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Evaluation of Ramp Metering Control on Urban Expressway in Cairo

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Abstract— Uncontrolled on-ramp merging section is considered as a bottleneck at several locations on urban expressways in Greater Cairo Region (GCR). This study aims to evaluate the impacts of applying ramp metering control on the traffic performance at three critical on-ramp sites on the 6th of October corridor using VISSIM. The simulation models were calibrated using the traffic data collected during peak period. Two different control strategies were tested; fixed-time ramp metering and actuated control for both mainline and on-ramp traffic, and compared to "no control" using average speed, average vehicle delay and on-ramp queue length as performance measures. The results indicated that fixed-time ramp metering could improve the overall traffic performance at merging sections by increasing the speed up to 100% and reducing the average vehicle delay up to 50%. However, fixed-time ramp metering control results in on-ramp queue spillback onto adjacent roads at some sites due to insufficient ramp storage length and huge on-ramp volumes. In this case, the actuated control strategy showed significant improvements on traffic performance at both the mainline and on-ramp, in addition to the whole system by increasing the speed by 25%, reducing the average delay by 11%, and reducing the queue length by 35%.

Keywords— Ramp metering, Microsimulation, VISSIM, Fixed-time control

I. INTRODUCTION

As other crowded big cities around the world, Greater Cairo Region (GCR), the capital of Egypt, roadway network is suffering from severe traffic congestions especially during peak periods. Traffic congestions at GCR cost nearly 4% of the Gross Domestic Product (GDP) according to the World Bank study 2013 [1]. Although the Egyptian Government has done great efforts to solve the traffic congestions during recent years, by constructing new roads, bridges, and new metro lines, main roads still suffer severe recurrent traffic congestions, especially at on-ramp merging sections on urban main roads. The 6th of October corridor is considered as one of the major urban corridors in GCR with a length of 20.5 km linked the east to the west regions of GCR and has 23 entry and exit. Recurrent traffic congestions are frequently observed at on-ramp merging sections on this corridor due to uncontrolled on-ramp merging traffic onto the mainstream. Currently, at some on-ramp sites, the Cairo traffic police department applies a manual control strategy by allocating a policeman at the on-ramp to control the entry traffic onto the mainline based on his own limited vision and judgment. Despite ramp metering control strategies have shown significant improvements on traffic operation around the world, no studies were conducted to test the efficiency of applying such control systems on urban expressways in GCR. Accordingly, this study mainly aims to evaluate the effectiveness of applying ramp metering control system at some on-ramp sites on the 6th of October corridor . In addition, the study aims to find the optimal signal timing of the on-ramp metering system and the best control scenario.

II. LITERATURE REVIEW

Ramp Metering is considered as the most effective traffic control management system that controls the entry traffic volumes onto freeways, or urban expressways to alleviate traffic congestions at merging sections [2]. Ramp meter is a special traffic signal placed at on-ramp to control the entry traffic volumes from on-ramp onto the mainline [3]. The main objectives of applying ramp metering control system are to improve traffic operation on freeways and enhance the traffic safety [4]. It aims to regulate the rate by which entry vehicles are allowed to enter the freeway by optimizing the use of available gaps between vehicles on the mainline of the freeway to keep the flow under its capacity [5]. Ramp metering also aims to break up the platoons of on-ramp vehicles tends to enter the mainline. The first implementation of ramp metering control was in 1963 on Chicago's Eisenhower Expressway in Illinois, where a policeman controlled the entering traffic by releasing one or more vehicles to enter at a predetermined rate [6].

Based on the entry mode, ramp metering strategy is classified into three modes: single lane one car per green, single lane multiple cars per green, and dual lane [7]. For dual lane entry, the on-ramp consists of two lanes and each lane has a signal controller with one car per green or multiple car per green. There are two operational ramp metering control strategies to determine the metering rates based on its response to real-time traffic conditions at the merging section: pre-timed (fixed) ramp metering control system and responsive ramp metering control system. In pre-timed ramp metering control, the metering rate is determined based on historical traffic data, regardless the fluctuation in traffic condition during operation time [8]. Fixed-time ramp metering control is effective in case of recurrent traffic congestion [9]. The metering rates in responsive control are calculated using algorithms. The responsive ramp metering control system are classified into two types: local (isolated) and coordinated ramp metering control. Local ramp metering control use the traffic data such as Demand/Capacity [10], and ALINEA algorithm [11] from detectors in the vicinity in a specific algorithm to find the optimum entry rate of traffic form the on-ramp. The coordinated ramp metering control algorithms use traffic data from detectors on a set of consecutive ramps to set the rate, such as BOTTLENECK algorithm [12] to control a set of on-ramps along the study corridor.

Several prior studies have been conducted to evaluate the benefits of different ramp metering control strategies in improving traffic performance [13], [14], [15], [16] and traffic safety [17], [18] by using both field test and microscopic/macroscopic simulation techniques. For example, [19] tested the impacts of applying fixed-time ramp metering control strategy on the traffic efficiency and equity on an urban freeway in Istanbul, Turkey, using VISSIM microsimulation. A set of fixed timing signal scenarios were evaluated to indicate the optimal fixed-time cycle length. The results concluded that fixed-time cycle length with 15 seconds showed the best results in improving the network efficiency by increasing the speed by 52% and reducing the network travel time, delay and number of stops by 32%, 60%, and 80%, respectively. Also, ramp metering could provide equity concerns for the ramp travelers when taking the spot speed in consideration. [20] used microsimulation AIMSUN to evaluate the effects of two ramp metering control strategies (including fixed-time control and one responsive control) on Shahid Kharrazi Freeway in Isfahan city at three demand levels (80%, 100%, and 110). The results concluded that didn't show any significant improvements for 100% demand level, while it improved traffic operation at 110% demand level. Also, they concluded that ramp metering showed negative effects at low demand level.

III. Case Study Selection and Data Collection

Three on-ramp sites along the 6th of October corridor with different geometric configurations were selected as a case study: Ramsis on-ramp (site 1), Abdel-Monem Riyadh on-ramp (site 2), and Al-Gazera on-ramp (site 3). The study sites were selected such that they suffer severe recurring traffic congestions during peak periods. Figure 1 shows the location of the three study sites along corridor. Each site includes a single lane on-ramp with 5 m, 5.5m and 6m width at site-1, site-2, and site 3, respectively. Due to the lane width of the on-ramps and mainlines, an additional lane always occurs during peak periods on each on-ramp and the mainline segments, as well, resulting from the drivers' behavior in Cairo that doesn't discipline the designed lane width. Only, at Ramsis on-ramp, the lane width is narrowed to 3 m just before entering the mainline, so it was considered as a dual-lane ramp which turns into a single lane before merging. Moreover, the max on-ramp storage length at each site is 160 m for site-1, 190 m for site-2, and 155 m for site-3. At sites (1) and (2), manual controlling by a policeman at on-ramp traffic is taken place during peak hours. At site-3, bottleneck mainly occurred downstream on-ramp due to the existence of a nearby off-ramp that creates a weaving section, in addition to the merging traffic. Traffic data were collected using video records technique and the traffic volumes were collected manually through the video records during peak hours. The maximum hourly mainline volumes were 3712, 3450, and 5402 veh/hr, at site-1, site-2, and site-3 respectively, while the cross ponding on-ramp traffic volumes were 1468, 1610, and 1490 veh/hr at site-1, site-2, and site-3, respectively.

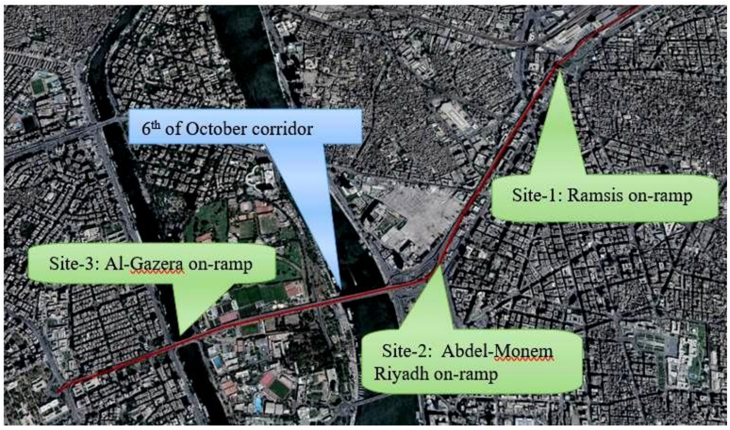

Figure 1. the 6th of October corridor layout with selected sites

IV. Developing of Microscopic Simulation Modeling

A. Model development

Microscopic simulation modeling technique is used to achieve the objectives of the study. The microscopic software package "PTV VISSIM-10" was used in modeling each on-ramp site and evaluating different control strategies. VISSIM is defined as a microscopic, behavior based and time step oriented simulation tool used for modeling urban streets, freeways, multimodal transport operations, and pedestrian flows [24]. It applies psychophysical car following models developed by Wiedemann: Wiedemann 99 and Wiedemann 74. For the network coding, each link in the network was specified to "Urban motorized" link type, while the links in the merging area were specified to a new introduced link type "Merging".

B. Models calibration and validation

Each simulation model was calibrated using traffic data set of one hour by adjusting the values of specific Vissim parameters until the model replicates the real traffic conditions. Geoffrey E. Haver (GEH) index was used in models calibration to compare between simulated S and observed V traffic volumes for both mainline and on-ramp directions. The GEH is calculated using the following equation [21] :

$$GEH = \sqrt{\frac{2*(S-V)^2}{(S+V)}}$$

Where S is the simulated traffic volume and V is the observed traffic volume. The simulation model is considered accurately reflect the prevailing conditions on the network, if more than 85 % of the GEH values are less than 5 [22]. All the calculated GEH values were found to be less than 5 for all sites with average values of 1.33, 1.96, and 0.94 for site-1, site-2, and site-3, respectively. Table 1 shows the final calibrated values of each simulation model parameters. In general, the calibrated values are the same for all simulation models, except the values of maximum deceleration for cooperative braking and min headway parameters of the "Merging" driver behavior type which they are same for site-2 and site-3 only.

TABLE I. CALIBRATED VALUES OF VISSIM PARAMETERS FOR EACH SIMULATION NETWORK

Parameter	Calibrated value	Applied sites
Car following model parameters (a_x, $b_{x\ add}$, $b_{x\ mult}$)	0.7m, 0.3m, 0.3m	site-1,site-2, site-3
Safety distance reduction factor	0.1	site-1,site-2, site-3
Min. headway for urban motorized	0.5 m	site-1,site-2, site-3
Min. headway for Merging	0.2 m	site-2, site-3
Max. deceleration (Own) for urban motorized	-5 m/sec^2	site-1,site-2, site-3
Max. deceleration (Trailing) for urban motorized	-4 m/sec^2	site-1,site-2, site-3
Max. deceleration (Own) for Merging	-6 m/sec^2	site-1,site-2, site-3
Max. deceleration (Trailing) for Merging	-6 m/sec^2	site-1,site-2, site-3
Max. deceleration for cooperative braking for urban motorized	-6 m/sec^2	site-1,site-2, site-3
Max. deceleration for cooperative braking for Merging	-6 m/sec^2	site-1
	-9 m/sec^2	site-2, site-3

The calibrated models were validated using another traffic data set by applying GEH statistics approach and ensuring the occurrence of bottlenecks on the mainline segments through visual inspection. All the GEH values for validation were less than 5 with average values of 1.17, 2.28, and 1.44 for site-1, site-2, and site-3, respectively. From the GEH values, the models are well calibrated and can be used for analysis.

V. DESIGN OF THE TESTED SCENARIOS AND RESULTS

Two different control strategies were tested: ramp metering strategy and actuated signal control strategy. The effectiveness of both control strategies was evaluated and compared to "no control" scenario as baseline scenario. A number of performance measures were used to evaluate the examined control scenarios such as average speed and average vehicle delay on the whole system (including corridor and the on-ramp), average speeds of mainline segments (upstream and downstream), and average on-ramp queue length.

A. Ramp metering control strategy evaluation

1) Design of fixed-time control scenarios

All the tested on-ramp sites suffer from recurrent congestions during study peak period with no variation in traffic volumes, so fixed-time ramp metering control strategy was proposed to be applied. A set of scenarios were designed based on the number of vehicles allowed to enter onto the mainline per green (entry mode) to find the optimum signal timing. As mentioned earlier, all studies on-ramps operate as dual lane ramps during peak periods. Therefore, they were considered as dual-lane ramps in the evaluation study to replicate the actual situation. Traffic signal was added at each lane such that the red-green cycles never occur at the same time. The proposed control scenarios for fixed-time ramp metering strategy at the selected sites and the signal display at each lane are listed in TABLE II.

TABLE II. THE PROPOSED SCENARIOS FOR FIXED SIGNAL TIMING

Control scenario no.	Cycle length (sec)	No. of vehicles per green per lane	Lane 1	Lane 2
No control				
1	6	1	2G+1AR+2R+1AR	2R+1AR+2G+1AR
2	8	1	2G+2AR+2R+2AR	2R+2AR+2G+2AR
3	10	1	2G+3AR+2R+3AR	2R+3AR+2G+3AR
4	10	2	4G+1AR+4R+1AR	4R+1AR+4R+1AR
5	12	2	4G+2AR+4R+2AR	4R+2AR+4G+2AR
6	14	2	4G+3AR+4R+4AR	4R+3AR+4G+3AR
7	16	2	4G+4AR+4R+4AR	4R+4AR+4G+4AR
8	14	3	6G+1AR+6R+1AR	6R+1AR+6G+1AR
9	16	3	6G+2AR+6R+2AR	6R+2AR+6G+2AR
*G=Green, R=Red, AR=All Red (all intervals are in second) * 2G+1AR+2R+1AR means 2 seconds green to allow one vehicle to enter from lane-1, 1 second all-red, 2seconds red and 1 second all-red.				

2) Simulation results of fixed-time scenarios

TABLE III. summarizes the performance results of fixed-time scenarios at site-1. The results indicated that all scenarios significantly improved the traffic performance, only scenarios no. 4, 8, and 9 showed reduction in the speed and increase in the vehicle delay compared to "no control". Scenarios with one and two cars per green with long cycle length, showed better results in improving traffic conditions on mainline and whole system compared to "no control" scenario and other control scenarios with short cycle length and same entry mode. On the other hand, all control scenarios increased the on-ramp queue length with no significant difference between the queue length under different scenarios, except scenarios no. 8 & 9 with 3-cars per green that showed significant reduction in the on-ramp queue length. Accordingly, scenario no. 3 with cycle length of 10 seconds and one car per green can be considered as the optimum control scenario as it showed the best whole system performance by increasing the speed by 38% and reducing the average vehicle delay by 38%.

TABLE III. PERFORMANCE RESULTS FOR FIXED SIGNAL TIMING SCENARIOS AT SITE-1

Control scenario	Whole system		Mainline upstream speed (km/h)	Mainline downstream speed (km/h)	On-ramp queue length (m)
	Speed (km/h)	Vehicle delay (sec/veh)			
no control	13.5	64.7	11	15	162.0
1	14.5	56.7	20	16	167.0
2	18.0	41.7	37	24	168.0
3	18.6	40.1	43	28	168.1
4	12.8	65.7	13	16	153.0
5	15.0	54.1	21	18	167.0
6	17.2	44.4	29	21	167.3

7	17.9	41.8	35	24	167.6
8	12.5	68.0	12	15	127.0
9	13.2	64.6	13	16	139.5

The simulation results of implementing fixed-timing signal control scenarios at site-2 are listed inTABLE IV. It is observed from the table that all control scenarios improved the traffic performance better than "no control". For the same entry mode, the increase in the speeds and reduction in the delay increased as the cycle length increase. It is also revealed from the table that ramp queue length exceeded the ramp storage length under all control scenarios with no significant difference between the queue lengths. Finally, scenario no.3 with cycle length of 10 seconds and one car per green is considered as the optimum scenario in term of increasing the whole system speed by 100% and reducing the vehicle delay by 50%.

TABLE IV. PERFORMANCE RESULTS FOR FIXED SIGNAL TIMING SCENARIOS AT SITE-2

Control scenario	Whole system		Mainline upstream speed (km/h)	Mainline downstream speed (km/h)	On-ramp queue length (m)
	Speed (km/h)	Vehicle delay (sec/veh)			
no control	8.2	113.4	6.5	9.1	200
1	9.9	96.4	10.0	10.6	206.3
2	14.7	64.6	24.4	13.0	206.8
3	16.4	57.1	38.7	16.4	207.1
4	8.6	109.5	8.2	9.7	198.8
5	10.1	94.3	9.7	10.5	206.2
6	13.2	72.9	15.2	11.4	206.6
7	14.3	66.7	21.9	12.4	206.7
8	8.5	109.1	7.8	9.5	199
9	9.3	102.3	8.8	10.0	200

For site-3, the mainline downstream segment is considered as a weaving segment, so the impact of ramp metering control was evaluated on the traffic performance on the weaving segment as well. The simulation results for each performance measure are listed in TABLE V. The results concluded that all fixed-time ramp metering control scenarios improved the traffic performance on whole system and the weaving segment, as well. Moreover, it is noticed that fixed-time ramp metering control increased average speed on mainline upstream segment compared to "no control", especially scenarios with long cycle length. Regarding the on-ramp queue length, all scenarios increased the queue length compared to "no control" without exceeding the ramp storage. The best whole system performance was provided in case of scenario no. 3 with 10 second cycle length and one car per green, so it is considered as the optimum signal timing control scenario. It improved the system performance by increasing the speed with 62% and reducing the average vehicle delay by 49%.

TABLE V. PERFORMANCE RESULTS FOR FIXED SIGNAL TIMING SCENARIOS AT SITE-3

Control scenario	Whole system		Mainline upstream speed (km/h)	Mainline downstream speed (km/h)	On-ramp queue length (m)
	Speed (km/h)	Vehicle delay (sec/veh)			
no control	12.4	66.7	6.8	10.9	115.1
1	16.4	47.1	19.8	12.1	152.7
2	19.1	36.9	30.7	16.3	153.2
3	20.1	34.1	35.1	19.5	153.5
4	13.5	60.5	9.2	10.6	144.6
5	15.3	52.2	15.3	11.2	152.4
6	17.8	41.5	23.4	13.6	153.0
7	19.4	35.4	32.6	16.7	153.1
8	13.6	60.9	9.0	10.6	124.2
9	14.1	58.0	10.5	10.5	115.1

B. Actuated control strategy for mainline and on-ramp traffic

1) Actuated control scenarios design

An actuated control strategy for mainline and on-ramp traffic with three different control methods were developed and evaluated. In the actuated control system, traffic signals and detectors are allocated at the on-ramp lanes and the mainline lanes upstream the on-ramp (see Figure 2. The main idea of this control strategy is to transfer the queue formed on the on-ramp to the mainline upstream segment when the on-ramp storage length can't accommodate the on-ramp queue and there is a sufficient storage space on mainline upstream segment. Occupancy rate at the mainline and on-ramp is used as the main performance measure to adjust the green and red duration of each signal groups to maintain the occupancy rate on both mainline and on-ramp less than or equal pre-defined critical values. The Occupancy rate is defined as the time percentage that the detector is occupied by a vehicle [21]. The occupancy rates are obtained from the installed detectors upstream the merging section and on-ramp as shown in Figure 2.

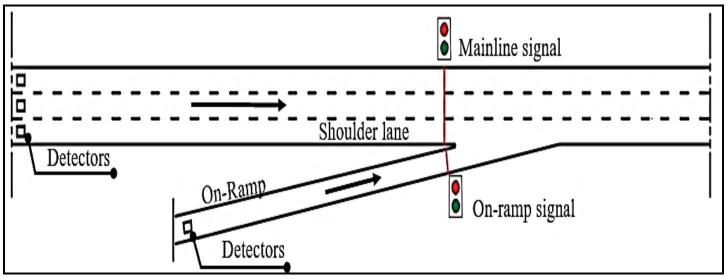

Figure 2. layout for the actuated control system components

The actuated control strategy has three main parameters that should be calibrated before applying any of the control methods: cycle update, mainline critical occupancy$(\hat{O}_m)$, and On-ramp critical occupancy $(\hat{O}_r)$.

At the beginning of each cycle update, the ramp occupancy(O_r) is firstly checked by comparing its vale with the predefined critical value $(\hat{O}_r)$ then the steps, illustrated in TABLE VI. , are proceeded based on the applied logic.

TABLE VI. ACTUATED CONTROL STRATEGY STEPS BASED ON THE APPLYING LOGIC

Control logic	If $(O_r) > (\hat{O}_r)$	If $(O_r) < (\hat{O}_r)$
Logic 1	Check the mainline occupancy • If $(O_m) > (\hat{O}_m)$, keep both signals groups green. • Else, Turn mainline signals into red.	Check mainline occupancy • If$(O_m) > (\hat{O}_m)$, Turn on-ramp signals into red • Else, keep both signals groups green.
Logic 2	Turn mainline signals into red	
Logic 3	Turn mainline signals into red	Keep both signals groups green

The three actuated signal logics were applied and evaluated at site-2 as there is a sufficient storage space on the mainline upstream segment of 400 m length that could accommodate the formed mainline queue. The 400 m is the distance on the mainline between the on-ramp and the upstream off-ramp to Ramsis. The mainline detectors were placed at 400 m upstream the merging area, while the on-ramp detectors were placed at the entrance of the ramp to make use of the whole ramp length. The calibrated values of cycle update, mainline and on-ramp critical occupancies were set by 10 seconds, 0.8, and 0.6, respectively. Each control logic was programmed using VisVap interface [25] to be simulated in VISSIM and compared to "no control" scenario in terms of the performance measures.

2) Simulation results of actuated control strategy

Performance results were obtained for each actuated control logic at site-2 in addition to the "no control" scenario and listed inTABLE VII.

TABLE VII. PERFORMANCE RESULTS FOR ACTUATED SIGNAL STRATEGY AT SITE-2

Control logic	Whole system		Mainline upstream speed (km/h)	Mainline downstream speed (km/h)	On-ramp queue length (m)
	Speed (km/h)	Vehicle delay (sec/veh)			
No control	8.2	113.4	6.5	9.1	200.0
Control logic-1	10.3	101	8.8	12.1	129.9
Control logic-2	9.9	102.1	8.7	12.9	122.1
Control logic-3	9.9	101.9	8.7	11.4	117.2

It is observed from the table that there was no significant difference between the simulation results of the control logics in increasing the speeds on the whole system and the mainline segments and reducing the average vehicle and delay. The on-ramp queue length was less than the on-ramp storage length (190 m) under all actuated control logics. Actuated control logic-1 could be selected as the best actuated control logic as it increased the mainline segments and whole system speeds by 25%, reduced the whole system delay by 11%. It also reduced the on-ramp queue length by 35% to reach 113m which is less than ramp storage length.

VI. CONCLUSION AND SUMMARY

The aim of this paper is to investigate the feasibility of applying ramp metering control strategy on congested urban expressways in Greater Cairo Region (GCR) and define the optimum cycle length and control strategy. Microscopic simulation models were developed using VISSIM microsimulation approach and the models were calibrated to reflect actual conditions. Three on-ramp merging sections were selected along the 6th of October corridor, as a case study. Both fixed signal timings scenarios and actuated traffic control strategies with different signal timing scenarios were evaluated and compared to "no control" scenario.

The simulation results indicated that fixed-time ramp metering control strategy in general improved the traffic performance at all examined merging sites. Despite the differences in the geometric layout and traffic volumes of the three sites, the optimum fixed-time scenario was the same at all sites: scenario no.3 with cycle length of 10 seconds and one car per green at all sites. It showed significant increase in the system speeds and reduction in the average vehicle delay, although it increased the queue length compared to "no control". On the other hand, all three actuated control logics improved traffic performance on the whole system and on the on-ramp at site-2 and also prevent ramp queue spilling back onto adjacent roads. Actuated control logic-1 is considered as it showed the best performance compared to no control and other actual control logics.

Over all, the findings of this study proved the importance of applying ramp metering control system based on the recommended signal timing at the examined sites, instead of the manual control strategy that is currently used, to mitigate the recurrent traffic congestions at on-ramp sections and weaving sections during peak periods on urban expressways in GCR network roads.

Since this paper focused on studying the impacts of fixed-time ramp metering control strategy on the traffic performance, it is recommended to study the impacts of ramp metering control strategies on the traffic performance and traffic safety.

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