Optimal Signal Control in Urban Road Networks with High Priority Congested Centers

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Abstract

Keeping the density of traffic flow and air pollution in an acceptable level and developing a good capacity for transit in the high priority areas of the city, is really a big deal in large and crowded cities. To address this problem, a new method of intersection signal optimization is presented in this paper. Based on network fundamental diagrams, an Internal–External Traffic Metering Strategy (IETMS) is developed for controlling density of traffic in high priority areas globally. Protecting the network from gridlock, optimizing the queue ratios in entrance arterials and utilizing the reserved capacity are the main objectives of the problem. The methods of mixed integer linear programming and quadratic programming are used for solving the problem. A traffic simulator software (VISSIM) has been used for simulation in which the coded program is developed in VISSIM-COM interface. Finally the model is applied in a part of urban network of Tehran, Iran. The results show that redistributing of traffic density in the whole network and protecting high density areas from gridlock can efficiently improve traffic flow measurement in high priority areas.

Keywords: Signal control, traffic metering, fundamental diagrams

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1. Introduction

The rise in the number of vehicles and the increasing need for faster transportation systems caused the urban networks to encounter gravely with the problem of congestion. Due to the fact that the traffic signals are the main tools for the regulation and optimization of the traffic flow in the urban networks, the exact planning of these signals in order to increase the network effectiveness and the improvement of its performance in the over saturation conditions is of great importance. In the issue of demand management and the other subjects related to the queue management, there is a discussion titled "traffic metering" which means preventing the traffic to enter in a link so that the high volume of demand would not lead to the blockage of that critical link. This issue could be discussed at a topical level (a link) or in a network scale.

In other words, in the conditions of traffic density where we encounter with a large volume of the vehicles, sometimes the strategies of equal split times in which the traffic conditions of crossing streets are also taken into account; or redistributing traffic density in the network, may be effective in the improvement of the network performance.

Gal zur and et al. presented a method of controlling signals based on traffic rating (metering).They represented a method for designing signal plans for dense urban networks ,in which one or several junctions attain to the over saturation conditions before the rest junctions.[Gal-Tzur, Mahalel and Prashker,1993] The main idea of the study is based on the limitation of input volumes to the network up to the capacity of critical junction and to prevent the network from the blocking of crossroads. This process gives a possibility to the designer for determining the location of queues and leading them to long storage links which can be in the buffer or surrounding areas. This strategy is called "queue allocation". The model has been created based on the integrating a mathematical programming with the TRANSYT model. The mathematical programming model and the TRANSYT model have been used respectively to determine the green splits, the rating level and for dynamic processes' simulation in order to optimize cycle length and phase offsets.[Gal-Tzur, Mahalel and Prashker, 1993].

Rathi suggested a process of signal controlling and queue management based on simultaneous use of offsets in the main road and the negative offsets and the invasion of green time in the crossing streets. This process is a sample of the traffic metering (rating) in the regional level. In this study, the formulation of the real time control technique for the over-saturated arterial has been represented. The goals of this mater are as follows: [Rathi, 1988]

A) Maximization of system output: this objective would be attained by:

1-prevention of queue spillback which blocks the junctions and wastes the green time

2- Prevention of starvation phenomenon

which cause the delay in arriving the vehicles in the cross street and the waste of green time.
3- The management of queue formation is performed in order to present the maximal services in the stop lines.
B) The full use of reserve capacity: the aim of this case is to limitation of density conditions to a determined limit through queue management feed-forward system.
C) Supply of an equal service: in this case, the goal is appropriation of services to the traffic of crossing streets and turning left movements in such a way that all drivers would receive appropriate services which is considered as a means for more safety in the crossroads.
This controlling technique which is recognized as real time internal metering policy to optimize signal timing (RT/IMPOST) has been designed for the control of queue growth in every saturated approach through appropriate traffic rating in order to holding queue length in an stable manner. Therefore, the limits of queue length and the offsets are determined .A mixed integer linear programming has been used for limiting the optimized quantities of the offsets and the queue length. [Lieberman, Chang and Prassas, 2000]This study is in fact the developed version of Choi study in 1997. Choi's study presented a new method of compatible signal timing optimizer for tow-way multi-phase arterials in the over-saturation conditions. The output of his work titled IMPOST (internal metering policy to optimize signal timing) has been produced based on achieving following objectives [Choi, 1997]:

1- Control queue formation for prevention of spillback to the crossroads.
2- The complete use of full time of providing services with highest rate service
3- Effective utilization of reserve capacity of existed roads
4- Minimization of vehicles' stop
5- Minimization of delay time in the elements of saturated networks

In the developed method by Chang and Liberman [Lieberman, Chang and Prassas, 2000] a non-linear programming would arrange the length of green time of arterial for each cycle in a manner that the length of actual queues of arterial in each saturation approach is always an amount very close to the length of calculated saturated queue by MILP.
In other study Rathi has examined largely the control strategies of traffic management which control the rate of input flow to a dense city limit .He divided the strategies for control rating into two categories of internal metering and external metering. [Rathi,1991]

The results of Rathi simulation indicated that the strategies of external metering have the potential of improvement of traffic performance inside the restricted traffic zone and in the approaches leading to the controlling density area. The results of this simulation suggest that the utilization of external metering in the surroundings of limits condensed in such a level that lead to decrease in providing services for vehicles(because of spillback) ,is necessary [Rathi,1991].

In most of the above mentioned works the strategies of control and queue control are in static form and priorities of queue management strategies are stable. In these processes, especially in case that the urgent changes in the control strategies would be necessary; the total process should be reformulated and optimized.

This problem is not easy practically because it needs the use of formulation and resolving of multi algorithms .In addition to over-saturated conditions, the synchronized control of traffic lights for effective management of traffic is a complicated matter and includes lots of limitations and choices.

The main question is that whether when the system becomes over-saturated it is preferable that it would transform in under saturation situation before entering in new density (prevention from the traffic entrance in the determined limit until the flow inside limit would reach under saturation level) or the alternative of better permitting for the entrance of new traffic flow and simultaneously the process of every vehicle would be possible or a mutual strategy will be better? The answer depends on the priority appropriated to the crossing streets? The traffic managers need the tools for evaluation of the benefits of control different options in order to respond to these questions.

In a study done by Ekbatani and his colleagues the fundamental diagram of urban networks has been used in order to improve mobility in saturated traffic conditions via application of gating measures, based on an appropriate simple feedback control structure. In this study the gating has been used with the aim of protection of an urban zone to avoid over-saturation conditions or in particular, for maximization of system throughput. The general scheme of protected zone and its gating control has been showed in figure 1. [Ekbatani et al., 2012]

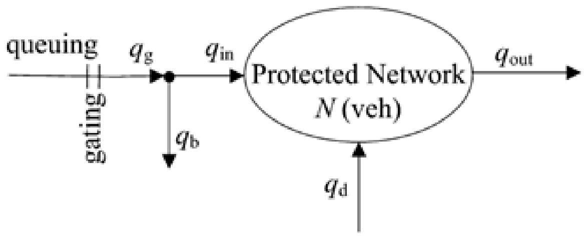

Figure 1. General scheme of the protected zone and gating control

In this figure, qg expresses the gating volume from which the determined quantity of qin enters to the protected zone and the quantity of qb could not enter the zone. In this picture qd shows the uncontrolled volume or internal volumes and qout indicates the output volume. NP is a protected zone that could include a part of central and condensed zone of the city and in it the N is equal to the number of vehicles in this zone. In accordance to network fundamental diagram, in case that N would be more than a determined quantity, the spillback of queue and blockage of cross streets results in decrease of qout quantity. For this reason, the gating control should remain the entrance volume in a lower level from the maximum amount of density in the protected zone so it will maximize the network outputs. [Ekbatani et al., 2012]

According the theory of Daganzo when a network places in the condensed conditions in such a way that the exit of the vehicles of the network would be, the least difference in opposite direction of input balanced flow would lead to profound influences in the network[Daganzo,2007] ; it is strongly advised that in such unstable systems, density and blockage in the network should be prevented by controlling entering flows .This situation could be occurred in the outside of network by application of metering strategy.

In this study, it is tried that by developing the metering model of arterials for urban road networks and by appropriate distribution of density in the surrounding limits of dense urban zones would prevent from the occurrence of blockage and density in the internal part of the high priority cores in the network. This issue has been performed by using the hypothesis of fundamental diagrams for the networks. Moreover, the presented model would improve the general performance the network at a good level by simultaneous optimization of queue length in the network from arterials and protecting the network density in an amount lower than the critical density .The discussed problem for the networks with hypothetical and supposed data has been resolved and the results have been studied.

2. Methodology

2.1 Approximation of Density Index in the Network

In order to estimate density index in the network, the common method is resolving the assignment problem. For this, the possibility of the path change of drivers in the middle of their route imposed as a reflection to the limitations should be considered, so it is better to use dynamic assignment method. It is evident that for resolving dynamic assignment problem it is required to have an initial origin-destination matrix that would be assigned to the existed links in the network. The schematic form of the mentioned network for exertion of optimization model of internal-external traffic metering has been showed in figure 2:

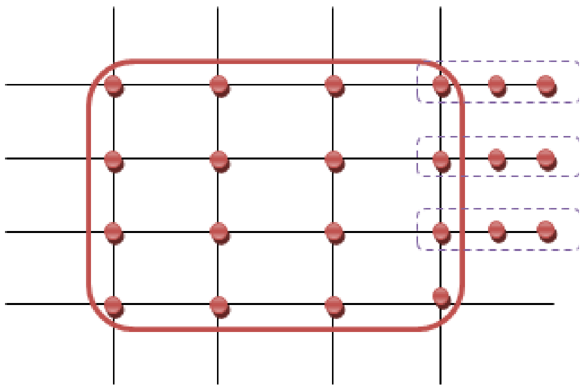

Figure 2.The schematic schema of IETMS problem

To do so, with entrance of origin-destination matrices in VISSIM (traffic simulator software)[VISSIM 5.4 user mannual,2012] and using of appropriation dynamic model of this software and also by utilization of the method presented by Ekbatani and drawing of fundamental diagram of network, the rate of network critical density will be obtained.

2.2 The traffic network referred to and drawing of fundamental diagram

The mentioned traffic network is a part of urban network of Tehran CBD that would be arrived to the congestion and spillback conditions in the morning peak hours based on the data and existed observations.

In figure 3, the aforementioned network along with the network of passageways around it modeled in the VISSIM simulator software, has been shown. (figure 3)

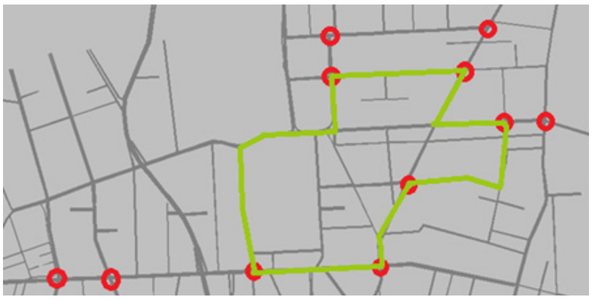

Figure 3. A part of Tehran city and the boundary of protected network

The network has 5 controlling entering points that in every point about two or three upstream intersections are controlled by optimization problem in a manner that in case of spillback to upstream, the length of queue in these links would be optimized.

As Degenzo suggested in his law of network optimization [Daganzo,2007], in case that internal density inside the protected network would be more than critical level, the entrance flow should be at its minimal level, equal to uncontrolled flow, otherwise the entrance flow should be maximized in order to maximize allowable traffic flow to increase performance of total network.

The shown network fundamental diagram in the picture has been approximated based on extracted OD 2011 statistics obtained from Tehran Traffic Control Company. (Figure 4)

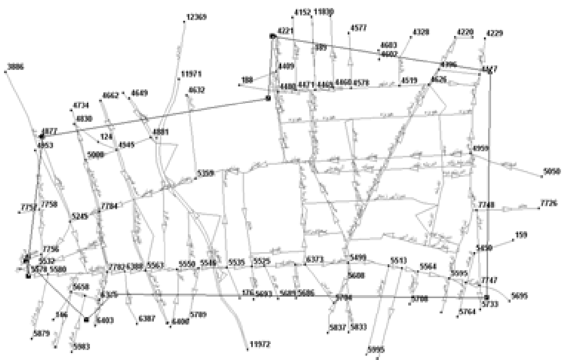

Figure 4. The links and nodes of the whole network is applied for solving the problem

The graph of the fundamental diagram has been achieved based on 8 times execution of program for two hours of peak period with different random seed numbers in VISSIM software eight times according to the following picture.(Figure 4)

Based on figure 4, it is observed that for critical density occurrence prevention in the protected network, the rate of traffic volume should be about 35 to 45 vehicle hours per hour.

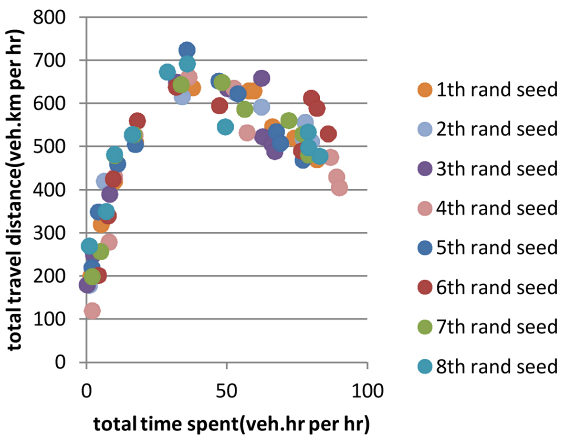

Figure 5. Fundamental diagram of mentioned network

2.3 The modeling of the internal-external metering network problem

The issue of internal –external metering of network has been designed in order to control the entrance volume to network for prevention from occurrence of blockage and gridlock in it. The distinguishing point of this problem with early studies is in the exact exertion of entrance link conditions to the network in order to prevention from spillback of queue in upstream links in a manner that not only it prevent from spillback in the upstream intersections but also it helps the optimization of queue length, for the maximal utilization of capacity reserve of upstream links. Because these links are in fact the warehouses of reserve of entrance flow in condensed density and so the maximal use should be done from their capacity and prevent from their spillback to upstream flow.

The represented model is a promoted model of rating issue for urban arterial presented by CHANG in order to resolve the problem of urban networks.

The formulation of problem solving is as follows:

In the first part the problem of an objective function for maximization of offsets between the successive intersections is resolved.

$$\text{Max} \sum \left[\alpha_i \delta_i + \bar{\alpha}_i \bar{\delta}_i\right] \qquad (1)$$

Where:

δ_i =out bound offset between two consecutive intersections

$\bar{\delta}_i$ =in bound offset between two consecutive intersections

α_i ,$\bar{\alpha}_i$ = related weights for outbound and inbound direction respectively

The limits of this issue include the limits of queue length, offsets and a limit of closed loop that because of this limitation the problem should be resolved in the form of mixed integer linear programming.

The previous problem outputs including the optimized extracted queues length enters as input in the next part of the problem:

$$\max\sum w_j q_{inj}/TTScri - w_i \sum (p_{(0,i)} - \hat{p}_{(0,i)})^2 - \sum \left| \left(^{(G(B,i)-G(B,i-1))} \right) / C \right| \qquad (2)$$

Where

i= index of saturated approaches

w_i= related weight for every entrance arterial

$p_{(0,i)}$ = standing queue ratio

$\hat{p}_{(0,i)}$ = optimal standing queue ratio

G_{Bi} = adjusted green time in intersection i(sec)
w_j = related weight for intersection j from the series of entrance intersections
C=cycle time (sec)
q_{inj} = ratio of entrance flow to entire flow of the network from intersection j

The conditions of the above problem include the conditions of problem solving for arterials (dealt with in the Chang problem) that would be exerted for all entrance arterials. It should be noted that these limits have been changed for connecting of the said arterials under the dense network.

In addition, a new part has been added to the problem for consideration of network conditions which includes the maximization of entrance flow to the network. The constraints of this part are as follows:

$$TTS \leq \hat{TTS} \quad (3)$$

$$TTS = A \times N(t) + \varepsilon_1 \quad (4)$$

$$N(t) = \sum_{j=1}^{m} qin_j + q_d - q_{out} \quad (5)$$

$$qin_j = LN_j \frac{G_j - s}{h} p_j + \tau \quad (6)$$

$$\tau = \frac{C_a - G_j + s}{h} \times LN_{c1} \times p_{c1} + \frac{C_a - G_j + s}{h} \times LN_{c2} \times p_{c2} \quad (7)$$

Where

$\hat{TTS}$=critical density in the protected network
A=error factor
ε_1 =measurement error factor
j=index of entrance intersection
LNj =number of lanes in main entrance arterial j
m=number of entrance intersections
Gj =green time of main arterial in entrance intersection j(sec)
s =start up lost time (sec)
h=saturation headway (sec)
pj =percent of turning movements in intersection j(turning from main arterial to cross streets)
qd =uncontrolled traffic flow(veh/hr)
qout =output traffic flow(veh/hr)
wj = related weight for intersection j from the series of entrance intersections
C=cycle time (sec)

For the simplicity the error factors of A and ε_1 are assumed to be equal 1. Second part of the problem is resolved by the help of planning non-linear method .The two parts of the above problem would be coded and resolved in the MATLAB software .The written program has connected to the VISSIM simulator software [VISSIM 5.4 user mannual,2012] with the help of VISSIM-COM interface [COM Interface Manual,2012] .In the next part of the essay the achieved results from the execution of the program are presented.

3. Results

Due to the fact that in rational software packages of traffic simulation, every replication would have different response, the results of all eight replications must be averaged to reach exact and reliable results before and after the implementation of controlling policy.

3.1 Network gridlock

First of all it must be controlled if the model could keep the density of the sub-network below than a critical amount or not. On the other hand it must be shown that if this is the case, how it can change the utilization of the network during simulation period. Figures 6(a, b) and 7(a, b) shows the changes of total time spent and total travel distance in the sub-network during the simulation period without and with IETMS respectively.

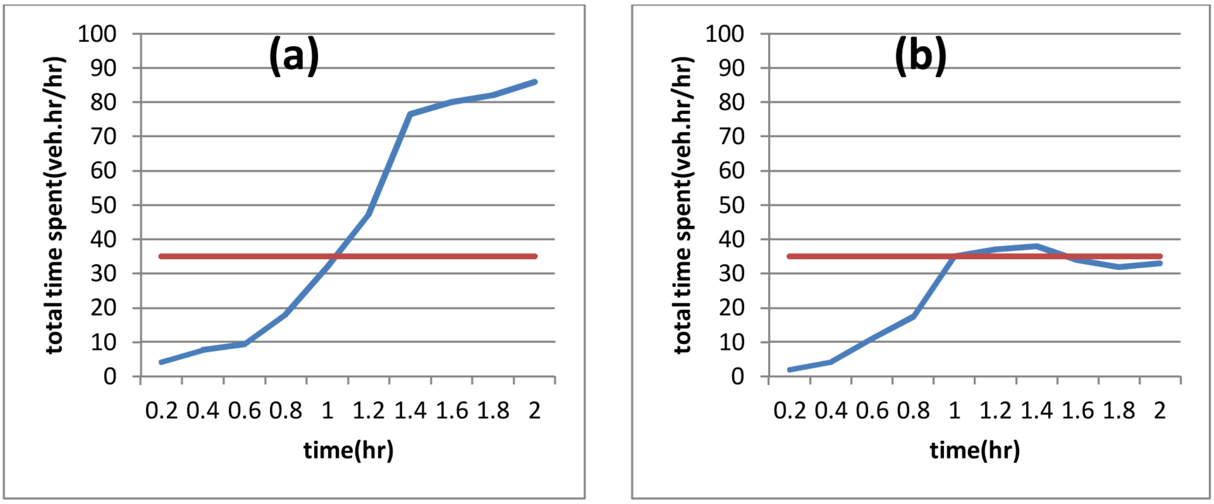

Figure 6. Total time spent in the sub network without IETMS(a) and with IETMS(b)

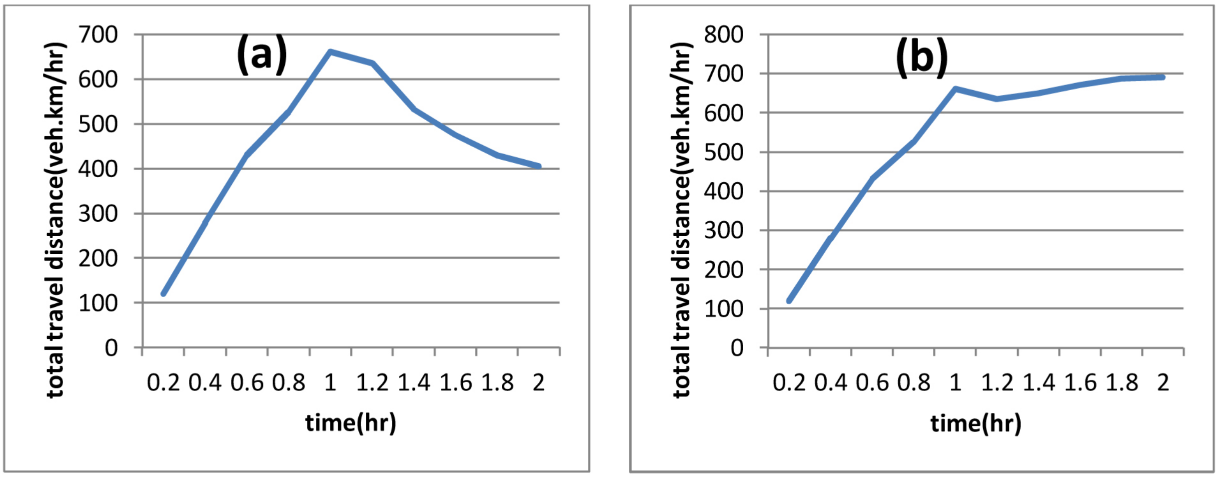

Figure 7. Total travel distance in the sub-network without IETMS(a) and with IETMS(b)

As it is shown in figure 6(a), as time passes by during the simulation time period, the amount of total time spent is vehicles in the sub network increases and it reaches values above the critical amount of density in the middle of the simulation. Consequently as shown in figure 7(a) output of the system decrease at the same time. This matter confirms that the aforementioned theory about network gridlock in which when the density goes higher than a critical amount, gridlock will happen and the output of the system will decrease.

Applying the new strategy (IETMS) in the network, it is shown in figure 6(b) that the density is remain below than the critical amount(here 35-40 veh-hr per hr for sub-network of Tehran).So, it is seen in figure 7(b) that the output will increase during the simulation period and the descent phenomenon will not occur.

It is clear that new strategy of metering in the network is able to satisfy the main objective of prevention from network gridlock and decrease of system output.

3.2 Performance Measures

Second discussion is about the changes of network performance measures. The new strategy must be able to improve the network performance measure that it could be used in the real environments. For this matter two measurements of average total delay and average speed are compared in two cases of applying IETMS and not.

For comparing the results of applying IETMS in the network, the network is simulated in another traffic simulator (Synchro) in which traffic signals could be optimized. The optimized green times have been gotten from Synchro and are applied in VISSIM. Table 1 shows the differences between averages of total delay and speed in the whole network under these two situations. As it is shown in the table, applying the new methodology in traffic signal reduces of total delay and speed by 14% and 18%, respectively.

These results show that redistribution of density in the network is an appropriate approach

Table 1. Performance measures in the whole network with without applying IETMS

replications	run1	run2	run3	run4	run5	run6	run7	run8	
NO IETMS									ave
ave delay (sec)	379	393	367	395	402	374	406	426	392.75
ave speed (km/h)	13	12	14	11	12	14	13	12	12.625
IETMS									ave
ave delay (sec)	346	325	330	327	352	338	362	321	337.625
ave speed (km/h)	14	15	14	16	15	16	14	16	15

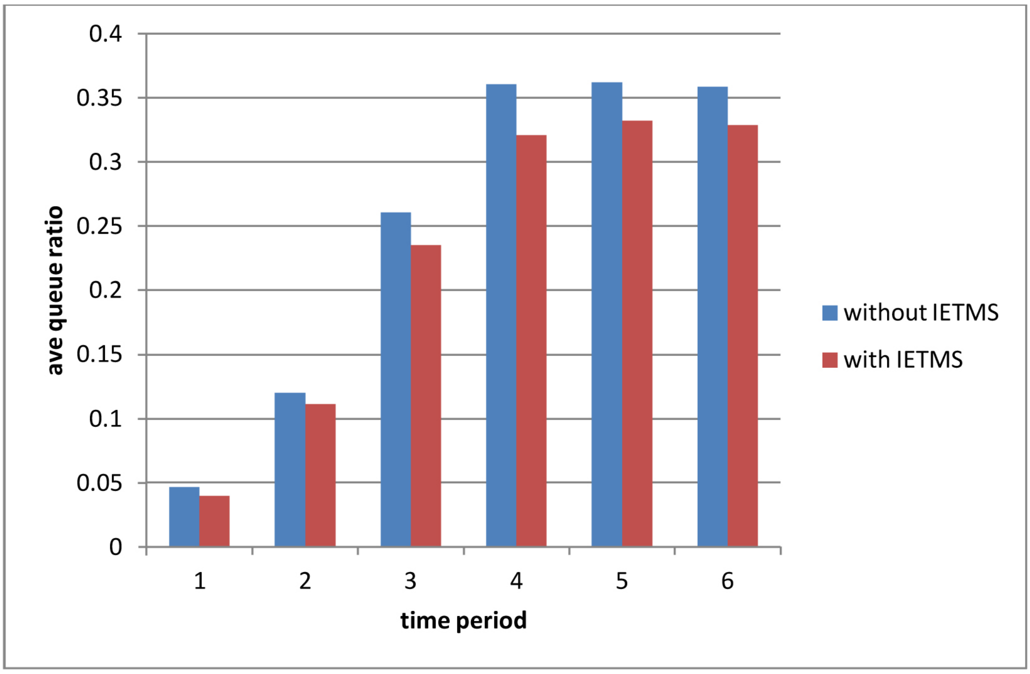

Figure 8. Average queue ratio in entrance arterials

that prevents from the gridlock to improve measure of effectiveness significantly.

One of the main objects of IETMS is to control and optimize upstream queue length of adjacent arterials. Results of comparing average queue ratios (average of queue length per length of each link) with and without applying IETMS (figure 8) determined that average of queue ratio will be reduced about 9.8% when the new strategy is applied in the network.

This is a very important issue because in the most cases, achieving an optimal solution that can consider efficiency of upstream capacity and downstream network gridlock simultaneously is a very difficult problem.

4. Conclusion

In this study, a new method of signal optimization is presented. Based on using network fundamental diagrams, an Internal–External Traffic Metering Strategy (IETMS) is developed for controlling density of traffic in high priority areas. Protecting the network from gridlock, optimizing the queue ratios in entering arterials and utilizing from the reserved capacity are the main objectives of the problem.

Results of applying the new strategy in a sample urban sub-network of Tehran show that the new strategy for network metering is able to satisfy the main objective of prevention from network gridlock and decrease of output as a result of congestion. It is also clear that redistribution of density in the network to prevent gridlock can improve effectiveness, significantly.

Another result of importance is considering the queue length in the upstream of entrance arterials. Results of comparing average queue ratios (average of queue length per length of each link) with and without applying IETMS determined that average of queue ratio will be improve about 9.8% when the new strategy is applied in the network.

For future researches it is recommended to investigate methods of solving the problem, applying the new strategy as a real time tool for optimization the signals in the network and also presenting new method for determining the boundary of sub-networks optimally considering appropriate parameters.

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