IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 27, 2019, accepted June 12, 2019, date of publication June 17, 2019, date of current version July 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2923438

Coordinated Ramp Metering Based on Real-Time OD Information

YONGHENG CHEN, FANGHONG LIU, QIAOWEN BAI, CHUQING TAO, AND XINGZU QI
School of Transportation, Jilin University, Changchun 130022, China

Corresponding author: Yongheng Chen (cyh@jlu.edu.cn) and Fanghong Liu (trafficliufh@foxmail.com)

ABSTRACT In the near future, the OD information of vehicles will be known in real time under the Internet of Vehicles (IoV) environment. To reduce total travel time and bottleneck breakdown on the expressway during rush hours, a new strategy of coordinated ramp metering (CRM) based on real-time OD information is presented. In this study, real-time OD information of traffic flow is effectively used at the level of traffic control. Flow priorities are determined according to real-time OD information based on the quantitative hierarchical model (QHM) algorithm. The new algorithm is named as OD-QHM. It gives priority to the on-ramp with short total travel distance. Since the traffic flow in the expressway system influences each other, this paper demonstrates the effectiveness of the proposed control algorithm by simulation analysis. Simulation results indicate both the validity and the stability of OD-QHM algorithm are good.

INDEX TERMS Internet of Vehicles, coordinated ramp metering, real-time OD information, quantitative hierarchical model, OD-QHM.

I. INTRODUCTION

Congestion problem of expressway seriously affects the operation of urban traffic system [1]–[6]. Many control strategies have been proposed to improve traffic efficiency of expressway system. Ramp metering (RM) is probably the more commonly used expressway traffic control strategy [7]–[15]. It can be divided into local/isolated ramp metering and coordinated ramp metering (CRM) by the range of control area. CRM considers a series of ramps as a whole and every ramp metering rate is determined according to the condition of the whole system. It can take into account the whole system compared with local ramp metering. Present studies have indicated CRM solutions are more efficient than isolated ones [16]–[18].

CRM can be realized through many different strategies. Heuristic coordination strategies based on various rules are widely studied and have a good effect [19]–[25]. But these control algorithms are designed to avoid bottleneck breakdown rather than to realize system optimum. On the basis of a heuristic rule, Vrancken et al. proposed quantitative hierarchical model (QHM) for network-level traffic control. QHM is based on Network Management concepts and on the theory of Hierarchical Control. It realized CRM by partitioning expressway system and determining flow priorities [26]. Nevertheless, this study proposed the framework of QHM without giving a method to determine the flow priority. Meshkat et al. verified the effectiveness of QHM in CRM [27]. This study still did not give a method to determine the flow priority. Tu et al. determined the control sequence of multiple ramps based on QHM [28]. But only the local information was used in determining the flow priority. It is not a system optimization algorithm. The control goal is still to avoid congestion, which is not equal to high-efficiency. Therefore, how to determine flow priorities and allocate ramp metering rates from the perspective of efficient system operation is the focus of this paper.

A real CRM algorithm should start with using all available information at system level. In the field of traffic control, the use of vehicle OD information is still limited on single point. The OD information in small spatial-scale is microscopic OD information. This kind of OD is easy to obtain through local traffic survey. In the field of traffic management, the required OD information is the origin and destination of a trip with a wide spatial range. This is macroscopic OD information. It is often need to conduct a large-scale survey of residents' travel combining with traffic zone division, and the cost is high. Urban expressway system is relatively independent due to less external disturbance. For CRM, microscopic OD information is far from enough, whereas

The associate editor coordinating the review of this manuscript and approving it for publication was Fabrizio Messina.

macroscopic OD information cannot be obtained in real-time. The OD information of vehicles in the expressway system is needed. This kind of OD information is between macroscopic OD information and microscopic OD information. It has time and space characteristics of system need in CRM. In the CRM, the origin and destination pairs (OD-pairs) are about the study network rather than the whole trip. For example, vehicles at the same entry point may travel toward different exit points and the travel distances of vehicle are determined by OD-pairs in the study area.

In the Internet of Vehicles (IoV) environment, vehicle path information, namely OD information, can be obtained in real time. OD information is a vector with both size and direction. There is a median strip between the opposite lanes of the expressway. Hence what can be used is the size of OD information. The size of OD information is the length of vehicle's path on the mainline of the expressway. When someone using OD information to control traffic, the first question is whether releasing the vehicle with big OD information first or releasing the vehicle with small OD information first has a better traffic effect on the system. That is the flow priority problem about the OD information.

Due to the time-space limitation, the traditional information such as flow rate, density and occupancy rate cannot reflect the impact of the current on-ramp traffic flow release on the expressway system. Whereas the real-time OD information can well reflect the impact. Therefore, the flow priority of on-ramps can be quantitatively allocated based on real-time OD information, and then the ramp metering rate can be determined. This is a good extension of CRM in allocating ramp metering rates to upstream on-ramps. Furthermore, the real-time OD information as a new index and its heuristic rules could be applied to other algorithms such as optimal control and intelligent control.

The algorithm proposed in this paper is based on the QHM framework and the assumption that every vehicle is connected to the IoV as well as the compliance rate is 100%. It uses real-time OD information to determine the flow priority, and allocates ramp metering rates according to the flow priority. Compared with indexes used in other algorithms, the real-time OD information can better reflect the time-space characteristic of expressway system. The OD-QHM aims to achieve the optimal total time vehicles spend in the expressway system, rather than to merely avoid the bottleneck breakdown. It is a CRM algorithm in the real meaning.

The remainder of this paper is organized as follows. The concept of the flow priority based on real-time OD information is proposed in Section 2. Then in Section 3, the relationship between real-time OD information and the optimal ramp metering rate is investigated by *VISSIM* simulation. In Section 4 we propose a new CRM algorithm, OD-QHM, by combining the flow priority based on real-time OD information with the QHM algorithm. Section 5 evaluates the efficiency of OD-QHM algorithm compared with other algorithms by simulation. Finally, conclusion and future work are provided in Section 6.

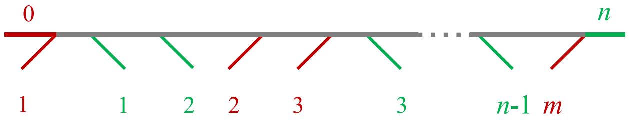


FIGURE 1. An example of expressway topology.

II. THE FLOW PRIORITY BASED ON OD INFORMATION

Before the realization of IoV technology, OD information is difficult to be applied in real-time traffic control. IoV is a big interactive network composed of location, velocity, route and other information. In the IoV environment, real-time location and potential travel routes of each vehicle in the expressway are available. Therefore, the flow priority of each ramp can be determined based on the information of vehicles that are entering the mainline.

As shown in Figure 1, the study area is an expressway section with m on-ramps and n-1 off-ramps. For convenience, the mainline entrance and on-ramps are uniformly numbered. Similarly, the mainline exit and off-ramps are uniformly numbered.

Parameters involved in the concept are as follows.

i is the number of mainline entrance or on-ramp.

j is the number of mainline exit or off-ramp.

k is the number of control period.

$q(i, j, k)$ is the number of vehicles entering from entrance i and heading for exit j in control period k.

$q\ (i, k)$ is the number of vehicles entering from entrance i in control period k.

Suppose distances traveled by vehicles with the same origin and destination are uniform, and the distance is denoted as $d\ (i, j)$.

$s(i,\ k)$ is the total distance traveled by vehicles entering from entrance i on the mainline in control period k, as shown in Eq. (1).

$$s(i, k) = \sum_{j=1}^{n} q(i, j, k) \cdot d(i, j) \tag{1}$$

$w\ (i,\ k)$ is the ratio of on-ramp i distance traveled by vehicles to all on-ramps distance traveled by vehicles on the mainline in control period k, as shown in Eq. (2).

$$w(i, k) = \frac{s(i, k)}{\sum_{i=1}^{m} s(i, k)} \tag{2}$$

Due to the fluctuation caused by car-following, lane-changing, interweaving and other behaviors, the longer the driving distance of vehicles on the expressway mainline, the greater the impact on the operation of the expressway. Therefore, the larger $s\ (i, k)$ is, the greater the absolute impact on the expressway system. The larger $w\ (i, k)$ is, the greater the relative impact on the expressway system. To achieve efficient operation of expressway system, the ramp of small $w\ (i,\ k)$ should be early released. It helps to reduce the travel time of the vehicles in the system. In this paper, this characteristic is called the flow priority based on real-time

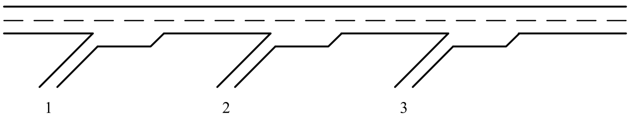


FIGURE 2. Part of an expressway with three on-ramps.

OD information. The next section verifies the idea through simulation.

III. THE RELATION BETWEEN OD INFORMATION AND OPTIMAL RAMP METERING RATE

Since the influence of OD information on ramp release is not determined, the purpose of the simulation in this section is to explore the influence of the release priority of ramps with different OD information on system delay. The minimum system delay corresponds to the optimal ramp metering rate. Because optimal ramp metering rate is influenced by many factors, the control variate method is used. In this study, all the factors are controlled for the same except for the OD information factor. In this simulation, a control period includes two sub-periods. The ramp metering rate in the first sub-period is called prior metering rate in this paper. To analyze the relation between the optimal ramp metering rate and OD information, the sum number of released vehicles in the two sub-periods should be identical in the same traffic condition. Hence the ramp metering rate in the second sub-period is called compensatory metering rate.

According to the research objective, the simulated road network should include several entrances and at least one exit, so that the priority can be allocated to different on-ramps and the validity of allocating flow priority based on OD information can be checked. As shown in Figure 2, three on-ramps are included in this simulation. These on-ramps are long enough to observe the queue. Overflow impact of the on-ramp queue is not considered for convenience. The length of each acceleration lane is 0.2 km. Each distance along the mainline between the entrances is 0.5 km. A 0.5 km interval is enough for the flow to recover from disturbances at the merging area [27]. The mainline has two lanes. Traffic signals are placed at all the entrances in the system to control the network inflow.

VISSIM 4.30 and its COM-interface are used for this simulation. The simulation warm-up time is 600 s. During the warm-up time, no control measure is adopted to make the road network reach a stable operation state. The control period is 600 s, and the two sub-periods are both 300 s. One-car-per-green mode is used to meter on-ramps. This allows flow control without stopping mainline traffic. Note that the actual prior metering rate is not greater than the arrival flow. The step size of the prior metering rate is 50 pcu/h. The compensatory metering rate can be calculated after determining the prior metering rate. All the vehicles in the simulation are small cars.

TABLE 1. Simulation cases of different input flows.

Case	Mainline input flow (pcu/h)	On-ramp 1 input flow (pcu/h)	On-ramp 2 input flow (pcu/h)	On-ramp 3 input flow (pcu/h)	Maximum average metering rate (pcu/h)	Sample size
1	1700	800	800	800	550	4913
2	2000	700	700	700	500	3375
3	2300	600	600	600	400	2197
4	2600	500	500	500	300	1331
5	2900	400	400	400	200	729

TABLE 2. Correlation analysis between the prior metering rate and ADR.

Case	On-ramp 1		On-ramp 2		On-ramp 3	
	Pearson	Significance (bilateral)	Pearson	Significance (bilateral)	Pearson	Significance (bilateral)
1	0.009	0.511	-0.287	0.000	0.054	0.000
2	-0.188	0.000	-0.555	0.000	0.008	0.647
3	-0.290	0.000	-0.243	0.000	-0.022	0.312
4	-0.310	0.000	-0.296	0.000	-0.055	0.046
5	-0.144	0.000	-0.247	0.000	-0.186	0.000

In the simulation, the mainline traffic supply is 3500 pcu/h, but the system traffic demand is 4100 pcu/h. Demand is greater than supply in a short time. To ensure the stability of the expressway system, the total flow released should be controlled within 3500pcu/h. Average ramp metering rate in each control period is the same in accordance with the queue balance rule. Simulation cases are shown in Table 1.

Average delay rate (ADR), the normalized average delay over traveled distances, is used as a congestion indicator [29]. Correlation analysis between the prior metering rate and ADR is conducted as shown in Table 2. It can be considered that prior metering rates of on-ramp 1 and on-ramp 2 is significantly correlated with the ADR of the expressway system. This indicates that the order of ramp releases can influence control effect.

In the case of the same flow input, the optimal metering rate corresponds to the minimum ADR. The optimal prior metering rate of each flow case is shown in Table 3. $m1$, $m2$ and $m3$ are used to respectively represent the optimal prior metering rates of on-ramp 1, on-ramp 2, and on-ramp 3. $d1$ and $d2$ are used to respectively represent the distance of on-ramp 1 and on-ramp 2 to on-ramp 3 along the mainline. Since all the vehicles entering from on-ramps travel toward the exit and the input flows of on-ramps are identical, $w\,(i, k)$ is only impacted by $d1$ and $d2$ according to Eq. (2) in this simulation. Both on-ramp 2 and on-ramp 3 in case 5 became bottlenecks due to high mainline input flow. Except for case 5, ratios of $m1$ to $m2$ in the other cases with a single bottleneck are around 0.55. Moreover, the ratio of $d1$ to $d2$ is 2:1. It can be approximately inferred that the optimal ramp metering rate is inversely proportional to $w\,(i, k)$. Therefore, it is feasible to

TABLE 3. The optimal prior metering rate of each case.

Case	*m1*	*m2*	*m3*	*m1/m2*
1	350	650	50-800	0.538
2	350	600	0-700	0.583
3	250	400	100-600	0.625
4	250	450	250-500	0.556
5	150	400	50-400	0.375

allocate ramp flow priorities according to the real-time OD information.

IV. OD-QHM: AN IMPROVED QHM ALGORITHM BASED ON REAL-TIME OD INFORMATION

After the relation between OD information and ramp metering is preliminarily determined, this section apply this relation to ramp metering.

The QHM algorithm coordinates ramp metering by implementing Network Management on the expressway system. It combines Systems Engineering and Heuristic Control. QHM consists of recursive sub-networks of a large network and its control strategy, which can hierarchically distribute the complexity of the network into sub-networks. In the view of system engineering, each sub-network can be considered as a system because each sub-network has the entrance and exit at boundary. For entire expressway network, only its sub-network boundaries need to be managed. The control method of entire expressway network is also applicable to each sub-network. Controlling the boundary reduces the managing complexity of each sub-network. The abstraction of boundary and interface improves the extensibility of control strategy. Therefore, QHM has the advantages of low complexity and good extensibility, and it is suitable for systems in any scales.

Two key problems need to be solved when applying QHM to CRM. The first problem is to determine the network partition and when to start control. The second problem is to determine the on-ramp flow priority. For the first problem, Tu et al. established an indicator of production stability (PS) on the basis of a macroscopic fundamental diagram (MFD) and the instability of traffic flows to determine when to start the control of CRM [30]. This paper focuses on the second problem. Tu et al. determined the control sequence of coordinated multiple ramps [28]. However, only local level information is used to determine flow priorities. It is not a system-level optimization. The authentic CRM should use system-level information to determine the flow priority. Section 2 introduced the flow priority based on real-time OD information. Section 3 verified the feasibility of determining flow priority based on real-time OD information. This section will explore how to implement CRM according to the flow priority based on real-time OD information under the QHM framework.

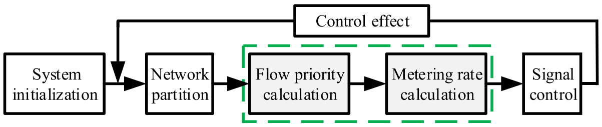


FIGURE 3. Control steps of the QHM algorithm.

As shown in Figure 3, two main steps of the QHM algorithm after network partition are flow priority calculation and ramp metering rate calculation. In this study, the two steps are improved as Figure 4. The variant of QHM algorithm is named as OD-QHM.

In Figure 4, $q(i, j, k)$, $d\ (i,\ j)$, and $s(i, k)$ have been explained in Section 2. The follows are some parameters have not been explained above.

$M(i, k)$ is the ramp metering rate of on-ramp i.

x is the number of bottleneck. In this study, the number of bottleneck is same as the number of on-ramp. It also means there are x on-ramps in control area when the bottleneck number is x.

l is the sum of possible bottlenecks. In this study, l is equal to m.

$w\ (i,\ k,\ x)$ is the ratio of on-ramp i distance traveled by vehicles to x on-ramps distance traveled by vehicles on the mainline in control period k.

$$w(i, k, x) = \frac{s(i, k)}{\sum_{i=1}^{x} s(i, k)} \tag{3}$$

Combined with the experiment in Section 3, the equation of the on-ramp i flow priority in control period k when possible bottleneck is x used in this study is as follows:

$$r(i, k, x) = \frac{\frac{1}{w(i, k, x)}}{\sum_{i=1}^{x} \frac{1}{w(i, k, x)}} \tag{4}$$

Since some vehicles will not pass through the bottleneck, the impact of these vehicles should be excluded to avoid underestimating the on-ramp metering rates. The metering rate of on-ramp i in control period k can be calculated as:

$$M(i, k, x) = \frac{(C_x - q(0, j, k)) \cdot r(i, k, x)}{\frac{q(i, j, k)}{q(i, k)}} \tag{5}$$

where C_x is the capacity of bottleneck x.

The core concepts of OD-QHM can be interpreted as following:

1. The last on-ramp is the bottleneck in the control sub-network. However, it is necessary to simultaneously calculate ramp metering rates under all possible bottleneck conditions in the current control process to avoid creating new bottlenecks in the upstream of the bottleneck.

2. The actual bottleneck is used as terminus to calculate each $s\ (i,\ k)$. Ramp flow priorities under all possible bottleneck conditions are calculated based on the $s\ (i,\ k)$.

```
Input: $q(i, j, k)$, $d(i, j)$, $m$, $l$, $C_x$
Output: $M(i, k)$
Begin
    For $i = 1$ to $m$
        $M(i, k) \leftarrow \infty$
        Calculate each $s(i, k)$
    For $x = 1$ to $l$
        For $i = 1$ to $m$
            Calculate each $w(i, k, x)$, $r(i, k, x)$ and $M(i, k, x)$
    For $i = 1$ to $m$
        For $x = 1$ to $l$
            If $M(i, k, x) < M(i, k)$
                $M(i, k) \leftarrow M(i, k, x)$
End
```

FIGURE 4. Flow priority and ramp metering rate calculation in OD-QHM algorithm.

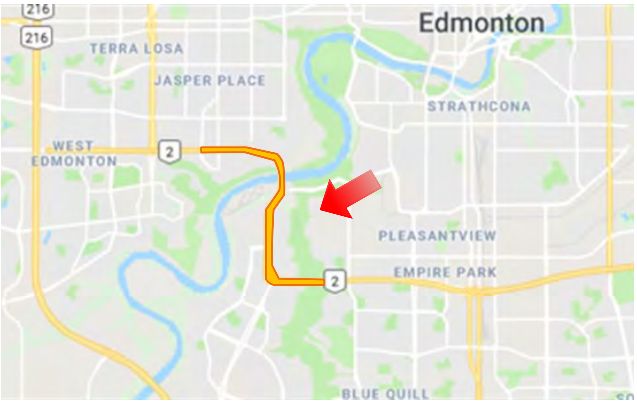


FIGURE 5. Geographical location of the study section.

3. Since the actual conditions at different possible bottlenecks may be different, capacity values at different bottlenecks should be selected according to the actual situation.

4. For all on-ramps in the control partition, flow priorities and ramp metering rates are calculated for all possible bottleneck conditions.

5. For each on-ramp, the minimum metering rate under all possible bottleneck conditions is selected for control.

V. TEST CASE

Whitemud Drive is an urban expressway in Edmonton, Alberta, Canada. Its basic speed limit is 80 km/h. The effect of OD-QHM algorithm is illustrated by taking the eastbound carriageway shown in Figure 5 as an example. Figure 6 shows the location of loop detectors. Assume that the area shown in Figure 6 is treated as a sub-network in control time. The distance between ramps along the mainline can be measured. According to the research needs, the loop detector data from 16:30 to 18:10 on August 10, 2015 were counted at the interval of 5 minutes as shown in Figure 7. *VISSIM 4.30* has been used as simulation engine, with control and data processing done by a *Visual Basic* program, communicating with *VISSIM 4.30* through the COM-interface.

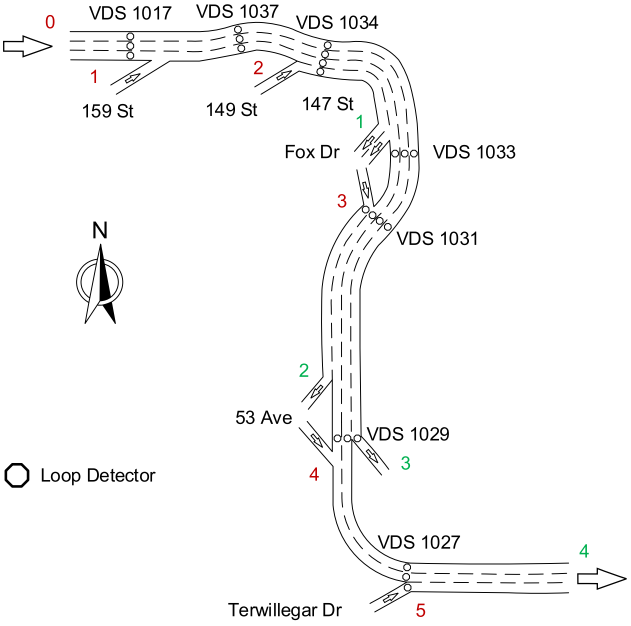


FIGURE 6. The location of loop detectors.

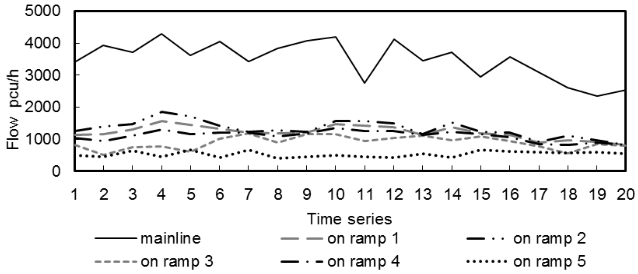


FIGURE 7. Flow data during 16:30-18:10.

To illustrate the effect of the OD-QHM algorithm, the simulation is conducted respectively in the case of no control, ALINEA, and the algorithm proposed in this study. ALINEA is a simple, mature and stable ramp metering algorithm [1], [31]. There are many researchers used ALINEA as the benchmark strategy to illustrate their study [8], [32]–[37].

TABLE 4. **OD distribution.**

Origin	Destination	Time Series																			
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
0	1	0.34	0.28	0.35	0.38	0.11	0.36	0.21	0.14	0.23	0.08	0.01	0.13	0.33	0.02	0.04	0.04	0.12	0.22	0.09	0.29
0	2	0.33	0.27	0.49	0.21	0.39	0.22	0.61	0.55	0.01	0.22	0.25	0.63	0.10	0.17	0.10	0.06	0.26	0.22	0.07	0.07
0	3	0.12	0.03	0.12	0.20	0.10	0.27	0.18	0.20	0.44	0.30	0.37	0.11	0.43	0.44	0.66	0.46	0.17	0.32	0.44	0.24
0	4	0.21	0.42	0.04	0.21	0.40	0.15	0.00	0.11	0.32	0.40	0.37	0.13	0.14	0.37	0.20	0.44	0.45	0.24	0.40	0.40
1	1	0.48	0.17	0.36	0.27	0.25	0.29	0.39	0.31	0.01	0.23	0.51	0.09	0.05	0.40	0.20	0.43	0.30	0.20	0.02	0.14
1	2	0.32	0.06	0.46	0.27	0.19	0.18	0.08	0.47	0.35	0.06	0.15	0.18	0.24	0.19	0.35	0.40	0.05	0.30	0.40	0.57
1	3	0.02	0.35	0.01	0.27	0.35	0.17	0.19	0.14	0.47	0.36	0.07	0.39	0.67	0.28	0.08	0.06	0.37	0.16	0.57	0.21
1	4	0.18	0.42	0.17	0.19	0.21	0.36	0.34	0.08	0.17	0.35	0.27	0.34	0.04	0.13	0.37	0.11	0.28	0.34	0.01	0.08
2	1	0.41	0.16	0.38	0.31	0.42	0.17	0.18	0.27	0.28	0.02	0.24	0.08	0.33	0.09	0.21	0.33	0.00	0.11	0.34	0.24
2	2	0.15	0.32	0.04	0.22	0.18	0.05	0.20	0.10	0.27	0.38	0.00	0.09	0.25	0.36	0.28	0.23	0.27	0.00	0.21	0.35
2	3	0.29	0.32	0.31	0.13	0.10	0.27	0.03	0.34	0.38	0.32	0.29	0.10	0.05	0.22	0.24	0.26	0.22	0.45	0.07	0.28
2	4	0.15	0.20	0.27	0.34	0.30	0.51	0.59	0.29	0.07	0.28	0.47	0.73	0.37	0.33	0.27	0.18	0.51	0.44	0.38	0.13
3	2	0.06	0.46	0.44	0.35	0.21	0.02	0.51	0.48	0.24	0.05	0.64	0.19	0.39	0.40	0.41	0.05	0.46	0.18	0.06	0.19
3	3	0.39	0.30	0.29	0.31	0.68	0.68	0.05	0.15	0.37	0.34	0.01	0.48	0.41	0.13	0.31	0.64	0.21	0.46	0.52	0.37
3	4	0.55	0.24	0.27	0.34	0.11	0.30	0.44	0.37	0.39	0.61	0.35	0.33	0.20	0.47	0.28	0.31	0.33	0.36	0.42	0.44
4	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 5. **Overview of network performance indicators. (a) Condition: Half of the flow. (b) Condition: 1 time flow. (c) Condition: 1.5 times flow.**

(a)

Scenario	**300s**				**600s**			
	TTS (%)	**TD (%)**	**TTD (%)**	**ADR (%)**	**TTS (%)**	**TD (%)**	**TTD (%)**	**ADR (%)**
No control	1838	1572	22926	247	1985	1718	22202	279
ALINEA	1769(-4)	1495(-5)	24146(5)	223(-10)	1999(1)	1727(1)	23201(4)	268(-4)
OD-QHM	916(-50)	619(-61)	25520(11)	87(-65)	1454(-27)	1155(-33)	24925(12)	167(-40)

(b)

Scenario	**300s**				**600s**			
	TTS (%)	**TD (%)**	**TTD (%)**	**ADR (%)**	**TTS (%)**	**TD (%)**	**TTD (%)**	**ADR (%)**
No control	2054	1781	23278	275	2142	1855	22790	293
ALINEA	1935(-6)	1662(-7)	23758(2)	252(-8)	2138(0)	1850(0)	23376(3)	285(-3)
OD-QHM	1572(-23)	1271(-29)	25702(10)	178(-35)	1829(-15)	1514(-18)	25213(11)	216(-26)

(c)

Scenario	**300s**				**600s**			
	TTS (%)	**TD (%)**	**TTD (%)**	**ADR (%)**	**TTS (%)**	**TD (%)**	**TTD (%)**	**ADR (%)**
No control	2100	1814	24311	269	2214	1906	24019	286
ALINEA	2022(-4)	1750(-4)	23720(-2)	266(-1)	2158(-3)	1863(-2)	23601(-2)	284(-1)
OD-QHM	1743(-17)	1439(-21)	25878(6)	200(-26)	1907(-14)	1578(-17)	25894(8)	219(-23)

It is also suitable to use ALINEA as the benchmark strategy in this study. Three parameters in ALINEA algorithm are calibrated according to the existing research [38]–[40]. The desired downstream occupancy is set to 0.20. Regulator parameter is set to 70 pcu/h. And the control cycle is set to 5 minutes. Evaluation indexes used are Total Time Spent (TTS) in hours, Total Delay (TD) in hours, Total Travel Distance (TTD) in kilometers and ADR in s/km.

TABLE 6. OD distribution (I).

Origin	Destination	Time Series																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	1	0.05	0.12	0.08	0.32	0.30	0.10	0.25	0.07	0.03	0.17	0.31	0.18	0.32	0.42	0.46	0.17	0.29	0.14	0.03	0.22
0	2	0.35	0.23	0.38	0.28	0.24	0.31	0.12	0.27	0.42	0.44	0.18	0.24	0.16	0.25	0.05	0.26	0.32	0.39	0.34	0.30
0	3	0.34	0.26	0.10	0.34	0.15	0.38	0.34	0.66	0.08	0.16	0.07	0.54	0.34	0.02	0.08	0.31	0.03	0.12	0.38	0.36
0	4	0.26	0.39	0.44	0.06	0.31	0.21	0.29	0.00	0.47	0.23	0.44	0.04	0.18	0.31	0.41	0.26	0.36	0.35	0.25	0.12
1	1	0.13	0.11	0.39	0.00	0.18	0.41	0.06	0.10	0.19	0.16	0.22	0.21	0.50	0.15	0.20	0.11	0.40	0.19	0.15	0.30
1	2	0.37	0.14	0.06	0.18	0.39	0.15	0.09	0.35	0.29	0.49	0.17	0.27	0.07	0.22	0.27	0.25	0.09	0.35	0.09	0.37
1	3	0.04	0.58	0.36	0.35	0.03	0.14	0.34	0.08	0.22	0.07	0.52	0.12	0.08	0.39	0.34	0.50	0.33	0.31	0.40	0.03
1	4	0.46	0.17	0.19	0.47	0.40	0.30	0.51	0.47	0.30	0.28	0.09	0.40	0.35	0.24	0.19	0.14	0.18	0.15	0.36	0.30
2	1	0.21	0.25	0.37	0.48	0.09	0.25	0.46	0.02	0.38	0.30	0.38	0.34	0.21	0.52	0.30	0.08	0.44	0.11	0.39	0.20
2	2	0.34	0.27	0.06	0.25	0.14	0.27	0.14	0.22	0.09	0.16	0.23	0.09	0.28	0.16	0.28	0.14	0.05	0.36	0.06	0.37
2	3	0.11	0.27	0.21	0.14	0.55	0.30	0.30	0.52	0.36	0.05	0.25	0.25	0.33	0.16	0.17	0.50	0.18	0.27	0.49	0.12
2	4	0.34	0.21	0.36	0.13	0.22	0.18	0.10	0.24	0.17	0.49	0.14	0.32	0.18	0.16	0.25	0.28	0.33	0.26	0.06	0.31
3	2	0.63	0.35	0.47	0.39	0.28	0.21	0.59	0.43	0.08	0.45	0.36	0.08	0.55	0.53	0.42	0.24	0.07	0.48	0.33	0.33
3	3	0.04	0.40	0.11	0.19	0.38	0.28	0.16	0.11	0.38	0.29	0.24	0.49	0.41	0.23	0.13	0.46	0.71	0.18	0.11	0.22
3	4	0.33	0.25	0.42	0.42	0.34	0.51	0.25	0.46	0.54	0.26	0.40	0.43	0.02	0.24	0.45	0.30	0.22	0.34	0.56	0.45
4	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Since the influence of warm-up time on the control initial state, cases of 300 s warm-up time and 600s warm-up time are given in this study. The initial traffic condition of 300 s warm-up time is better than that of 600 s warm-up time. Because control algorithm has different effects in different traffic demand cases, this study conducted simulations in three traffic demand cases. Based on the flow data in Figure 7 and the OD distribution in Table 4, simulations under half of the flow condition, 1 time flow condition and 1.5 times flow condition were conducted. Results are shown in Table 5. Compared with the uncontrolled case, the number in parenthesis is the change percentage of the corresponding indicator.

As shown in Table 5, TTS and TD under the OD-QHM are obviously lower than that of ALINEA in these conditions. Moreover, the two parameters of OD-QHM under lower flow and 300s warm up time are lower than other conditions.

Under the ALINEA, the increase of TTD value is very limited and there is a slightly decrease when the flow is high. The TTD index of OD-QHM is better than that of ALINEA. It indicates that OD-QHM algorithm can effectively improve the throughput of expressway. This corresponds well with the traffic demand of rush hour.

The ADR index of OD-QHM is better than that of ALINEA. In addition, the ADR index of both algorithms under lower flow and 300s warm up time are lower than other conditions.

Noted that the effect of ramp metering algorithms should be judged synthetically according to various indexes rather than single index. A better ramp metering algorithm should make the TTD higher as well as make the TTS, TD, and ADR lower. In general, the control effect of OD-QHM is significantly better than that of ALINEA under 6 different combinations of warm-up time and flow. When the warm-up time is 300 s, both using the two control algorithms can effectively reduce delay. It indicates that conducting on-ramp metering before bottleneck breakdown can improve the control effect. Under the low traffic demand condition, the effects of the two control algorithms are good. Improvement effects of both algorithms are reduced with the increase of traffic demand. The improvement effect of ALINEA decreases rapidly, whereas the OD-QHM still has considerable improvement effect. It shows the OD-QHM algorithm is stable. To reduce the contingency, simulations under different OD distributions are carried out in this study. The results of these cases are consistent with each other. Three of these cases are shown in Appendix. Therefore, it is feasible to apply real-time OD information of on-ramp vehicles to CRM.

VI. CONCLUSION

The OD-QHM algorithm is proposed based on the QHM framework and real-time OD information. In the IoV environment, the use of real-time OD information will eliminate the time-space limitation in traditional traffic control. The control algorithm not only settle the current bottleneck breakdown, but also prevent congestion in a short time. Simulation results indicate that the validity and stability of the OD-QHM algorithm are superior to the widely used ALINEA algorithm. Therefore, it is feasible to introduce real-time OD information

TABLE 7. OD distribution (II).

Origin	Destination	Time Series																			
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
0	1	0.24	0.72	0.05	0.35	0.34	0.02	0.18	0.38	0.17	0.48	0.33	0.26	0.48	0.18	0.26	0.29	0.39	0.08	0.27	0.34
0	2	0.31	0.18	0.33	0.09	0.51	0.26	0.31	0.12	0.28	0.23	0.19	0.24	0.08	0.00	0.27	0.66	0.31	0.42	0.25	0.29
0	3	0.23	0.09	0.33	0.27	0.09	0.22	0.25	0.14	0.15	0.21	0.18	0.40	0.31	0.35	0.33	0.01	0.15	0.07	0.19	0.16
0	4	0.22	0.01	0.29	0.29	0.06	0.50	0.26	0.36	0.40	0.08	0.30	0.10	0.13	0.47	0.14	0.04	0.15	0.43	0.29	0.21
1	1	0.13	0.15	0.02	0.39	0.14	0.19	0.04	0.28	0.21	0.10	0.12	0.38	0.01	0.24	0.13	0.37	0.02	0.15	0.05	0.09
1	2	0.36	0.25	0.65	0.07	0.37	0.10	0.44	0.26	0.18	0.25	0.15	0.08	0.07	0.74	0.19	0.29	0.36	0.12	0.35	0.18
1	3	0.14	0.20	0.24	0.38	0.19	0.35	0.51	0.20	0.12	0.30	0.39	0.19	0.76	0.01	0.24	0.26	0.43	0.29	0.35	0.36
1	4	0.37	0.40	0.09	0.16	0.30	0.36	0.01	0.26	0.49	0.35	0.34	0.35	0.16	0.01	0.44	0.08	0.19	0.44	0.25	0.37
2	1	0.22	0.09	0.32	0.13	0.04	0.25	0.16	0.07	0.36	0.11	0.14	0.25	0.06	0.08	0.51	0.41	0.12	0.02	0.33	0.06
2	2	0.42	0.38	0.30	0.40	0.43	0.09	0.37	0.15	0.11	0.04	0.17	0.10	0.13	0.33	0.37	0.42	0.29	0.41	0.05	0.22
2	3	0.31	0.46	0.00	0.10	0.22	0.41	0.36	0.36	0.15	0.17	0.10	0.35	0.64	0.21	0.11	0.08	0.13	0.24	0.35	0.37
2	4	0.05	0.07	0.38	0.37	0.31	0.25	0.11	0.42	0.38	0.68	0.59	0.30	0.17	0.38	0.01	0.11	0.46	0.33	0.27	0.35
3	2	0.01	0.39	0.26	0.62	0.30	0.10	0.37	0.24	0.43	0.44	0.45	0.37	0.44	0.16	0.22	0.05	0.33	0.39	0.58	0.38
3	3	0.02	0.36	0.45	0.31	0.13	0.03	0.25	0.50	0.28	0.49	0.48	0.18	0.53	0.11	0.42	0.67	0.24	0.32	0.15	0.03
3	4	0.97	0.25	0.29	0.07	0.57	0.87	0.38	0.26	0.29	0.07	0.07	0.45	0.03	0.73	0.36	0.28	0.43	0.29	0.27	0.59
4	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 8. OD distribution (III).

Origin	Destination	Time Series																			
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
0	1	0.16	0.26	0.08	0.21	0.07	0.39	0.26	0.18	0.06	0.05	0.19	0.41	0.05	0.89	0.18	0.16	0.33	0.30	0.15	0.28
0	2	0.12	0.06	0.28	0.48	0.33	0.33	0.46	0.41	0.21	0.02	0.43	0.01	0.31	0.00	0.23	0.29	0.62	0.06	0.41	0.42
0	3	0.18	0.42	0.38	0.12	0.04	0.07	0.20	0.07	0.51	0.67	0.02	0.30	0.21	0.04	0.33	0.28	0.01	0.32	0.44	0.26
0	4	0.54	0.26	0.26	0.19	0.56	0.21	0.08	0.34	0.22	0.26	0.36	0.28	0.43	0.07	0.26	0.27	0.04	0.32	0.00	0.04
1	1	0.18	0.10	0.12	0.12	0.10	0.26	0.25	0.08	0.14	0.15	0.36	0.41	0.21	0.33	0.30	0.21	0.01	0.29	0.15	0.26
1	2	0.69	0.01	0.29	0.44	0.11	0.39	0.14	0.18	0.25	0.15	0.02	0.46	0.19	0.27	0.41	0.41	0.07	0.36	0.10	0.29
1	3	0.12	0.51	0.27	0.38	0.32	0.05	0.21	0.51	0.35	0.29	0.35	0.02	0.35	0.20	0.25	0.35	0.47	0.18	0.39	0.23
1	4	0.01	0.38	0.32	0.06	0.47	0.30	0.40	0.23	0.26	0.41	0.27	0.11	0.25	0.20	0.04	0.03	0.45	0.17	0.36	0.22
2	1	0.30	0.33	0.03	0.24	0.17	0.24	0.31	0.14	0.16	0.31	0.26	0.24	0.32	0.17	0.33	0.43	0.38	0.23	0.10	0.24
2	2	0.31	0.17	0.37	0.02	0.22	0.44	0.24	0.35	0.41	0.21	0.15	0.34	0.49	0.32	0.13	0.14	0.08	0.38	0.29	0.20
2	3	0.33	0.49	0.51	0.43	0.29	0.03	0.08	0.07	0.40	0.33	0.18	0.05	0.10	0.14	0.23	0.25	0.34	0.17	0.48	0.19
2	4	0.06	0.01	0.09	0.31	0.32	0.29	0.37	0.44	0.03	0.15	0.41	0.37	0.09	0.37	0.31	0.18	0.20	0.22	0.13	0.37
3	2	0.13	0.00	0.40	0.41	0.15	0.71	0.07	0.30	0.15	0.72	0.15	0.27	0.40	0.11	0.18	0.41	0.59	0.01	0.36	0.33
3	3	0.41	0.72	0.28	0.14	0.14	0.22	0.34	0.27	0.37	0.06	0.76	0.42	0.42	0.53	0.28	0.38	0.14	0.78	0.36	0.05
3	4	0.46	0.28	0.32	0.45	0.71	0.07	0.59	0.43	0.48	0.22	0.09	0.31	0.18	0.36	0.54	0.21	0.27	0.21	0.28	0.62
4	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

into traffic control. How to use the real-time OD information will become a new research hotspot in traffic control area.

It is obvious that pure OD information cannot represent all system information. This paper is only a preliminary study on the application of real-time OD information in CRM. Other factors remain the same in this study for convenience. The equation used to determine ramp flow priority is from simple generalization. Our follow-up study will improve the OD-QHM algorithm by taking other factors into account. Furthermore, the vehicles releasing in the same control period arrive

TABLE 9. Overview of network performance indicators (I). (a) Condition: Half of the flow. (b) Condition: 1 time flow. (c) Condition: 1.5 times flow.

(a)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2003	1731	23438	266	2005	1728	23592	264
ALINEA	1409(-30)	1124(-35)	25247(8)	160(-40)	1793(-11)	1512(-13)	24494(4)	222(-16)
OD-QHM	779(-61)	488(-72)	25138(7)	70(-74)	1394(-30)	1111(-36)	24013(2)	167(-37)

(b)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2233	1959	23404	301	2325	2051	22487	328
ALINEA	1820(-18)	1532(-22)	25245(8)	219(-27)	2200(-5)	1917(-7)	23993(7)	288(-12)
OD-QHM	1183(-47)	881(-55)	25838(10)	123(-59)	1945(-16)	1646(-20)	24691(10)	240(-27)

(c)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2266	1977	24758	287	2355	2062	23838	311
ALINEA	1886(-17)	1606(-19)	24534(-1)	236(-18)	2211(-6)	1930(-6)	23543(-1)	295(-5)
OD-QHM	1181(-48)	865(-56)	26957(9)	116(-60)	1975(-16)	1671(-19)	24907(4)	242(-22)

TABLE 10. Overview of network performance indicators (II). (a) Condition: Half of the flow. (b) Condition: 1 time flow. (c) Condition: 1.5 times flow.

(a)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	1826	1571	21961	258	1827	1584	20435	279
ALINEA	1620(-11)	1364(-13)	22684(3)	216(-16)	1824(0)	1576(0)	21479(5)	264(-5)
OD-QHM	1225(-33)	966(-39)	22420(2)	155(-40)	1225(-33)	966(-39)	22420(10)	155(-44)

(b)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2125	1850	23442	284	2173	1889	23018	295
ALINEA	1889(-11)	1626(-12)	23156(-1)	253(-11)	2034(-6)	1768(-6)	22189(-4)	287(-3)
OD-QHM	1480(-30)	1198(-35)	24137(3)	179(-37)	1668(-23)	1385(-27)	22968(0)	217(-26)

(c)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2156	1867	24596	273	2240	1936	24288	287
ALINEA	1874(-13)	1618(-13)	22355(-9)	261(-4)	2029(-9)	1756(-9)	22188(-9)	285(-1)
OD-QHM	1499(-30)	1211(-35)	24548(0)	178(-35)	1687(-25)	1395(-28)	23283(-4)	216(-25)

the bottleneck in different time due to the distance between on-ramps. It is also necessary to consider this problem in future studies.

APPENDIX

Table 6, Table 7 and Table 8 are the OD distribution used in different simulations. Table 9, Table 10 and Table 11 are the

TABLE 11. Overview of network performance indicators (III). (a) Condition: Half of the flow. (b) Condition: 1 time flow. (c) Condition: 1.5 times flow.

(a)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	1913	1644	23200	255	1932	1659	23206	257
ALINEA	1496(-22)	1221(-26)	24275(5)	181(-29)	1606(-17)	1320(-20)	24844(7)	191(-26)
OD-QHM	1046(-45)	763(-54)	24350(5)	113(-56)	1178(-39)	894(-46)	24092(4)	134(-48)

(b)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2252	1991	22321	321	2343	2071	21840	341
ALINEA	1764(-22)	1494(-25)	23613(6)	228(-29)	2189(-7)	1901(-8)	23781(9)	288(-16)
OD-QHM	1451(-36)	1148(-42)	25881(16)	160(-50)	1917(-18)	1610(-22)	24910(14)	233(-32)

(c)

Scenario	300s				600s			
	TTS (%)	TD (%)	TTD (%)	ADR (%)	TTS (%)	TD (%)	TTD (%)	ADR (%)
No control	2303	2016	24412	297	2344	2049	23632	312
ALINEA	1794(-22)	1523(-24)	23671(-3)	232(-22)	2271(-3)	1990(-3)	23229(-2)	308(-1)
OD-QHM	1550(-33)	1249(-38)	25645(5)	175(-41)	1858(-21)	1545(-25)	25242(7)	220(-29)

network performance indicators under the OD distributions in Table 6, Table 7 and Table 8.

ACKNOWLEDGMENT

We thank the Research Center of Intelligent Transportation, University of Alberta for providing us with valuable data on Whitemud Drive.

REFERENCES

[1] M. Papageorgiou and A. Kotsialos, "Freeway ramp metering: An overview," *IEEE Trans. Intell. Transp. Syst.*, vol. 3, no. 4, pp. 271–281, Apr. 2002.
[2] X. B. Qu, J. Zhang, and S. A. Wang, "On the stochastic fundamental diagram for freeway traffic: Model development, analytical properties, validation, and extensive applications," *Transp. Res. B, Methodol.*, vol. 104, pp. 256–271, Oct. 2017.
[3] K. Chung, J. Rudjanakanoknad, and M. J. Cassidy, "Relation between traffic density and capacity drop at three freeway bottlenecks," *Transp. Res. B, Methodol.*, vol. 41, no. 1, pp. 82–95, 2007.
[4] L. Leclercq, J. A. Laval, and N. Chiabaut, "Capacity drops at merges: An endogenous model," *Transp. Res. B, Methodol.*, vol. 45, no. 9, pp. 1302–1313, Nov. 2011.
[5] J. C. Muñoz and C. F. Daganzo, "The bottleneck mechanism of a freeway diverge," *Transp. Res. A, Policy Pract.*, vol. 36, no. 6, pp. 483–505, Jul. 2002.
[6] M. J. Cassidy, "Freeway on-ramp metering, delay savings, and diverge bottleneck," *Transp. Res. Rec.*, vol. 1856, pp. 1–5, Jan. 2003.
[7] A. Dabiri and B. Kulcsár, "Distributed ramp metering—A constrained discharge flow maximization approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 9, pp. 2525–2538, Sep. 2017.
[8] Z. Li, C. Xu, D. Li, P. Liu, and W. Wang, "Comparing the effects of ramp metering and variable speed limit on reducing travel time and crash risk at bottlenecks," *IET Intell. Transp. Syst.*, vol. 12, no. 2, pp. 120–126, Mar. 2018.
[9] G. Zhang and Y. Wang, "Optimizing coordinated ramp metering: A preemptive hierarchical control approach," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 28, no. 1, pp. 22–37, 2013.
[10] R. C. Carlson, I. P. M. Papamichail, and A. Messmer, "Optimal mainstream traffic flow control of large-scale motorway networks," *Transp. Res. C, Emerg. Technol.*, vol. 18, no. 2, pp. 193–212, 2010.
[11] R. C. Carlson, I. Papamichail, and M. Papageorgiou, "Local feedback-based mainstream traffic flow control on motorways using variable speed limits," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1261–1276, Dec. 2011.
[12] Y. Kan, Y. Wang, M. Papageorgiou, and I. Papamichail, "Local ramp metering with distant downstream bottlenecks: A comparative study," *Transp. Res. C, Emerg. Technol.*, vol. 62, pp. 149–170, Jan. 2016.
[13] Y. Han, A. Hegyi, Y. Yuan, S. Hoogendoorn, M. Papageorgiou, and C. Roncoli, "Resolving freeway jam waves by discrete first-order model-based predictive control of variable speed limits," *Transp. Res. C, Emerg. Technol.*, vol. 77, pp. 405–420, Apr. 2017.
[14] P. Goatin, S. Göttlich, and O. Kolb, "Speed limit and ramp meter control for traffic flow networks," *Eng. Optim.*, vol. 48, no. 7, pp. 1121–1144, Jul. 2016.
[15] M. Zhou, X. Qu, and S. Jin, "On the impact of cooperative autonomous vehicles in improving freeway merging: A modified intelligent driver model-based approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 6, pp. 1422–1428, Jun. 2017.
[16] J. R. D. Frejo and E. F. Camacho, "Global versus local MPC algorithms in freeway traffic control with ramp metering and variable speed limits," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1556–1565, Dec. 2012.
[17] L. Y. Chu, H. X. Liu, W. Recker, and H. M. Zhang, "Performance evaluation of adaptive ramp-metering algorithms using microscopic traffic simulation model," *J. Transp. Eng.*, vol. 130, no. 3, pp. 330–338, May 2004.
[18] R. L. Landman, A. Hegyi, and S. P. Hoogendoorn, "Coordinated ramp metering based on on-Ramp saturation time synchronization," *Transp. Res. Rec.*, vol. 2484, pp. 50–59, Jan. 2015.
[19] A. Kotsialos, M. Papageorgiou, M. Mangeas, and H. Haj-Salem, "Coordinated and integrated control of motorway networks via non-linear optimal control," *Transp. Res. C, Emerg. Technol.*, vol. 10, no. 1, pp. 65–84, Feb. 2002.

[20] I. Papamichail, A. Kotsialos, I. Margonis, and M. Papageorgiou, "Coordinated ramp metering for freeway networks—A model-predictive hierarchical control approach," *Transp. Res. C, Emerg. Technol.*, vol. 18, no. 3, pp. 311–331, Jun. 2010.

[21] A. Ferrara, A. N. Oleari, S. Sacone, and S. Siri, "Freeways as systems of systems: A distributed model predictive control scheme," *IEEE Syst. J.*, vol. 9, no. 1, pp. 312–323, Mar. 2015.

[22] L. N. Jacobson, K. C. Henry, and O. Mehyar, "Real-time metering algorithm for centralized control," *Transp. Res. Rec.*, vol. 17, no. 5, pp. 17–26, 1989.

[23] L. E. Lipp, L. J. Corcoran, and G. A. Hickman, "Benefits of central computer control for Denver ramp-metering system," *Transp. Res. Rec.*, vol. 1320, no. 1320, pp. 3–6, 1991.

[24] G. Paesani, J. Kerr, P. Perovich, and F. Khosravi, "System wide adaptive ramp metering (SWARM)," in *Proc. 7th Annu. Meeting Expo. ITS Amer.*, Washington, DC, USA, 1997.

[25] Y. J. Stephanedes, "Implementation of on-line zone control strategies for optimal ramp metering in the Minneapolis ring road," in *Proc. 7th Int. Conf. Road Traffic Monitor. Control*, London, U.K., 1994, pp. 181–184.

[26] J. L. M. Vrancken, Y. B. Wang, and J. H. van Schuppen, "QHM: The quantitative hierarchical model for network-level traffic management," in *Proc. 16th Int. IEEE Conf. Intell. Transp. Syst.*, The Hague, The Netherlands, Oct. 2013, pp. 223–230.

[27] A. Meshkat, M. Zhi, J. L. M. Vrancken, A. Verbraeck, Y. Yuan, and Y. B. Wang, "Coordinated ramp metering with priorities," *IET Intell. Transp. Syst.*, vol. 9, no. 6, pp. 639–645, Aug. 2015.

[28] H. Z. Tu, Y. Wang, and X. R. Xie, "Control priorities of coordinated on-ramps metering based on quantitative hierarchical model," *J. Tongji Univ. (Natural Sci.)*, vol. 45, no. 1, pp. 39–45 and 52, Jan. 2017.

[29] D. Helbing, A. Hennecke, V. Shvetsov, and M. Treiber, "Micro-and macro-simulation of freeway traffic," *Math. Comput. Model.*, vol. 35, no. 5, pp. 517–547, Mar. 2002.

[30] H. Tu, H. Li, Y. Wang, and L. Sun, "When to control the ramps on freeway corridors? A novel stability-and-MFD-based approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 6, pp. 2572–2582, Dec. 2014.

[31] M. Papageorgiou, H. S. Habib, and F. Middleham, "ALINEA local ramp metering: Summary of field results," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1603, pp. 90–98, Jan. 1997.

[32] A. Kotsialos, M. Papageorgiou, and F. Middelham, "Local and optimal coordinated ramp metering for freeway networks," *J. Intell. Transp. Syst.*, vol. 9, no. 4, pp. 187–203, Oct. 2005.

[33] I. Papamichail and M. Papageorgiou, "Traffic-responsive linked ramp-metering control," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 1, pp. 111–121, Mar. 2008.

[34] D. Zhao, X. Bai, F. Wang, and J. Xu, "DHP method for ramp metering of freeway traffic," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 990–999, Dec. 2011.

[35] N. Bhouri, H. Haj-Salem, and J. Kauppila, "Isolated versus coordinated ramp metering: Field evaluation results of travel time reliability and traffic impact," *Transp. Res. C, Emerg. Technol.*, vol. 28, pp. 155–167, Mar. 2013.

[36] Y. Wang, E. B. Kosmatopoulos, M. Papageorgiou, and I. Papamichail, "Local ramp metering in the presence of a distant downstream bottleneck: Theoretical analysis and simulation study," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2024–2039, Oct. 2014.

[37] F. Belletti, D. Haziza, G. Gomes, and A. M. Bayen, "Expert level control of ramp metering based on multi-task deep reinforcement learning," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 4, pp. 1198–1207, Apr. 2018.

[38] M. Papageorgiou, H. Hadj-Salem, and J. M. Blosseville, "ALINEA: A local feedback control law for on-ramp metering," *Transp. Res. Rec.*, vol. 1320, no. 1, pp. 58–64, 1991.

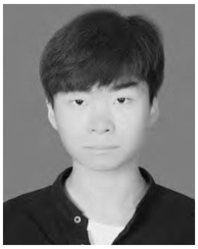
[39] X. Yang, L. Y. Chu, and W. Recker, "GA-based parameter optimization for the ALINEA ramp metering control," in *Proc. 5th Int. IEEE Conf. Intell. Transp. Syst.*, Singapore, Oct. 2002, pp. 627–632.

[40] M. Papageorgiou, E. Kosmatopoulos, I. Papamichail, and Y. Wang, "A misapplication of the local ramp metering strategy ALINEA," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 2, pp. 360–365, Jun. 2008.

YONGHENG CHEN received the B.S. degree in civil engineering and the Ph.D. degree in traffic information engineering and control from Jilin University, China, where he is currently an Associate Professor with the School of Transportation. His research interests include traffic control, traffic flow theory, and traffic organization.

FANGHONG LIU received the B.S. degree in traffic engineering from Jilin University, China, where she is currently pursuing the M.S. degree with the School of Transportation. Her research interests include traffic control on urban expressway, traffic safety, and traffic organization.

QIAOWEN BAI received the B.S. degree in traffic engineering from Jilin University, China, where he is currently pursuing the Ph.D. degree. His research interests include traffic flow theory, traffic control, traffic organization, and traffic big data.



CHUQING TAO received the B.S. degree in traffic engineering from Jilin University, China, where he is currently pursuing the M.S. degree with the School of Transportation. His research interests include traffic flow theory and traffic forecast on urban expressway.

XINGZU QI received the B.S. degree in traffic engineering from Jilin University, China, where he is currently pursuing the M.S. degree with the School of Transportation. His research interests include traffic organization, traffic control, and traffic forecast.

• • •