Investigating the Impacts of Fixed-Time Ramp Metering through Microsimulation

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Abstract: Ramp metering is an effective strategy used to manage highway traffic by regulating the on-ramp traffic flow in order to avoid traffic congestion on highway networks. This study aims to investigate the impacts of fixed-time ramp metering on operational characteristics of highway networks via microscopic simulation. A fixed-time ramp meter is modelled for a highway section using Aimsun micro simulator and the traffic condition is evaluated under two ramp control scenarios: no-control and time-of-day metering plan. Three metering plans including one-car-per green, 2-vehicle-platoon releasing and 3-vehicle-platoon releasing are developed for peak and off-peak periods. The results show that ramp metering improves the highway performance, especially at peak hour. However, it leads to serious issues for the ramp and consequently for the entire system.

Keywords: Ramp Metering, Ramp Control, Microsimulation, Aimsun

1. INTRODUCTION

Ramp metering is an effective and practical strategy utilised to manage highway traffic. It is widely recognised as an efficient highway management strategy to avoid or reduce traffic congestion by limiting access to highways. Ramp metering has received emphasis in recent years due to some successful implementations and it is currently being used in numerous cities all over the world.

Ramp metering is able to improve the whole network operation. It can restrict the total flow entering highways by temporarily storing some traffic on the ramps to ensure that the highway is operated within its capacity and prevent congestion. Moreover, it breaks up platoons of vehicles entering highways in order to facilitate their merging to the highway flow. This effect improved the safety by reducing the conflicts between the entering vehicles to the highway and the mainline flow. Furthermore, ramp metering diverts some vehicles to other routes because of the waiting time on the ramps and consequently, it can reduce demand going to highways.

A ramp meter is a traffic signal installed on entering ramps in order to regulate the traffic flow to the freeway. In theory, a vehicle is given a green light and allowed to enter the highway by taking the existing gaps in the highway traffic flow. Therefore, the bottleneck and delay resulted by a platoon of vehicles which compete for the existing gaps are avoided. However, in reality there is the risk of shifting the bottleneck to the ramp. In fact, the highway performance is improved at the cost of imposing delay to the ramp users. Therefore, it seems essential to assess the impacts of such a strategy on each network component individually, as well as on the entire system in order to take appropriate decisions.

The success or failure of traffic management strategies is case-dependent. While a measure, like ramp metering, is successfully implemented in a number of cases, it may cause severe issues for some other cases. Ramp metering strategies are different in operation and implantation, not all of them are effective measures for all cases. Generally, traffic management policies are tested through either limited implementation or simulation. The latter approach has drawn the attention of planners in the recent years due to its numerous advantages. Traffic simulation is less time consuming and more economical compared to the real-world implementation for the purpose of assessing various traffic management measures. That is why this approach is increasingly being used by planners to assess traffic management measures under different scenarios.

This study intends to investigate the probable impacts of ramp metering on an urban highway section via microscopic simulation. The structure of this paper is as follows. First, we explain the methodology of this study. Then, we present the classification of ramp metering strategies, as well as the principles of the fixed-time ramp metering, which is the focus of this study. Afterwards, we apply various ramp metering plans to a case study and analyse their impacts using a microsimulation model. A detailed discussion is also presented in the rest of the paper on the effects of the selected ramp control plans.

2. MATERIALS AND METHODS

In this study, we intend to assess the effectiveness of ramp metering on a highway section comprising an on-ramp. The site is selected from Tehran's highway network, where ramp metering has not been implemented yet. Since the selected highway network is not completely equipped with traffic detectors, the real-time traffic data were not available for traffic-responsive ramp metering. Therefore, fixed-time metering approach is considered for the purpose of this research and the required data were collected by observation. The site specification and data collection will be presented in the following sections.

The Aimsun microsimulation (TSS, 2009) is also employed in this study in order to model the intended ramp metering scenarios. This software is a widely-used and powerful traffic simulation package equipped with a toolbox for ramp metering. In order to investigate the impacts of ramp metering, we simulated the site under two major scenarios: un-controlled ramp (the existing situation) and metered-ramp. It should be noted that the model parameters are adjusted so that the simulation model reasonably represents the site situation. Since the metering rate (i.e. the number of vehicles allowed to enter the highway via ramp) plays an important role in ramp metering, we selected three metering plans on the basis of different vehicle-releasing patterns and metering rates. We chose the key operational parameters, including mean delay time, total travel time, queue length, density and mean speed, as measures of effectiveness (MOEs) in order to investigate the impacts of these plans. We analysed the scenarios for two periods (peak and off-peak) to examine the efficiency of ramp metering under different circumstances.

3. LITERATURE REVIEW

Ramp metering limits the number of vehicles entering highways by utilising a pulsing meter at on-ramps. While the philosophy is the same for all ramp metering methods, there are different types of ramp metering corresponding to their regulations and their area of control. Based on the operational mode, ramp metering can be classified into two classes: fixed-time and traffic responsive.

Fixed-time (or pre-timed) control uses a metering rate that is fixed during the planning period regardless to the variation of traffic within the planning period. In other words, Pre-timed control systems use time-of-day (TOD) metering rates which are pre-determined in order to manage expected conditions according to an analysis of historical data. In contrast, traffic-responsive control determines a metering rate based on real-time traffic information collected by detectors. Ramp metering strategies can also be categorised according to the area of application. Local traffic responsive control specifies metering rates based on the existing traffic conditions in the vicinity of the ramp. Coordinated responsive control determines metering rates based in the traffic conditions of a more extended section of the network (Chu *et al.,* 2009). Although the concept seems good, this system still experiences difficulties in terms of implementation due to technological problems in communication between street and highway systems (Sarintorn, 2007).

A variety of ramp metering algorithms have been proposed in the literature so far, such as optimisation techniques, automatic control, optimal control theory or artificial intelligence methods. There have been significant theoretical developments in ramp metering strategies. However, implementations of ramp metering based on these developments have been growing slowly (Chu *et al.*, 2009). Since this study aims to examine the fixed-time ramp metering, this type is addressed here in more details.

Fixed-time ramp metering strategies are derived off-line for specific times of day according to constant historical demands, without using real-time traffic data. These strategies are based on simple static models. A highway with several ramps is divided into sections. Therefore, the mainline flow of each section can be determined by the following equation (Hall, 2003):

$$q_j = \sum_{i=1}^{j} \alpha_{ij} \, r_i \qquad (1)$$

Where, q_j is the mainline flow of section j, r_i is the entering volume of section i and $\alpha_{ij} \in [0,1]$ expresses the known portion of vehicles that enter the freeway in section i and do not exit the freeway upstream of section j. The following inequality must be held in order to avoid congestion:

$$q_{(j)} \leq q_{(capj)} \qquad (2)$$

Where, q_{capj} is the capacity of section j. Furthermore, another constraint is:

$$r_{j(min)} \leq r_j \leq \min \{r_{j(max)} \ and \ d_j\} \qquad (3)$$

Where, d_j is the demand on the entering ramp j.
As an objective, it can be wished to maximise the number of served vehicles, which is equivalent to minimising the total spent time. Therefore (Hall, 2003):

$$\sum_j r_j \rightarrow Max \qquad (4)$$

Or, to maximise the total travel distance

$$\sum_j \Delta_j \, q_j \rightarrow Max \qquad (5)$$

Where, Δ_j is the length of section j. Hence, to balance the ramp queues

$$\sum_j (d_j - r_j)^2 \to Min \tag{6}$$

These formulations result in linear programming or quadratic programming problems and can be used through optimisation techniques.

Fixed-time ramp metering strategies may lead to either overload of the mainstream flow (congestion) due to the absence of real-time measurement or under-utilisation of the freeway (Hall, 2003). In fact, ramp metering is efficient but sensitive to the control measure. If the control measure (i.e. metering rate) is not accurate enough, either congestion may be inevitable or the mainstream capacity might be underutilised. Thus, metering rate play a significant role in the fixed-time ramp metering.

The capacity and traffic flow at metered ramps are influenced by practical limits of the upper and lower metering rates. Arnold (1998) addresses that there is a minimum reasonable cycle length of 4 seconds, including 2.5 seconds for red (or red plus yellow) and 1.5 seconds for green. Hence, the maximum volume of a single metered lane is around 900 vph (3600 seconds per hour divided by 4). If two vehicles are allowed per green, the minimum cycle length should be increased to around 6 or 6.5 seconds. In this case, the maximum volume becomes 1100 to 1200 vph. Arnold (1998) also mentions that widening the ramp to two or more lanes at the meter and allowing one or two vehicles per lane per green is another technique utilised at high-volume ramps. The maximum volume on a ramp with two lanes and one vehicle releasing per lane is around 1800 vph. However, this rate can be increased by adding more lanes and releasing more than one auto per green. Practical experiences have shown that a 15-second cycle length is the maximum wait that motorists will tolerate before occurring significant violations. Accordingly, the minimum volume for that ramp metering is suitable is around 240 vph (FHWA, 1995).

It should be noted that there are two patterns of ramp entry modes for all types of ramp metering: *one-car-per-green metering (OCPG)* and *platoon metering.* In the OCPG pattern, one vehicle per cycle per lane is permitted to enter the highway and the metering rate varies from 3 to 15 cars per minute. The metering cycle in such pattern varies from 4 to 20 seconds. Assuming that the typical green time is 2 seconds, the remaining cycle interval is red time varying from 2 to 18 seconds. In the platoon metering, however, two to three vehicles per cycle per lane are allowed to enter the highway per green. Typically, platoon metering is used where more entering volumes are needed.

As mentioned earlier, simulation has recently become as a powerful tool to study and evaluate the performance of traffic management plans. Since macroscopic and mesoscopic simulation methods are based on traffic flow models with theoretical limitations, they are not capable to simulate the interrupted flow, such as complex on-ramp merging behaviour and weaving. However, microscopic simulation avoids such problems by considering individual vehicle movements in discrete time period based on vehicle-to-vehicle interactions. Hence, this approach is more appropriate for evaluating the performance of ramp metering strategies (Beegala *et al.,* 2005).

A number of studies have been conducted to study the effectiveness of ramp metering strategies by computer simulation. Several types of simulation packages have also been used to develop the models. In a research using INTEGRATION as the simulation tool, it was discovered that total network travel time reduced slightly after ramp metering under the absence of diversion of the vehicles (Khoo *et al.*, 2005). Chen et al (1997) used MITSIMLab for evaluation of the effectiveness of ramp metering operation. They compared the performance of an area-wide control of ramp metering. Khoo et al. (2005) address some more simulation packages used so far to study the effectiveness of ramp metering, like

PARAMICS, MITSIM and METANET. Ruijgers & Berkum (2005) discuss that a through comparison of simulation results with field data show that lane changing and merging behaviour in AIMSUN is acceptable to model merging behaviour on on-ramps.

4. SITE SPECIFICATION AND DATA COLLECTION

In order to investigate the impacts of fixed-time ramp metering, a highway section was selected in Tehran's highway network. The site is a 400m-section of Niyayesh highway, including an entering ramp from Saadat Abad Blvd to the highway (Figure 1).

Figure 1. The selected site

The selected highway is an E-W highway, playing an important role in the metropolitan road network. It has four 3.3m lanes in each direction, with the speed limit of 110 km/h. The on-ramp connects Saadat Abad Blvd, which is an important N-S arterial, to the highway. It is an one-lane ramp which is 4.5 m wide with the speed limit of 60 km/h. It ends at a 70m taper that facilitates the merging of the ramp flow with the mainstream. Currently, this ramp is not controlled and the ramp flow can enter the highway without any restriction. Since both of the highway and the entering ramp are experiencing huge traffic volumes, particularly at peak hours, this site was chosen to assess the ramp metering impacts. The selected site is not influenced by other entrances and exits.

The preliminary evaluations of the site revealed that the most critical situations occur during the afternoon peak periods, when most commuters travel from west to east. Hence, the required data were collected over a three-hour period from 15:00 to 18:00 in order to cover both the inter-peak and the peak hours. The travel volumes were recorded in 15-minute intervals. Different types of vehicles were also considered to reflect the impact of heavy vehicles. Based on the data, the percentage of heavy vehicles varied between 0.4- 1.6%. Figure 2 illustrates the variation of traffic volumes at the ramp and the highway. The accumulation of the 15-min traffic volumes showed that the 16:30-17:30 is the peak period for both the highway section and the ramp.

5. MEASURES OF EFFECTIVENESS

Performance of ramp metering strategies can be assessed through measuring a number of objectives. Despite a variety of operational factors, some certain parameters are typically

considered by professionals to evaluate the effectiveness of ramp metering. Table 1 presents the summary of such factors. Depending on the evaluation objective, generally one or more of these factors are selected in order to evaluate the performance of the selected ramp metering method (Beegala et al. 2005).
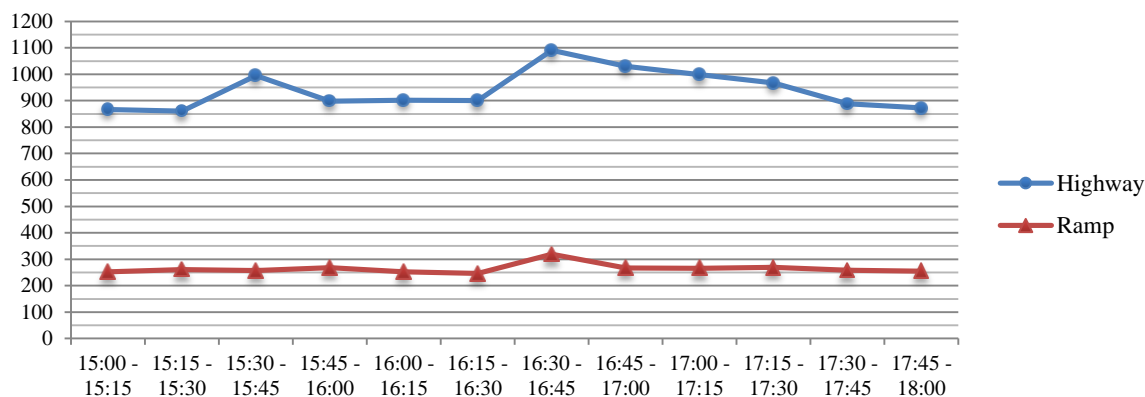

Figure 2. Variation of traffic volumes at the site (PCU)

Table 1. Typical measures of effectiveness for ramp metering plans

Objectives	MOEs	
Efficiency and Equity	Total System Delay	Total Mainline Delay
	Total Ramp Delay	Average Mainline Speed
	Mainstream Travel Time	Freeway Throughput
	Total Time Reliability	Total Travel Distance
	Mean Congestion Duration	
	Total Time Spent (Total Ramp Delay + Total Travel time on the mainstream)	
Safety	Accident Rate	Total Number of Stops
Environmental Impact	Pollutant Emissions	Fuel Consumption

Travel time and delay are important factors, as they are expected to decrease by implementing ramp control. The queue behind the meter is always a big concern with ramp metering since the spillback may block the surrounding roads. Thus, the queue length of the ramp is also chosen as a measure in this study. Moreover, the highway speed and density are also selected to evaluate the impacts on highway traffic flow. Table 2 shows the selected MOEs for the case study.

Table 2. The selected MOEs

MOE	highway section	ramp	whole system
Delay	✓	✓	✓
Travel time	✓		✓
Queue length		✓	
Density	✓		
Speed	✓		

6. RAMP CONTROL SCENARIOS

The un-controlled ramp (the existing situation) and ramp metering are two main scenarios considered in this study. Since metering rate is a fundamental factor in the fixed-time approach, three different scenarios are developed for the controlled-ramp situation. These scenarios are different based on the car releasing pattern and the metering rate. We consider a one-car-per-green (OCPG) plan, as well as two platoon-releasing patterns (2-car platoon and 3-car platoon) for this purpose. The characteristics of these scenarios are presented in Table 3.

Table 3. The ramp metering scenarios

Scenario	cycle time (c) (sec)	green time (g)	g/c	metering rate (veh/h)
No control	-	-	-	-
One-car-per green (OCPG)	6	3	0.50	600
2-car platoon releasing (2P)	10	6	0.60	720
3-car platoon releasing (3P)	12	8	0.67	900

All these scenarios are modelled for both the peak and off-peak hours using Aimsun microscopic simulator (Figure 3). Typically, the location of the meter-limit line is determined corresponding to the transition taper. In this study, the ramp meter is located 30m behind the ramp exit to ensure acceleration of the vehicles waiting behind the ramp meter. Correspondingly, the distance between the ramp meter and the ramp entrance becomes 168.2m, which is considered as the ramp storage.

7. ANALYSIS AND DISCUSSION

This section presents the simulation outputs for the ramp controls scenarios at the peak and off-peak hours. The outputs are categorised and discussed corresponding each MOE in order to reveal the impacts of the ramp control plans on them.

7.1 Impacts on the mean delay time

Generally, ramp metering is expected to increase the ramp delay time. In contrast, it is supposed to decrease the whole system delay time because it aims to increase the highway speed. Figure 4 shows the impacts of ramp control plans on the mean delay.

The results showed that the all ramp metering plans significantly decreased the highway downstream delay at the peak hour in comparison with the no control condition. Moreover, the charts reveal that the highway delay was affected by the ramp flow rate (i.e. metering rate) and the OCPG plan had the most effect on decreasing the highway delay. Compared to the peak hour, the impacts of ramp control plans on the highway delay is less at the off-peak period. In spite of decreasing the highway delay, the ramp control plans increased the ramp delay, as expected. In other words, all the ramp metering plans imposed long delays to the ramp users at both peak and off-peak hours. This delay varied amongst the control plans corresponding to their metering rates.
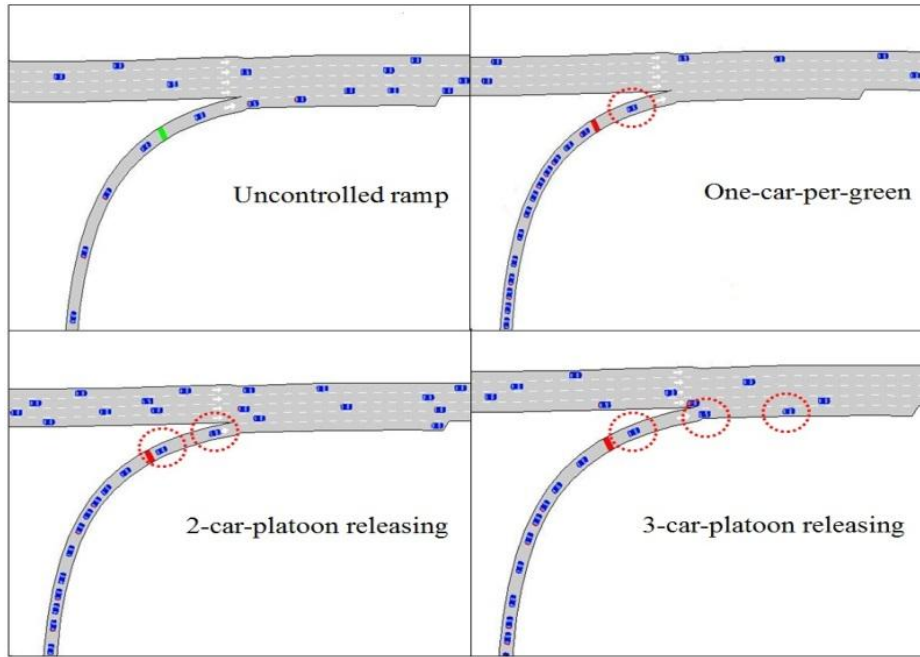
Figure 3. The ramp control scenarios

The outputs also revealed that the all ramp metering plans increased significantly the whole system delay in comparison with the un-controlled condition. Although the mean delay for the whole system was 7.34 (sec/km) under the no-control situation, this value increased by 5-7 times under the ramp metering plans at the peak hour. The worst situation occurred under OCPG plan.
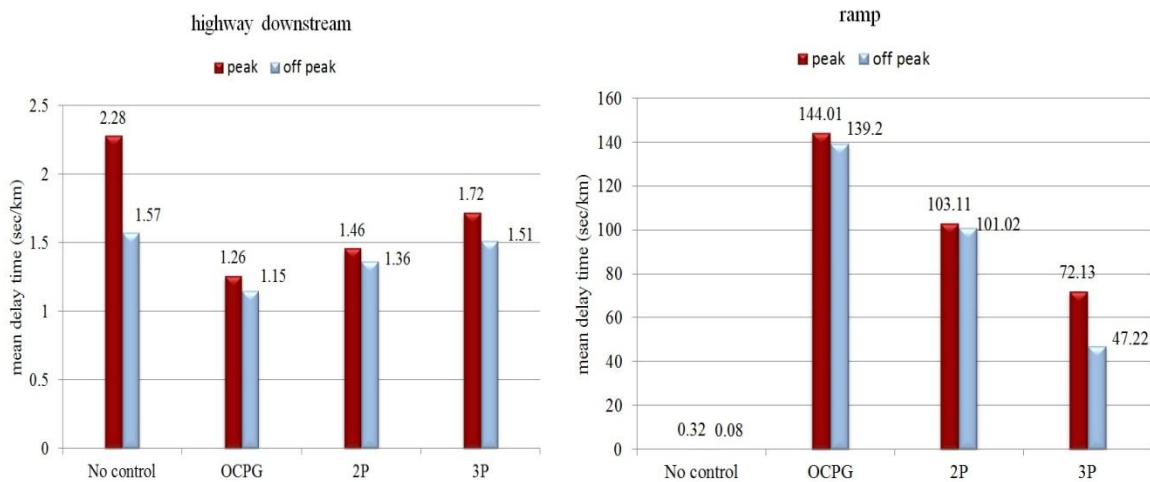

Figure 4. The impacts of ramp control plans on delay

7.2 Impacts on the total travel time

Figure 5 illustrates the variation of the total travel time under different ramp control plans at the peak hour. While the ramp control plans decreased the travel time for the highway users, they increased considerably the travel time for the entire system. That is, the control plans did not benefit the whole system in terms of decreasing the total travel time although they reduced the travel time for the highway users. This finding is different from what obtained in

some of the previous studies, as they have evidenced that ramp metering can reduce the total travel time for the entire system, as well as the highway sections. Amongst the ramp control plans, the OCPG plan which imposes more restrictions to the ramp flow had more negative effects on the system travel time.
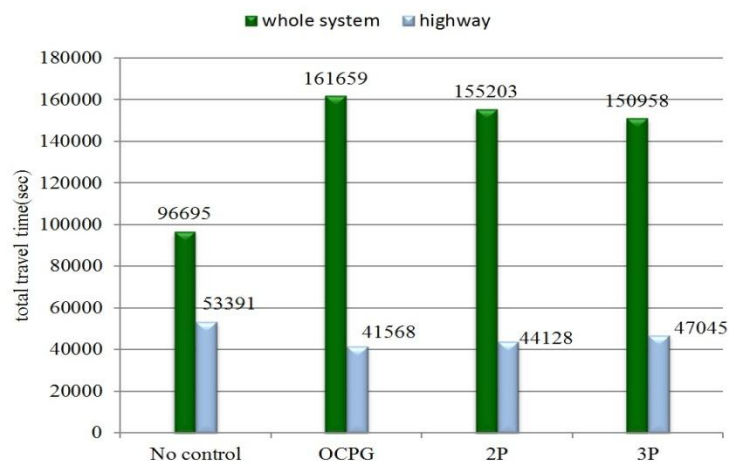

Figure 5. The impacts on the total travel time at the peak hour

7.3 Impacts on the ramp queue

As mentioned earlier, the ramp queue is a big concern with ramp metering, especially when the spillback reaches the ramp entrance and blocks the surrounding road network. Hence, ramp metering strategies are developed so that the ramp queue length does not exceed the ramp storage. In the selected site, the ramp length is 198.3m which equals the ramp storage in the no-control condition. However, the ramp storage in the metered-ramp conditions is 168.2m long (i.e. the distance between the ramp meter and the ramp entrance). Therefore, the ramp storage is estimated to accommodate 33 and 28 vehicles under no-control and metered-ramp conditions, respectively.

The outputs showed that the maximum queue length exceeded the ramp storage under the all ramp metering plans; that is, the spillback reached Saadat Abad Blvd, even at the off-peak period. In contrast, the ramp storage is sufficient to accommodate the ramp queue under the no-control situation. This is what already observed during the data collection and site observation, as the ramp queue does not exceed the ramp storage even at the peak period. As can be seen in Figure 6, the length of the ramp storage is way less than the length of the queue caused under ramp metering schemes and consequently, the adjacent road network is negatively affected by the ramp metering.

7.4 Impacts on the highway speed and density

Ramp metering is expected to reduce the density for the highway downstream because it reduces the entering traffic flow through the on-ramp. According to the results, the all ramp metering plans reduced the highway density. The OCPG plan decreased the highway density from 17.72 (veh/km) in no-control condition to 13.80 (veh/km), by 22.1 % at the peak hour. This reduction under the 2P and 3P plans was 17.2% and 12%, respectively. The impacts of the control plans on the highway density at off-peak were less than the peak hour. For instance, the OCPG plan reduced the highway density by 13.3% at the off-peak hour.

The ramp metering plans also increased the speed at the highway section, as expected. The mean speed on the highway downstream was 80.12 (km/h) at the peak hour under no-control plan. This value increased to 85.85 (km/h), by 7.2%, under the OCPG plan. This increase was lesser under the 2P and 3P plans. The similar results were found at the off-peak hours with some slight difference.
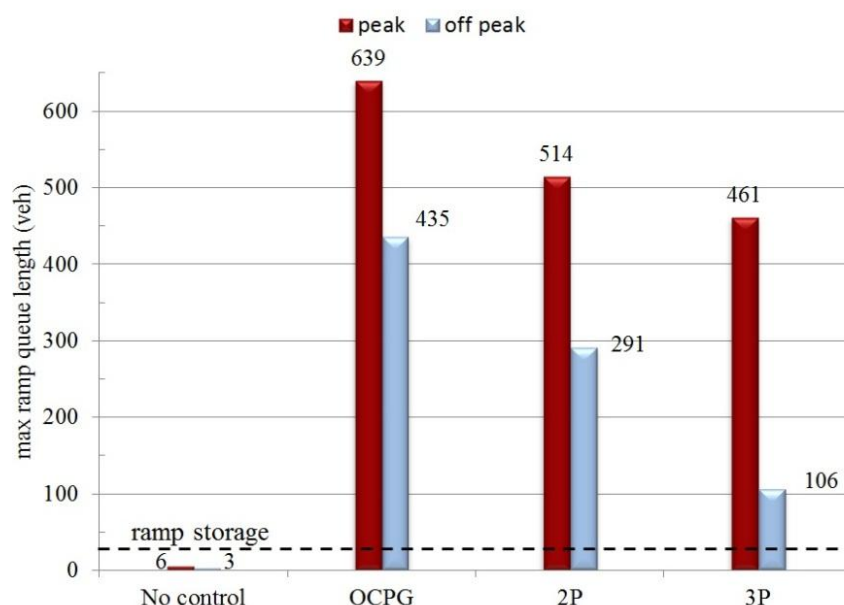
Figure 6. The impacts on the ramp queue length

7.5 Summarising the results

Table 4 presents the summary of the ramp metering impacts at the peak and off-peak hours. The negative numbers indicate the reduction in the corresponding values. As shown in this table, the ramp metering strategies are more effective on the highway performance at peak period. Nevertheless, their negative effects on the ramp performance are more considerable at off-peak.

Table 4. The ramp metering impacts compared to the no-control condition

MOE		Change (%)					
		Peak			Off-peak		
		OCPG	2P	3P	OCPG	2P	3P
mean delay time	highway	-44.7	-36	-24.6	-26.8	-13.4	-3.8
	ramp	45000	32222	22541	174000	126275	59025
	whole system	665	576	505	1081	946	1324
total travel time	highway	-22.1	-17.3	-11.9	-12.9	-9.4	-3.3
	whole system	67.2	60.5	56.1	96.1	85.2	52.4
ramp queue length		10650	8567	7683	14500	9700	3533
highway density		-22.1	-17.2	-12	-13.3	-9.6	-3.2
highway mean speed		7.2	5.7	3.8	3.1	2.2	0

8. CONCLUSION

This study investigates the impacts of fixed-time ramp metering on a site consisting of a highway section and an on-ramp. Three ramp metering scenarios are developed based on various vehicle-releasing patterns and metering rates. Then, a microscopic simulation model is developed using Aimsun in order to evaluate the impacts of these ramp control plans on the site performance. The results showed that the ramp metering can improve the highway performance by reducing the total travel time and the mean delay for the highway users, especially at peak hour. However, all these control plans negatively affect the ramp users by imposing long delays, even at off-peak period. In other words, ramp metering can improve the traffic condition at the highway section at the cost of increasing the delay for the ramp users. The adjacent road network is also influenced by this issue, as the ramp queue exceeds the ramp storage and leads to a situation which is even worse that the existing situation. Overall, this study showed that the selected ramp metering plans cannot benefit the whole system.

Similar to any traffic management strategy, the success of the ramp metering is case-dependent, relying on the physical and operational characteristics of the site. While it cannot be an effective measure in a site, it may improve the traffic condition in another. Therefore, deep investigation is required to assess the probable impacts in order to take appropriate and effective decisions. This study shows that microsimulation is a useful tool in this regard. Due to the delay imposed to the ramp users, it is expected that the ramp traffic is shifted to other alternatives. Hence, further studies can be dedicated to the diversion of traffic to the adjacent road network. Furthermore, if the site is equipped with real-time traffic information facilities in the future, traffic-responsive strategies can also be examined in order to reveal the efficiency of ramp control measure in improving the site performance.

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