm delivers reliable performance. The findings also suggest that RM loses effectiveness in cases with heavy traffic congestion [46].

Implementation of ALINEA depends on four parameters: the update cycle of the metering rate, a constant regulator, the location, and the desired occupancy of the downstream detector station [48]. ALINEA has been successfully deployed in many locations due to its simplicity and classical feedback nature [49].

ALINEA is an RM algorithm for local traffic-responsive feedback control. The method calculates the metering rate as a control variable that responds to motorway occupancy changes after taking freeway occupancy as an input. ALINEA installs a single detector per lane of the freeway at a distance of 40 or 400 m downstream. At regular intervals, typically every 40 s, the downstream detectors take an occupancy rate reading and transmit it to the controller. The controller sets the metering rate for the following interval by computing the difference between the desired occupancy threshold and the measured occupancy (40 s). ALINEA aims to set the metering rate at which the flow will not exceed the freeway capacity [3].

Local RM techniques are put into practice for a single ramp by computing the metering rates while considering the traffic circumstances in the area around the ramp. However, for a larger portion of the network, coordinated RM schemes set the metering rates based on the traffic circumstances [50]. The most well-known responsive RM control algorithms are demand capacity, percent-occupancy, and ALINEA [15], although other algorithms have been created to regulate the ramp locally. ALINEA, which can set its control rate by the congestion level and reclassify it adaptively [3], employs traffic flow rather than occupancy as the control parameter.

Derived from the notion that the metering rate should not be more than the gap between the highway capacity downstream of the merge and the flow of traffic upstream. To distinguish between normal (uncongested) and congested traffic conditions, congestion is defined as the downstream occupancy above a threshold value (hence referred to as the critical occupancy) [18]. In this case, only the minimum metering rate ($\mathrm{qr}_{\min}$) will be allowed at the merge.

$$\mathrm{qr}_{(k)} = q_{\mathrm{cap}} - q_{\mathrm{in}}, \quad \text{if} \quad O_{\mathrm{out}} < O_{\mathrm{cr}}, \tag{1}$$

$$\mathrm{qr}_{(k)} = \mathrm{qr}_{\min}, \quad \text{if} \quad O_{\mathrm{out}} \geq O_{\mathrm{cr}}, \tag{2}$$

where O_{out} is the measured downstream occupancy (in percent), O_{cr} is the critical occupancy (in percent), $\mathrm{qr}_{(k)}$ is the metering rate for the current time interval k (in vehicles per hour), q_{cap} is the motorway capacity (in vehicles per hour), q_{in} = upstream flow (in vehicles per hour), $k-1$ represents the previous cycle.

To prevent major changes in the metering rates for smooth functioning, the algorithm also takes into account the metering rate from the previous intervals determining the metering rate for the upcoming period. In order to prevent the flow from going over the motorway capacity, ALINEA attempts to establish the metering rate [3]. In contrast to relying solely on the capacity value, Meng and Khoo [47] claimed that utilizing a critical occupancy equivalent to the maximum flow yields more consistent results. The ALINEA algorithm, which stands for Asservissement LINeaire d'entrée Autoroutiere [51], is based on this strategy and aims to maintain occupancy levels close to the critical occupancy downstream of the merging area. To evaluate occupancy in this situation, just one detector needs to be placed downstream of the merge area (O_{out}). The algorithm employs equation (3) to calculate the current metering rate qr(k) using the system output qr(k − l) from the previous cycle, which typically ranges between 10 and 40 s.

$$\text{qr}(k) = \text{qr}(k-1) + \text{KR}(O_{\text{cr}} - O_{\text{out}}(k-1)) \times 100, \quad (3)$$

where O_{out} is the measured downstream occupancy (in percent), O_{cr} is the critical occupancy (in percent), $\text{qr}(k)$ is the metering rate for the current time interval k (in vehicles per hour), and $k-1$ is the previous cycle.

Based on the work done, KR, the regulator parameter, was discovered to be 70 vehicles per hour. And Odes is the desired occupancy (%), which may be equal to the critical occupancy but need not always be (O_{cr}). The ALINEA algorithm maximizes the mainline throughput as a local-feedback RM policy [16] by maintaining a desired occupancy on the downstream mainline freeway. The ALINEA algorithm can only be used if there are two detector stations. On the mainline freeway, a loop detector is located on the downstream of the entry ramp. It is possible to see a clog due to the heavy traffic flow coming from the ramp entry. Upstream is the second loop station that contain a loop detector [2]. The volume of the on-ramp is measured using the volume of ramp entry. The metering rate for an on-ramp is controlled by ALINEA, which can calculated by the following equation:

$$r(t) = r(t-\Delta t) + \text{KR}[O^* - O(t-\Delta t)], \quad (4)$$

where t is the update cycle [1] of the ramp-metering implementation, $O(t-t)$ is the measured occupancy of the time interval $(t-t, t)$ at the downstream detector station, KR is the regulator parameter used to adjust the constant disturbances of the feedback control, and O^* is the desired occupancy at the downstream detector station. According to the volume-occupancy relationship [2], the value of O^* is commonly selected to be equal to or slightly below the critical occupancy or occupancy at capacity.

2 Methodology

The main steps of this study could be summarized by adopting two sets of field data from loop detectors in the UK and AIMSUN simulation software. After verification, calibration, and validation of the software with the field data, the effect of loop detector location on the critical values of occupancy has been tested.

2.1 Field data from loop detectors

Field data from the loop detector in the UK [52] were obtained. These data are from two motorway sites; the first set is from a motorway named M56 J2 and includes flow rate and 5-min average speed. These data are from the off-peak loop detectors from 11.00 am to 1.00 pm on 09/15/2009. The input data and analyses were averaged for each 10- and 5-min period, as illustrated in Figure 1. This site consists of a two-lane section of freeway with a two-lane on-ramp section. The figure also shows the loop detector on

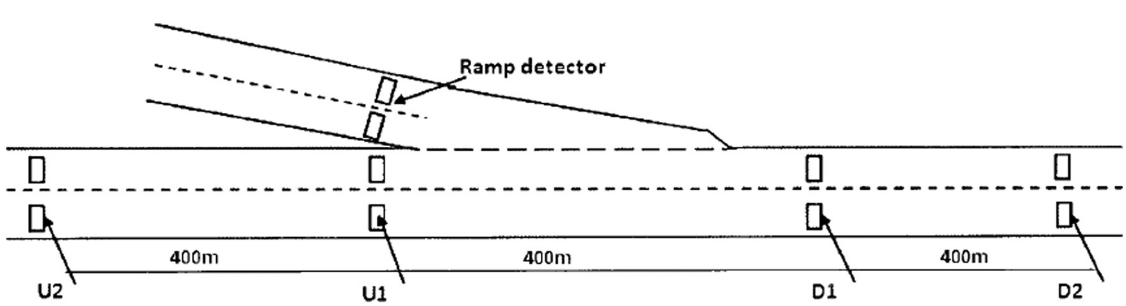

Figure 1: Locations of the loop detectors on M56 J2 [45].

M56 J2. Then, the AIMSUN software program was used to analyze the data and the same highway was designed to get the best results.

The second set of data has been obtained from the M56 J2 site. At this location, a one-lane on-ramp section merges with a three-lane highway segment. As depicted in Figure 2, numerous loop detectors are situated on the ramp, upstream, and downstream of the merge portion. On the morning of 7/6/2010, one data set was utilized for 4 h. Every 5 min, the inputs and analyses were averaged. As seen in Figures 1 and 2, data from U2 and the ramp detectors are used as input for comparing the simulation results with the data from the other loops (Ul, Dl, and D2).

The third set of data has been obtained from M602/6056B in the UK [53]. This section consists of a normal section with two lanes in each direction. The date and time of this set are 1/3/2010 for 24 h. The data represent the relationship between flow and occupancy.

2.2 Calibration of AIMSUN

Calibration is one of the critical processes to ensure that the software operates accurately. Two methods have been adopted to calibrate the software: graphically and statically using the GEH formula as indicated in equation (5). The GEH statistic is a formula used in traffic engineering, traffic forecasting, and traffic modeling to compare two sets of traffic volumes. If the results are less than 5, the simulation is close to reality [54]. In this work, the heavy vehicle (HV) is used for simulation simplicity. Bus, truck, and trailer are considered HV [15]

$$\mathrm{GEH} = \sqrt{\frac{2(m-c)^2}{m+c}}, \quad (5)$$

where m is the output traffic volume from the simulation model (vph) and c is the input traffic volume (vph).

Applying this formula, if the GEH ≤ 5, the simulation is fit for representing reality.

3 Results and discussion

3.1 Calibration: Site No. 1 (off-peak)

The calibration process has been implemented graphically for the two-lane section in flow and speed, as shown in Figures 3 and 4. The value of GEH is equal to 1.01 for Figures 3 and 4.

3.2 Calibration: Site No. 2 (on-peak)

For the same site (Site No. 1), the data collected during the on-peak period were also used in the calibration process, demonstrating an acceptable behavior to mimic reality, as shown in Figures 5 and 6. In addition, the statistical test (GEH) also indicates a good consistency with a value of 2.6.

3.3 Validation

It is an important step to improve the behavior of simulated data. The data from two sites were used. These sites are Site No. 2 with three lanes in addition to flow and occupancy data from Site No. 3. Figure 7 graphically

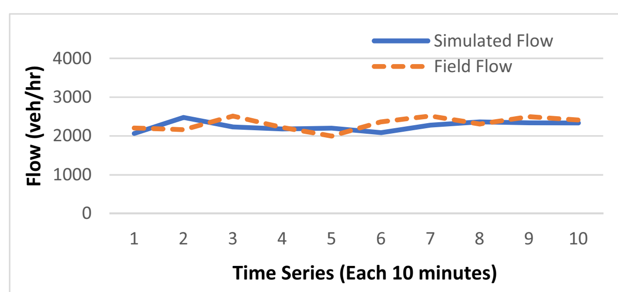

Figure 3: Simulated and field flow for M56 J2.

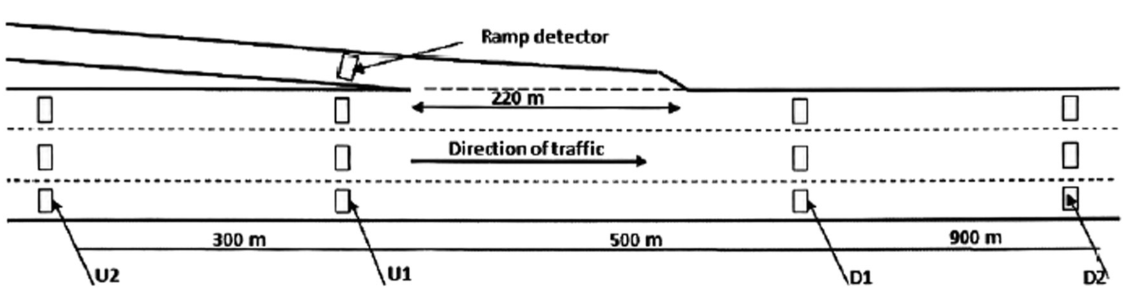

Figure 2: Locations of the loop detectors at M62 J11 [45].

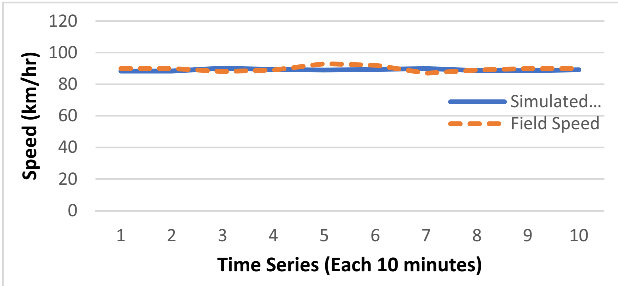

Figure 4: Simulated and field speed for M56 J2.

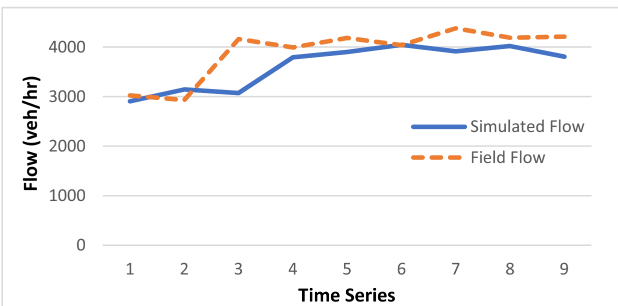

Figure 5: Simulated and field flow for M56 J2 (each 5 min).

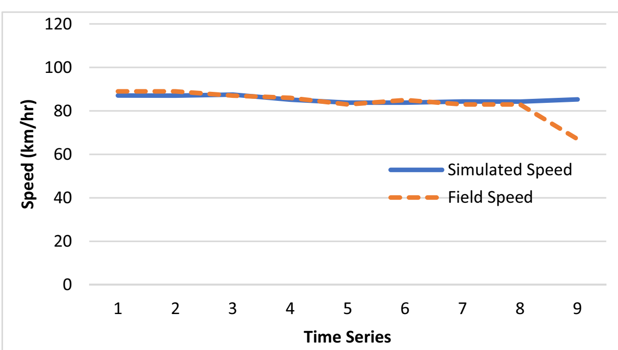

Figure 6: Simulated and field speed for M56 J2.

indicates a good consistency between field and simulated data. In addition, it statistically shows a good agreement with GEH equal to 0.5. Figure 8 indicates the relationship between simulated and field speed in the third site.

Another set of data has been used for the validation process. This set of data is from the normal section (M602), which has been used to validate the data from the AIMSUN with field data. The results indicate a significant correspondence between the simulated and field data, as shown in Figure 9. Moreover, speed data from the same site (M602) were used to show the consistency between field and simulated data, as shown in Figure 10. Figure 9 indicates that

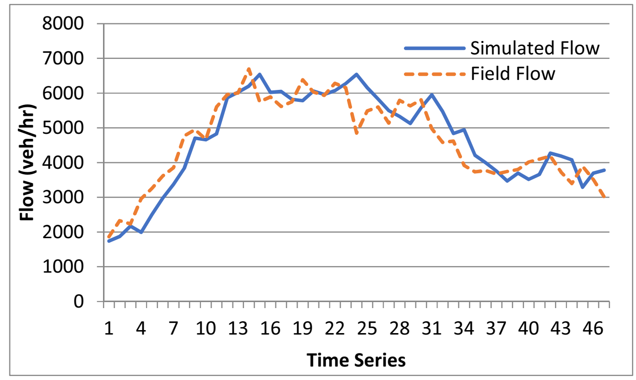

Figure 7: Simulated and field flow for M62 J11.

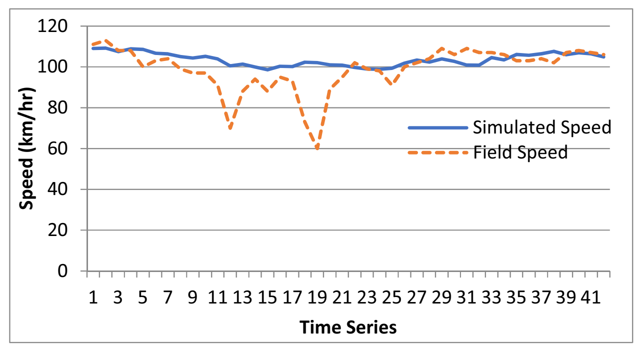

Figure 8: Simulated and field speed for M62 J11.

the status of flow is under capacity because the value of occupancy is less than 17%, as indicated by previous studies [16,17,19].

3.4 Applications of the simulated model

After conducting both calibration and validation processes, the model is now able to represent reality to some extent. Two scenarios have been used for testing two important

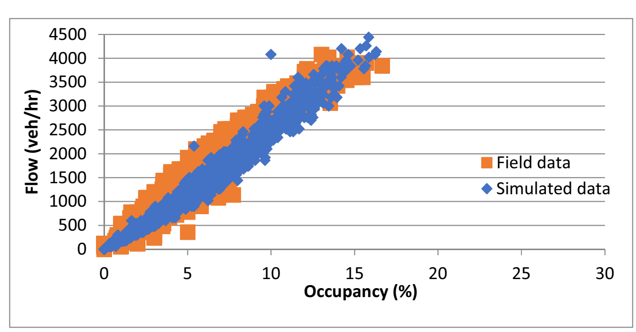

Figure 9: Simulated and field flow and occupancy for M602.

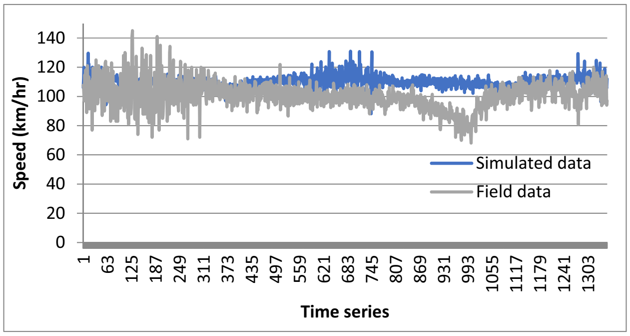

Figure 10: Simulated and field speed for M602.

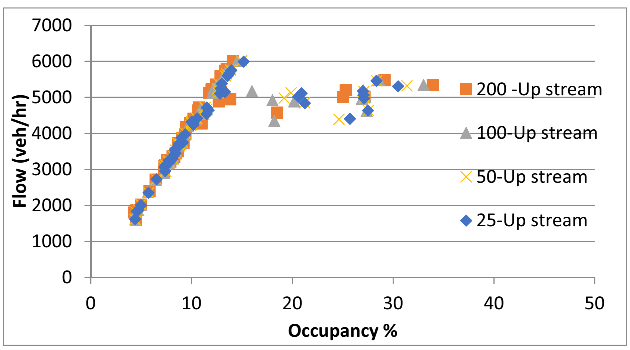

Figure 11: The effect of the upstream location of the loop detector on the occupancy value.

parameters. The first one is the effect of loop detector location on the occupancy value, as indicated in Figures 11 and 12. The second parameter is the effect of the percentage of HVs on the value of occupancy, which increases because lengthy vehicles wait longer on the detector and move slowly, as indicated in Figures 13 and 14. Figure 11 illustrates the case in which there is a congested state because the occupancy value is above 17% [16,17,19]. While Figure 12 indicates the uncongested case because the occupancy value is under 17%.

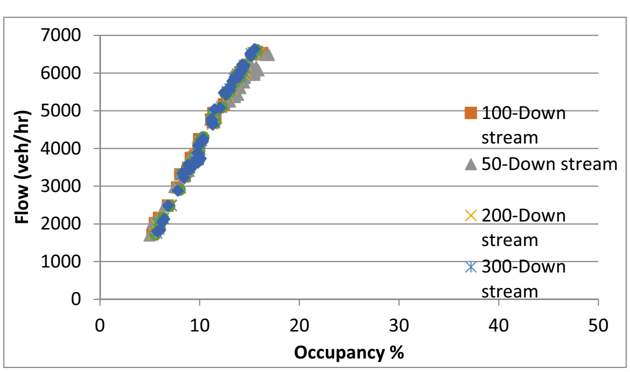

Figure 12: The effect of the downstream location of the loop detector on the occupancy value.

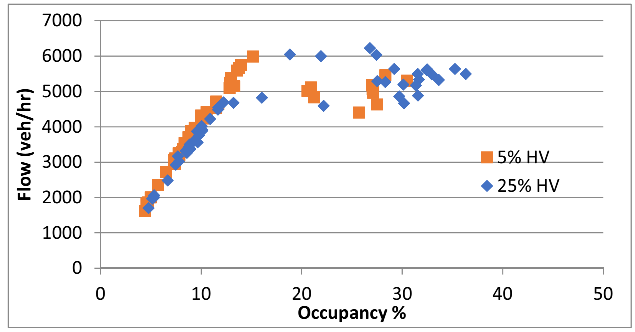

Figure 13: The effect of HV% on the occupancy value at 25 m upstream from the merging section.

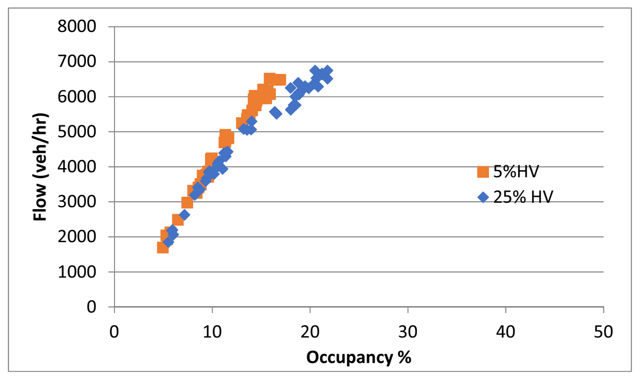

Figure 14: The effect of HV% on the occupancy value at 50 m downstream from the merging section.

Referring to Figures 13 and 14, it was noticed that the occupancy values upstream are higher than those downstream for the same flow level. These high values could be attributed to the presence of platoons of vehicles upstream resulting from competing vehicles to get a suitable gap to do their maneuvers. While the low values of occupancy downstream are due to relaxation behaviors after merging the area. These values represent approximately the reality at such sections. On the contrary, the effect of HVs is represented by Figures 13 and 14. As the percentage of HV increases, the value of occupancy increases.

4 Conclusion

In this article, the most critical factors that affect highway performance are highlighted.

- AIMSUN shows a significant consistency in representing field data of merging sections. This behavior has been proved graphically and statically with low values of GEH (0.5).

- According to previous theories, congestion is from 17% to less than 30%.
- The occupancy values (17%) for upstream are higher than those for downstream for the same flow level due to relaxation behaviors after merging the area. These values represent approximately the reality in such sections.
- The effect of loop detector location is a significant factor in determining the critical occupancy for the merging section. The downstream location is more appropriate for determining the congestion or critical status.
- The percentage of HVs (25%) significantly affects the occupancy value.
- The occupancy value at upstream is above 30%.
- Low downstream occupancy values are less than 17%.
- The congested state for the high value 30% of the upstream is due to attribution to the existing platoons of vehicles at upstream resulting from competing vehicles to get a suitable gap to do their maneuvers.
- The uncongested state for low-value downstream is due to relaxation behaviors after the merge section.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

References

[1] Dunphy RT, Fisher K. Transportation, congestion, and density: new insights. Transp Res Rec. 1996;1552(1):89–96.
[2] Jin PJ, Fang J, Jiang X, DeGaspari M, Michael Walton C. Gap metering for active traffic control at freeway merging sections. J Intell Transp Syst. 2017;21(1):1–11.
[3] Shaaban K, Khan MA, Hamila R. Literature review of advancements in adaptive ramp metering. Procedia Comput Sci. 2016;83:203–11.
[4] Chen X, Li T, Ma Z, Sun J. Integrated mainline and ramp signal control for expressway on-ramp bottleneck with unequal lane-setting. J Intell Transp Syst. 2021;26(1):100–15.
[5] Yang G, Tian Z, Xu H, Wang Z, Wang D. Impacts of traffic flow arrival pattern on the necessary queue storage space at metered on-ramps. Transportmetrica A: Transp Sci. 2018;14(7):543–61.
[6] Kotsialos A, Papageorgiou M, Mangeas M, Haj-Salem H. Coordinated and integrated control of motorway networks via non-linear optimal control. Transp Res Part C: Emerg Technol. 2002;10(1):65–84.
[7] Koukol M, Zajíčková L, Marek L, Tuček P. Fuzzy logic in traffic engineering: a review on signal control. Math Probl Eng. 2015;2015:1–14.
[8] Jiang R, Lee JB, Chung E. A multi-hierarchical strategy for on-ramp coordination. Int J Intell Transp Syst Res. 2017;15(1):50–62.
[9] Abuamer IM, Celikoglu HB. Local ramp metering strategy ALINEA: microscopic simulation based evaluation study on Istanbul freeways. Transp Res procedia. 2017;22:598–606.
[10] Mitkas DZ, Politis I. Evaluation of alternative Ramp Metering scenarios on freeway on-ramp with the use of microscopic simulation software Vissim. Transp Res Procedia. 2020;45:483–90.
[11] Hourdakis J, Michalopoulos PG. Evaluation of ramp control effectiveness in two twin cities freeways. Transp Res Rec. 2002;1811(1):21–9.
[12] Xu YX, Zhang GD. Models and algorithms of QoS-based routing with MPLS traffic engineering. In 5th IEEE International Conference on High Speed Networks and Multimedia Communication (Cat No 02EX612). IEEE; 2002, July. p. 128–32.
[13] Masher D, Ross D, Wong P, Tuan P, Zeidler H, Petracek S. Guidelines for design and operation of ramp control systems. Vol. 86. Washington, USA: NCHRP Research Results Digest; 1975.
[14] Trubia S, Curto S, Barberi S, Severino A, Arena F, Pau G. Analysis and evaluation of ramp metering: From historical evolution to the application of new algorithms and engineering principles. Sustainability. 2021;13(2):850.
[15] Al-Jameel HAE, Al-Jumaili MAH. Analysis of traffic stream characteristics using loop detector data. Jordan J Civ Eng. 2016;10(4):403–16.
[16] Green D, Lewis K. Guide to traffic management part 2: Traffic theory concepts (No. AGTM02-20). Australia, Sydney: Book, Austroads association; 2020.
[17] Hall FL, Allen BL, Gunter MA. Empirical analysis of freeway flow-density relationships. Transp Res Part A: Gen. 1986;20(3):197–210.
[18] Al-Obaedi J, Yousif S. Microsimulation model for motorway merges with ramp-metering controls. IEEE Trans Intell TransportatiSyst. 2011;13(1):296–306.
[19] Kianfar J, Edara P. A data mining approach to creating fundamental traffic flow diagram. Procedia-Soc Behav Sci. 2013;104:430–9.
[20] Yousif S, Al-Obaedi J. Modeling factors influencing the capacity of motorway merge sections controlled by ramp metering. Procedia-Soc Behav Sci. 2011;16:172–83.
[21] Knoop VL, Duret A, Buisson C, Van Arem B. Lane distribution of traffic near merging zones influence of variable speed limits. In 13th International IEEE Conference on Intelligent Transportation Systems. IEEE; 2010, September. p. 485–90.
[22] Davis LC. Driver choice compared to controlled diversion for a freeway double on-ramp in the framework of three-phase traffic theory. Phys A: Stat Mech Appl. 2008;387(25):6395–410.
[23] Reinolsmann N, Alhajyaseen W, Brijs T, Pirdavani A, Hussain Q, Brijs K. Investigating the impact of a novel active gap metering signalization strategy on driver behavior at highway merging sections. Transp Res part F: Traffic Psychol Behav. 2021;78:42–57.
[24] Kherroubi ZEA. Novel off-board decision-making strategy for connected and autonomous vehicles (Use case: Highway on-ramp merging). Doctoral dissertation. Université Claude Bernard Lyon 1; 2020.

[25] Asgharzadeh M, Gubbala PS, Kondyli A, Schrock SD. Effect of on-ramp demand and flow distribution on capacity at merge bottleneck locations. Transp Lett. 2020;12(8):550–8.
[26] Jia A, Williams BM, Rouphail NM. Identification and calibration of site-specific stochastic freeway breakdown and queue discharge. Transp Res Rec. 2010;2188(1):148–55.
[27] Zhu J, Tasic I. Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles. Accid Anal Prev. 2021;152:105966.
[28] Li H, Zhang J, Li Y, Huang Z, Cao H. Modeling and simulation of vehicle group collaboration behaviors in an on-ramp area with a connected vehicle environment. Simul Model Pract Theory. 2021;110:102332.
[29] Zhang L, Levinson D. Ramp metering and freeway bottleneck capacity. Transp Res Part A: Policy Pract. 2010;44(4):218–35.
[30] Stylianopoulou E, Kontorinaki M, Papageorgiou M, Papamichail I. A linear-quadratic-integral regulator for local ramp metering in the case of distant downstream bottlenecks. Transp Lett. 2020;12(10):723–31.
[31] Arasan VT, Dhivya G. Measurement of occupancy of heterogeneous traffic using simulation technique. IFAC Proc Vol. 2009;42(15):19–24.
[32] Barceló J. Microscopic traffic simulation: A tool for the analysis and assessment of its systems. In Highway Capacity Committee, Half Year Meeting; 2001, July.
[33] Greguric M, Ivanjko E, Mandžuka S. Cooperative ramp metering simulation. In 2014 37th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO). IEEE; 2014, May. p. 970–5.
[34] Li Z, Liu P, Xu C, Wang W. Development of analytical procedure for selection of control measures to reduce congestions at various freeway bottlenecks. J Intell Transp Syst. 2018;22(1):65–85.
[35] Shehada MK, Kondyli A. Evaluation of ramp metering impacts on travel time reliability and traffic operations through simulation. J Adv Transp. 2019;2019:1–12.
[36] Barceló J, Codina E, Casas J, Ferrer JL, García D. Microscopic traffic simulation: A tool for the design, analysis and evaluation of intelligent transport systems. J Intell Robot Syst. 2005;41:173–203.
[37] Baza-Solares N, Velasquez-Martínez R, Torres-Bohórquez C, Martínez-Estupiñán Y, Poliziani C. Traffic simulation with open-source and commercial traffic microsimulators: a case study. Commun-Sci Lett Univ Zilina. 2022;24(2):E49–62.
[38] Hounsell N, McDonald M, Breheret L. 'Models and strategies for dynamic route guidance, Part A: The modelling of dynamic route guidance. In Proceedings of the DRIVE Conference: Advanced Telematics in Road Transport, February 4–6, 1991, CEC, Brussels. Vol. 1;1992. p. 89–98.
[39] Haj-Salem H, Papageorgiou M. Ramp metering impact on urban corridor traffic: Field results. Transp Res Part A: Policy Pract. 1995;29(4):303–19.
[40] Hadj-Salem H, Blosseville JM, Papageorgiou M. ALINEA: A local feedback control law for on-ramp metering; a real-life study. In Third International Conference on Road Traffic Control, 1990. IET; 1994, March. p. 194–8.
[41] Taale H, Middelham F. Ten years of ramp-metering in The Netherlands. IEE 2000 Road Transport Information and Control, Conference Publication, London, UK; 2000.
[42] Smaragdis E, Papageorgiou M. Series of new local ramp metering strategies: Emmanouil smaragdis and markos papageorgiou. Transp Res Rec. 2003;1856(1):74–86.
[43] Sisiopiku VP, Oh HU. Evaluation of roundabout performance using SIDRA. J Transp Eng. 2001;127(2):143–50.
[44] Xuewen C, Dianhai W, Sheng J. On-ramp metering on Beijing urban expressway. In 2007 IEEE International Conference on Automation and Logistics. IEEE; 2007, August. p. 504–7.
[45] Al-Obaedi JTS. Development of traffic micro-simulation model for motorway merges with ramp metering, PhD thesis. United Kingdom: University of Salford; 2011.
[46] Chu L, Liu HX, Recker W, Zhang HM. Performance evaluation of adaptive ramp-metering algorithms using microscopic traffic simulation model. J Transp Eng. 2004;130(3):330–8.
[47] Meng Q, Khoo HL. A Pareto-optimization approach for a fair ramp metering. Transp Res Part C: Emerg Technol. 2010;18(4):489–506.
[48] Chu L, Yang X. Optimization of the alinea ramp-metering control using genetic algorithm with micro-simulation. In TRB Annual Meeting; 2003, January. p. 6.
[49] Jiang R, Lee JB, Chung E. Proportional-derivative (PD) controller for heuristic rule-based motorway coordinated ramp meters. KSCE J Civ Eng. 2018;22(9):3644–52.
[50] Hu SR, Peeta S, Chu CH. Identification of vehicle sensor locations for link-based network traffic applications. Transp Res Part B: Methodol. 2009;43(8–9):873–94.
[51] Papageorgiou M, Hadj-Salem H, Blosseville JM. ALINEA: A local feedback control law for on-ramp metering. Transp Res Rec. 1991;1320(1):58–67.
[52] Al-Obaedi J. Development of traffic micro-simulation model for motorway merges with ramp metering. Doctoral dissertation. Salford: University of Salford; 2011.
[53] Al-Jameel HAE. Developing a simulation model to evaluate the capacity of weaving sections. Doctoral dissertation. University of Salford; 2011.
[54] Feldman O. The GEH measure and quality of the highway assignment models. Association for European Transport and Contributors; 2012. p. 1–18.