Network-Based Optimization of Traffic Signals Timing Using Internal Metering Policy by Paying Attention to Upstream Intersections

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Abstract

Timing actuated traffic signals is usually done by methodologies considering minimizing delay times, stop times, queue length etc. as the core idea. In none of such methodologies the effects of other adjacent intersections are considered. In other words, there is no control over queue congestion in such methodologies. In the proposed algorithm of traffic signs optimization, using an internal (RT/IMPOST) metering policy maintains an optimum queue length ratio within the network. In this method, the effect of upstream intersection is considered in timing procedure.

In this paper a traffic signals optimization method is elaborated and proposed for the whole network and has been particularized in three aspects: 1) The queue length ratio within the whole network: in this aspect, the queue length ratio has been conserved within an optimum interval 2) the queue time ratio: the time ratio of vehicles movement in congested condition to the free flow condition has been restricted and 3) the queue speed ratio: in this case the proportion of vehicles speed in congested condition to free flow speed has been restricted and conserved. The aim of these algorithms is to minimize the difference of queue length, time and speed ratios with their corresponding optimum values which could lead into a more optimized timing and determining efficient green phase timing for each intersection. With comparison of the results taken from each of these three algorithms, it was cleared up that queue length ratio algorithm has better results for oversaturated networks and could ameliorate the traffic conditions better compared to the other algorithms.

Keywords: Network internal metering, queue length ratio algorithm, queue time ratio algorithm, queue speed ratio algorithm, traffic signals coordination

1. Introduction

In today’s developed world, telecommunication, transportation and transport of goods and passengers have a very significant importance. Materializing such services in the shortest time possible is an outstanding task. Due to the overwhelming increase in the number of passengers and vehicles as well as the limitations in capacity of arterials, using modern technologies within the field of traffic control and management has become a must. Traffic signal control methods consist of two categories of separate network control and coordinated control. Coordinated control category, consists of arterial-based and network-based control methods while separated category consist of two pre-timed and traffic-compatible methods. One of the most disadvantages in separated network traffic control is ignoring the influence of other intersections and hence imposing local traffic congestion to the network.

Among current studies there are some papers that analyzed traffic signal timing in arterials. In these researches signal timing of intersections is calculated based on stability of queue light ratio, upstream intersections and arterial capacity. These relationships could not be used directly for the whole network because only the upstream intersection contributes in calculations and simultaneous effects of all other intersections are neglected. Therefore, there is a necessity to propose a model in which the effects of all intersections are simultaneously considered in calculations.

2. Literature review

Presently several researches have been carried out regarding network traffic control. Foroughi et al. have proposed an urban traffic control method which used Ant Colony Optimization. In their research, they have introduced a comparative route scheduler for analysis of the system function. This research has successfully determined a method to optimize the congestion flow and length of the queue [1].

Ghods and Rahimi-Kian in their research, worked on coming into an instantaneous control of traffic flow within freeway networks by using traffic signal coordination and integration. They have
used the Game Theory in their research and have also evaluated their proposed method by testing it in ramp control and speed variable constraint control. They have also evaluated this system performance based on its accuracy and quickness [2].

Derek has analyzed several methods of queue management and control and proposed two methods of (1) gate management (2) determining lag of timing at intersections in traffic peak period. Rathi and Liberman discussed that for traffic management and control of the network, it is possible to manage the flow inbound into congested areas, they have categorized network control into two categories of (1) internal metering control and (2) external metering control [3].

**Traffic congestion in urban scale, usually consists of congestion in different intersections. Based on such different intersections characteristics, Cheng Wei et al. in their study described the traffic bottlenecks. They described in their paper that traffic congestion in urban network end up in traffic blockage and flow stoppage. In their approach, this would affect free flow of traffic and in this regard, it is like Domino game. Domino phenomenon happens when the traffic reaches expansion along the route(s). A traffic Domino phenomenon happens when the traffic signal timing and design along the route is incorrect [4].**

Webster has proposed a comprehensive theory regarding traffic signal timing. This theory introduces a basis for urban traffic signal management. Based on this research, two types of traffic congestion are proposed: (1) a congestion formed based on traffic queues expansion in controlled junctions and (2) a congestion caused by blocking other junctions [5].

According to Gordon’s idea, traffic signal timing should help reducing queue length in each phase [6]. Inosi and Hamada proposed that in oversaturated condition a more appropriate aim would be maximizing system functionality [7]. Rathi et al. comprehensively categorized control strategies into internal control and external control methodologies. Internal control is a control strategy used in a control area while external control strategy controls the volume of traffic which could enter the area [8].

Gazis proposed a method to control 2 adjacent oversaturated intersections but the queue length restrictions are not taken into account [9]. Rathi et al. have proposed that the main route should have coordinated control and the secondary crossing routes should have confined offset for controlling queue length.

Kim and Messer have proposed an optimization method of traffic signal timing of saturated rhomboid intersections. Gal-Tzur has proposed a volume control strategy for urban oversaturated intersections [10]. Liu Zhang has designed a fuzzy controller for a congested network traffic signal timing [4].

Live and Kuwahara have proposed a linear optimization algorithm. In this algorithm, a signaled intersection is called oversaturated when demand is more than the intersection capacity. During peak demand periods, an actuated traffic signal is approximately similar to a signal with fixed cycles. Here the goal is optimization of green phase assignment when the flow is oversaturated assuming an instantaneous situation. In oversaturated flow “stability situation” models depending on traffic flow, become more than separation capacity because queues could not be moved and they may happen to remain during several cycles. In such situation description of dynamic queue formulation and dispersion will become critical and instantaneous formulation becomes necessary [11].

Earnst a member of Zurich Transportation Organization, in year 2000 introduced a new traffic signal system in which connecting traffic flow to oversaturated area is avoided and the flow is directed to calmer areas. This system tries to avoid a network with oversaturated traffic conditions and in order to achieve a more stable traffic flow, accessibility to different areas within the network is controlled by detection of critical congestions [12].

Some optimization software are used to control traffic signals in arterials. With aid of such software, a continuous green phase ensures an optimum flow speed. A constraint with such software is lack of accurate volume and capacity estimation in each route for optimization purposes. Furthermore, such software do not propose an appropriate plan for traffic flow sampling.

Gartner et al. have proposed a new optimization method for optimizing arterial traffic flow which uses a systematic criterion dependent to traffic. This method was effective in optimization of arterial flow and could be extended to traffic networks. [13]

Akgunor has proposed a methodology to identify the delay parameter in signalized intersection delay models. He has modeled the delay parameter as a function of analysis period instead of a fixed value used by the existing delay models. [14]

Pranevicius and Kraulis have presented a traffic signal control method based on expert knowledge for an isolated signalized intersection. Their method has had the adaptive signal timing ability to adjust its signal timing in response to changing traffic conditions. They have concluded that the proposed method has improved traffic conditions. [15]

3. Research Aims

The aim of this research is to propose algorithms for controlling network traffic at intersections by applying metering policies to control queue length ratio, queue time ratio and queue speed ratio. Each of these criteria is proposed by different algorithms which are tested in traffic network situation to find which one could best optimize traffic conditions. None of these methods has been researched up to now by paying attention to upstream intersections, and therefore the functionality and effectiveness of the approach could not be measured. In this paper, some methodological approaches for instantaneous traffic control and simulation in saturated unsaturated and oversaturated networks are proposed and evaluated.

4. Research principles

The basis is RT/IMPOST algorithm of arterials and balancing the length of queue related to successive cycles. For initializing stable queues, the number of vehicles inbound to each cycle named $i$ should be equal to the vehicles discharged considering an oversaturated condition.

Equation (1) shows there is a balance between the inbound and discharge flows. It also shows the queue length at the beginning of green phase of the next cycle (Qi+1) based on the queue length in the current cycle (Qi) and corresponding to the traffic flow [16].

Based on eq. (1) the number of vehicles within the queue is proportional to percentage of turners and time needed for each vehicle to cross the intersection

$$\frac{Q_{i+1}}{Q_i} = \frac{\frac{(G-A)}{h} + \frac{(G-A)}{h} - P + N}{\frac{(L-V)}{h} + N} = \frac{(L-V)}{h} + N$$

*Note: the definitions of each parameter in equations could be found in the Appendix*
As for balanced condition, the number of vehicles in queue should be equal. Then equation 2 could be concluded.

\[
\frac{(G_A-s)}{h} = \frac{(G_B-s)}{h} (1-P_B) + N_{C1} P_{C1} \frac{(LN)_{C1}}{(LN)_{A}} + N_{C2} P_{C2} \frac{(LN)_{C2}}{(LN)_{A}} \tag{2}
\]

The average number of vehicles exiting cross-street in intersection B in each cycle is \( N_{C1} \) and \( N_{C2} \) respectively which are determined by arterial green phase.

\[
N_{C1,C2} = \frac{(C-G_B-s)}{h} \tag{3}
\]

\( X_{C1,C2} \) is the ratio of volume to capacity in cross-street approaches \( C_1 \) and \( C_2 \).

\[
G_B = \frac{G_A - P_B s - X_{C1}(C-s)P_{C1} \frac{(LN)_{C1}}{(LN)_{A}} - X_{C2}(C-s)P_{C2} \frac{(LN)_{C2}}{(LN)_{A}}}{1 - P_B - X_{C1}P_{C1} \frac{(LN)_{C1}}{(LN)_{A}} - X_{C2}P_{C2} \frac{(LN)_{C2}}{(LN)_{A}}} \tag{4}
\]

The minimum queue length to route length ratio of \( [r_{0}]_{\text{min}} \) in arterial approach which is formed from inbound traffic of cross-street per upstream intersection:

\[
[r_{0}]_{\text{min}} = \text{max} \left[ \frac{L_{E}}{L} N_{C2} \frac{(LN)_{C2}}{(LN)_{A}} \frac{2L_{V}}{L} \right] \tag{5}
\]

The maximum queue length ratio to route length of \( [r_{0}]_{\text{max}} \) is calculated in each cycle for avoiding expansion of length of congested queue. Larger queues would result in unnecessary stops of the vehicles. The other factor is the need to avoid detector break-down. This precaution is applied where queue length is expanded too much on the detector and there is a risk this will cause a negative effect on queue estimation algorithm. [5]

\[
[r_{0}]_{\text{max}} = \text{min} \left[ \frac{1}{L} \frac{W + F}{L} 1.1 \frac{(G_A - s) L_{P}}{hL} 1.1 \frac{L_{P}}{L} \right] \tag{6}
\]

Liberman et al. have devised an instantaneous metering policy for optimization of traffic signal timing in oversaturated arterials intersections. They have used the above-mentioned equation 1 through 6 to come to a target function. This function is based on minimizing the deference between the queue length ratio of the queue generated in arterials and the optimized length. Solving this equation, the green phase duration could be determined. For determining green phase, arterial queue length ratio and cross-street offset time should be maximized and minimized respectively.

\[
\text{Min} = \sum_{i,j} (r_{ij} - \hat{r}_{ij})^2 + \sum_{i,j} (\hat{r}_{ij} - \bar{r}_{ij})^2 \tag{7}
\]

\[ S.T: \]

\[
[r_{0,i,j}]_{\text{min}} \leq r_{ij} = \hat{r}_{ij} + \Delta_{0,i,j} \leq [r_{0,i,j}]_{\text{max}} \]

\[
\Delta_{i,j} \leq \Delta = \left[ \frac{1}{v_i} \left( 1 + \frac{1}{w_i} \right) - \frac{1}{w} \frac{1}{u} \right] \leq \Delta_{\text{max}}
\]

\[
\tau = \text{the calculation method of this variable is given in equation 7.}
\]

The queue length could vary from one cycle to another depending to service ratios, turn movements and traffic composition in short term. For this policy approach, it is necessary to maintain queue length by means of traffic control. This equation is used to schedule the arterial green phase duration of \( G_{A-i,j} \). Therefore, actual arterial queues of \( r_{0,i,j} \) and \( \hat{r}_{0,i,j} \) in each saturated approach of \( i \) are calculated approximately close to optimum queue length ratios and considered as \( r_{0,i,j} \) and \( \hat{r}_{0,i,j} \) [16].

The above description and equations are used for controlling signalized intersections against traffic congestion. Yet no other intersection effects have been considered in them. This means that the congestion of each questioned intersection is affected by the adjacent intersections and only considering the upstream intersection is not enough. Hence arterial equations should be extended and used for the whole network. By extension of these equations the queue length ratio algorithm is made up. Such algorithm just controls the queue length ratio in each approach and prevents forming long queues. But this algorithm does not consider the vehicle discharge duration and their movement speed. Therefore, queue time and queue speed ratios algorithms are determined as well. The queue duration ratio algorithm better controls queues discharge flow time and prevents formation of long queues. The queue speed ratios algorithm similarly optimizes the speed of vehicles movements.

Fig. 1 shows the schematic of congestion in the arterial and the network respectively. As shown in this figure for timing control of these intersections only the upstream intersection is considered. Yet the traffic is affected by other adjacent intersections as well. Fig. 1 indicates the necessity of extension of arterial relationships to the network.
5. Formulation of algorithms

Liberman et al., as mentioned, proposed an algorithm for controlling spillback in arterials [16]. In this paper by applying some alterations to this algorithm, some new relationships for controlling queue length, time and speed ratios within the network have been proposed.

These alterations consist of extension of offset and queue ratios restrictions as well as time and queue speed to the whole network. Furthermore, the proposed corrected algorithm for calculating green phase time of an intersection, all the adjacent intersections are taken into account. Fig. 2 shows traffic relationships of adjacent intersections.

The algorithms of queue length ratio, queue time ratio and queue speed ratio are based on applying balance between queue length, time and speed of different cycles. The strategy of designing this algorithm is to impose restrictions for the queue length ratio, queue time and queue speed ratios in order to bring them into stability.

Below are the relationships of traffic network control obtained after applying some alterations on typical arterial relationships [16]. For calculation of green phase time of downstream intersection, based on equation 4, cycle duration, the percentage of cross-street turn movements, percentage of turns from downstream intersection, the saturation percentage in cross-street and number of lanes for all adjacent intersections have been used.

\[
G_{i-1} = \frac{G_i - P_i \cdot s - X_{C1}(C-s)P_{C1} \cdot (LN)_{i1} - X_{C2}(C-s)P_{C2} \cdot (LN)_{i2}}{1 - P_i - X_{C1}P_{C1} \cdot (LN)_{i1} - X_{C2}P_{C2} \cdot (LN)_{i2}} \quad (8)
\]

System restrictions could not be applicable for control of all intersection phases. Hence queue lengths in all saturated approaches are designed in the optimized state. The first restrictor is the minimum queue length ratio \([r_0]_{\text{min}}\) which is generated from the inbound flow from cross-street for upstream intersection.

This is calculated for avoiding green phase time loss. The minimum queue length ratio is given in eq. 9.

\[
[r_0]_{\text{min}} = \max \left[ \frac{L_F}{L} N_C P_C \cdot \frac{(LN)_{i1} - 2L_F}{(LN)_{i1} - L} \right] \quad (9)
\]

The second restrictor, is the maximum queue length ratio \([r_0]_{\text{max}}\) which is used to avoid congestion and is given in eq. 10.

\[
[r_0]_{\text{max}} = \min \left[ 1 - \frac{W + F \cdot s - L}{L}, 1 \frac{(G_i - s)L_F}{hL}, 1 \frac{L_D}{L} \right] \quad (10)
\]

In eq. 11, 14 and 17, the target function of each three algorithms are presented. In eq. 11, the target is minimizing the queue length ratio. For solving this target function, queue length ratio, offset time and duration of green phase should fall between maximum and minimum calculated values.

\[
\text{Minimize} = \sum_{i,j} \left( r_{0,ij} - \hat{r}_{0,ij} \right)^2 + \sum_{i,j} \left( \hat{r}_{0,ij} - \tilde{r}_{0,ij} \right)^2 \quad (11)
\]

S.T.: 
\[
\begin{align*}
\hat{r}_{0,ij} &= r_{0,ij} + \Delta r_{0,ij} \\
\hat{r}_{0,ij} &\geq [r_0]_{\text{min}} \\
\hat{r}_{0,ij} &\leq [r_0]_{\text{max}} \\
\Delta_{\text{min}} &\leq \Delta = L \left[ \frac{1 - r}{v_1} \right ] - \frac{r}{w} + R \left [ \frac{1 - w}{1 - w} \right ] \leq \Delta_{\text{max}} \\
\Delta_{\text{max}} &\leq L \left[ \frac{1 - r}{v_1} \right ] - \frac{r}{w} + R \left [ \frac{1 - w}{1 - w} \right ] \leq \Delta_{\text{max}} \\
\Delta_{\text{min}} &\leq L \left[ \frac{1 - r}{v_1} \right ] - \frac{r}{w} + R \left [ \frac{1 - w}{1 - w} \right ] \leq \Delta_{\text{max}} \\

\end{align*}
\]
Journal of Geotechnical and Transportation Engineering - 2017 vol. 3 (1)

\[ \tau = \left[ (LN)_{i-1} X_{C1} P_{C1} S^{C1} + (LN)_{i-1} X_{C2} P_{C2} S^{C2} \right] C - G_{i-1} - s \]

Let: \( R_i = \frac{(LN)_{i-1}}{(LN)_{i}} \)

Then

\[ \Delta_0 = (G_{i-1} - s) \left[ R_i S_i \left( 1 - P_i^f + P_i^c P_{i-1} - P_{i-1} \right) \frac{1}{v_0} - G_i S_i \frac{1}{v_0} + \frac{\tau}{(LN)_{i}} \frac{L}{T_i} + s \right] \frac{1}{L} \]

Proposing this algorithm is for avoiding formation of long queues along with network routes. In this algorithm, the ratio of queue length caused by the vehicles within the queue is not considered, on the other hand, queue length, the discharge flow time and the delay time decrease should be considered in network control. Based on this algorithm the ratio of queue time is proposed. The first restrictor is minimizing free flow movement time to the congested situation \( m_{0\min} \) which is formed for upstream intersection from traffic inbounds of cross-street. This is shown in eq. 12. This value is dependent to the ratio of the average time loss of the vehicle to the time the vehicles moves in congested situation (i.e. the average delay time).

\[ m_{0\min} = \max \left[ \frac{1}{v_0} N_{C_P C} (LN)_C (2T_i) \right] \]

(12)

The second restrictor is maximum ratio of movement time in the free flow situation to the congested flow situation \( m_{0\max} \) which is calculated in each stage for avoiding the increase of movement time. This restriction is given in eq. (13)

\[ m_{0\max} = \min \left[ 1 + \frac{W + F}{L} - \frac{1}{1.1} \frac{(G_i - s)T_i}{v_0} \frac{1.1L/D}{L} \right] \]

(13)

In eq. 14 the aim is minimizing the queue time ratio. What is meant by queue time ratio, is the ratio of movement time in free flow to congested flow situation. For formation of target function, queue time ratio, offset time and green phase time should remain between maximum and minimum situation.

\[ \text{Minimize } = \sum_{i,j} (m_{0i,j} - \tilde{m}_{0i,j})^2 + \sum_{i,j} (m_{0i,j} - \tilde{m}_{0i,j})^2 \]

S.T.:
\[ m_{0i,j} = \frac{T_0}{T} + \Delta m_0 \]

\[ \tau = \left[ (LN)_{i-1} X_{C1} P_{C1} S^{C1} + (LN)_{i-1} X_{C2} P_{C2} S^{C2} \right] C - G_{i-1} - s \]

Let: \( R_i = \frac{(LN)_{i-1}}{(LN)_{i}} \)

Then

\[ \Delta_0 = (G_{i-1} - s) \left[ R_i S_i \left( 1 - P_i^f + P_i^c P_{i-1} - P_{i-1} \right) \frac{T_i}{v_0} - G_i S_i \frac{T_i}{v_0} + \frac{\tau}{(LN)_{i}} \frac{T_i}{v_0} + s \right] \frac{1}{L} \]

\[ m_{0i,j} \geq m_{0i,j} \] \[ m_{0i,j} \leq m_{0i,j} \]

\[ \Delta_{\min} \leq \Delta = T_0 \left[ \frac{1 - m}{v_1} - \frac{m}{w} + m \left( \frac{1}{w} - \frac{1}{u} \right) \right] \leq \Delta_{\max} \]

\[ \Delta_{\min} = T_0 \left[ \frac{1 - m}{v_1} + \frac{G_i - s}{P_i - P_{i-1}} \frac{L}{W} \left( \frac{1}{w} - \frac{1}{u} \right) \right] \]

\[ \Delta_{\min} = T_0 \left[ \frac{1 - m}{v_1} + \frac{G_i - s}{P_i - P_{i-1}} \frac{L}{W} \right] \]

Algorithms of queue length and queue time ratios are proposed to avoid congestion of queues and increase in delay time. None of these algorithms alone have any consideration regarding the optimum speed of vehicles within the network. Therefore, the queue speed ratio algorithm is proposed to control the speed of vehicles within the network. This algorithm considers the interrelated effects of queue length and queue time.

The first constraint is the minimum ratio of movement speed in congested situation to free flow situation \( \bar{V}_{0\max} \) which forms for upstream intersection by the inbound traffic from cross-street. This constraint is given in eq. (15)

\[ \bar{V}_{0\max} = \max \frac{V_f}{V_0} \frac{N_{C_P C} (LN)_C (2T_i)}{(LN)_i} \frac{v_0}{V_f} \]

(15)

The second restrictor is the proportion maximum movement time in congested situation to free situation \( \bar{V}_{0\max} \). For avoiding the increase of movement time, it is calculated in each stage and is give in eq. 16

\[ \bar{V}_{0\max} = \min \left[ 1 - \frac{W + F}{L} - \frac{1}{1.1} \frac{(G_i - s)T_i}{v_0} \frac{1.1L/D}{L} \right] \]

(16)

In eq. 17, the aim is minimizing the ratio of queue movement speed. The queue movement speed ratio means the proportion of vehicles speed in congested flow situation to free flow situation. To solve this target function, it is necessary to put the queue speed ratio, offset value and green phase duration between maximum and minimum values.

\[ \text{Minimize } = \sum_{i,j} (V_{0i,j} - \tilde{V}_{0i,j})^2 + \sum_{i,j} (V_{0i,j} - \tilde{V}_{0i,j})^2 \]

(17)

S.T.:
\[ v_{0i,j} = \frac{V_f}{V_0} + \Delta v_0 \]

\[ \tau = \left[ (LN)_{i-1} X_{C1} P_{C1} S^{C1} + (LN)_{i-1} X_{C2} P_{C2} S^{C2} \right] C - G_{i-1} - s \]

Let: \( R_i = \frac{(LN)_{i-1}}{(LN)_{i}} \)

Then

\[ \Delta_0 = (G_{i-1} - s) \left[ R_i S_i \left( 1 - P_i^f + P_i^c P_{i-1} - P_{i-1} \right) \frac{T_i}{v_0} - G_i S_i \frac{T_i}{v_0} + \frac{\tau}{(LN)_{i}} \frac{T_i}{v_0} + s \right] \frac{1}{L} \]

\[ m_{0i,j} \geq m_{0i,j} \] \[ m_{0i,j} \leq m_{0i,j} \]

\[ \Delta_{\min} \leq \Delta = T_0 \left[ \frac{1 - v}{v_1} - \frac{v}{w} + v \left( \frac{1}{w} - \frac{1}{u} \right) \right] \leq \Delta_{\max} \]

\[ \Delta_{\min} = T_0 \left[ \frac{1 - v}{v_1} + \frac{G_i - s}{1 - P_i^f} \frac{L}{W} \left( \frac{1}{w} - \frac{1}{u} \right) \right] \]

\[ \Delta_{\min} = T_0 \left[ \frac{1 - v}{v_1} + \frac{G_i - s}{1 - P_i^f} \frac{L}{W} \right] \]

\[ \frac{G_{i-1,j}}{\min} \leq G_{i-1,j} \leq \frac{G_{i-1,j}}{\max} \]

\[ \frac{G_{i-1,j}}{\min} = 15 \text{sec} \]
\[ \frac{G_{i-1,j}}{\max} = 120 \text{sec} \]
In each route, taking into account the density and vehicles speed, the flow could be calculated (in veh/sec) then downstream green phase time could be calculated. This time could be responsible for satisfying the aim of minimizing the difference of queue length, time and speed with the optimum situation. To this end, considering the constraints is a must. These ratios should fall between the maximum and minimum values. Furthermore, offsets should as well remain between maximum and minimum determined values.

6. The results of computer simulation of algorithms

Queue length ratio, queue time ratio and queue speed ratio algorithms have been simulated in TSS Transport Aimsun traffic simulation software. To evaluate the performance of each algorithm in traffic networks, three entering volumes were considered and each algorithm is applied to each of these three volumes.

The traffic network considered is a dummy 3*3 network. Below the results of each simulated algorithm are discussed:

6.1. Results in saturated traffic condition

Table 1 shows the network parameters after one hour application of each algorithm to the network. Considering the above table, by applying queue length ratio algorithm, delay time, speed and density are increased by 12%, 14% and 6% respectively. Flow rate is decreased by 45%. By applying queue time ratio algorithm, delay time and density are decreased by 45% and 53% respectively. Flow rate and speed are increased by 30% and 53% respectively. By applying queue speed ratio algorithm, delay time density and Flow rate are decreased by 20%, 18% and 14% respectively. The speed is increased by 25%.

The queue length ratio per each three algorithms of queue length ratio, queue time and speed ratio has been found out. Table 2 shows the queue length ratio of each the algorithms and compares them to the initial value.

As seen in Table 2, by applying restrictions for queue length ratio in the whole network, queue length ratio has been decreased by 12%. However, in some routes this has caused an increase in queue length but this increase was not noticeable.

Queue time ratio algorithm has caused the highest decrease of 51% in queue length. The queue speed ratio algorithm has decreased the queue length by 24%. The highlighted cells in the Table 2, indicate an increase in comparison to the previous situation. Considering these cells, we can conclude the routes that have an increase in queue length ratio are the queues with lesser initial queue lengths. This means that by applying the algorithm, not only the congestion of the network is removed but also the waste in green phase time and shortage of traffic by low volumes of traffic has been well treated.

6.2. Results in oversaturated traffic condition

Table 3 shows the results after one hour of applying each algorithm to an oversaturated network. Considering Table 3, by applying queue length ratio algorithm, density and speed are increased by 9% and 15% respectively. Delay time and flow rate are decreased by 7% and 25% respectively. By applying queue time ratio algorithm, delay time and density are decreased by 20%, 18% and 14% respectively. The speed is increased by 25%.

As seen in Table 2, by applying restrictions for queue length ratio in the whole network, queue length ratio has been decreased by 12%. However, in some routes this has caused an increase in queue length but this increase was not noticeable.

Queue time ratio algorithm has caused the highest decrease of 51% in queue length. The queue speed ratio algorithm has decreased the queue length by 24%. The highlighted cells in the Table 2, indicate an increase in comparison to the previous situation. Considering these cells, we can conclude the routes that have an increase in queue length ratio are the queues with lesser initial queue lengths. This means that by applying the algorithm, not only the congestion of the network is removed but also the waste in green phase time and shortage of traffic by low volumes of traffic has been well treated.
Table 3- Aimsun simulation results after applying queue length, time and speed ratio

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Initial value</th>
<th>Queue length ratio algorithm</th>
<th>Queue time ratio algorithm</th>
<th>Queue speed ratio algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay time</td>
<td>second/km</td>
<td>484.5</td>
<td>453</td>
<td>361.5</td>
<td>282.5</td>
</tr>
<tr>
<td>Density</td>
<td>veh/km</td>
<td>72.1</td>
<td>78.7</td>
<td>55.58</td>
<td>76.2</td>
</tr>
<tr>
<td>Flow</td>
<td>veh/h</td>
<td>5243</td>
<td>3936</td>
<td>6170</td>
<td>2553</td>
</tr>
<tr>
<td>Speed</td>
<td>km/h</td>
<td>10.23</td>
<td>11.74</td>
<td>13.5</td>
<td>15.22</td>
</tr>
<tr>
<td>Stop time</td>
<td>second/km</td>
<td>459.6</td>
<td>430</td>
<td>337.8</td>
<td>259.7</td>
</tr>
<tr>
<td>Stop</td>
<td>#/veh/km</td>
<td>4.63</td>
<td>4.8</td>
<td>5.4</td>
<td>4.3</td>
</tr>
<tr>
<td>The Total travel lengths</td>
<td>km</td>
<td>7422.7</td>
<td>5641.7</td>
<td>8839.3</td>
<td>3436.55</td>
</tr>
<tr>
<td>The Total travel times</td>
<td>hours</td>
<td>1069.5</td>
<td>758</td>
<td>998.1</td>
<td>322.1</td>
</tr>
<tr>
<td>Travel time</td>
<td>second/km</td>
<td>549.4</td>
<td>517.8</td>
<td>426.4</td>
<td>347.3</td>
</tr>
</tbody>
</table>

Flow rate and speed are increased by 18% and 32% respectively. By applying queue speed ratio algorithm, delay time density and speed are increased by 6% and 49% respectively. The delay time and flow rate are decreased by 42% and 51% respectively.

The queue length ratio per each three algorithms of queue length ratio, queue time and speed ratio has been found out. Table 4 shows the queue length ratio of each three algorithms and compares them to the initial value.

Table 4-The ratio of queue length and the change percentage in network routes before and after applying proposed algorithms with 20% increase in incoming volume

<table>
<thead>
<tr>
<th>Intersection</th>
<th>The average initial queue length ratio</th>
<th>Queue length ratio algorithm</th>
<th>Queue time ratio algorithm</th>
<th>Queue speed ratio algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72</td>
<td>0.54</td>
<td>0.48</td>
<td>0.59</td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
<td>0.51</td>
<td>0.28</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>0.63</td>
<td>0.74</td>
<td>0.46</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>0.56</td>
<td>0.48</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>0.39</td>
<td>0.23</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>0.54</td>
<td>0.63</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>7</td>
<td>0.46</td>
<td>0.39</td>
<td>0.42</td>
<td>0.38</td>
</tr>
<tr>
<td>8</td>
<td>0.35</td>
<td>0.38</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>9</td>
<td>0.63</td>
<td>0.58</td>
<td>0.38</td>
<td>0.79</td>
</tr>
<tr>
<td>Total network</td>
<td>0.5</td>
<td>0.47</td>
<td>0.36</td>
<td>0.45</td>
</tr>
</tbody>
</table>

As seen in Table 4, by applying restrictions for queue length ratio in the whole network, queue length ratio has been decreased by 7%. However, in some routes this has caused an increase in queue length but this increase was not noticeable.

According to Table 4, queue time ratio algorithm has caused the highest decrease of 27% in queue length. The queue speed ratio algorithm has decreased the queue length by 10% at whole network scale. The highlighted cells in the Table 2, indicate an increase in comparison to the previous situation.

6.3. Results in non-saturated traffic condition

Table 5 shows the results after one hour of applying each algorithm to a non-saturated network.

Table 5- the Aimsun simulation results after applying queue length, time and speed ratio

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Initial value</th>
<th>Queue length ratio algorithm</th>
<th>Queue time ratio algorithm</th>
<th>Queue speed ratio algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay time</td>
<td>second/km</td>
<td>329</td>
<td>238.2</td>
<td>195.6</td>
<td>231.7</td>
</tr>
<tr>
<td>Density</td>
<td>veh/km</td>
<td>59.6</td>
<td>41</td>
<td>36.5</td>
<td>45.1</td>
</tr>
<tr>
<td>Flow</td>
<td>veh/h</td>
<td>6436</td>
<td>7308</td>
<td>6583</td>
<td>5304</td>
</tr>
<tr>
<td>Speed</td>
<td>km/h</td>
<td>12.82</td>
<td>15.7</td>
<td>18.7</td>
<td>16.9</td>
</tr>
<tr>
<td>Stop time</td>
<td>second/km</td>
<td>305.6</td>
<td>216.4</td>
<td>175.4</td>
<td>210.9</td>
</tr>
<tr>
<td>Stop</td>
<td>#/veh/km</td>
<td>4.21</td>
<td>3.61</td>
<td>3.62</td>
<td>3.63</td>
</tr>
<tr>
<td>The Total travel lengths</td>
<td>km</td>
<td>9455</td>
<td>10963</td>
<td>9391</td>
<td>7757</td>
</tr>
<tr>
<td>The Total travel times</td>
<td>hours</td>
<td>1000</td>
<td>852.4</td>
<td>662</td>
<td>606.2</td>
</tr>
<tr>
<td>Travel time</td>
<td>second/km</td>
<td>394</td>
<td>303</td>
<td>260.5</td>
<td>296.8</td>
</tr>
</tbody>
</table>

Considering the above table, by applying queue length ratio algorithm, delay time and density are decreased by 28% and 31% respectively. Flow rate and speed are increased by 14% and 22% respectively. By applying queue time ratio algorithm, delay time and density are decreased by 41% and 39% respectively. Flow rate and speed are increased by 2% and 46% respectively. By applying queue speed ratio algorithm, delay time and density are decreased by 30% and 24% respectively. The Flow rate decreased by 18% and speed is increased by 32%.

By 20% decrease in O-D matrix, the maximum green phase time in Aimsun software becomes 5 seconds higher than the value determined by target function. For each of these three algorithms, queue length, time and speed ratios in each approach have been calculated and the results have been compared to the base case situation.
As seen in Table 6, by applying restrictions for queue length ratio in the whole network, queue length has been decreased by 28%. Queue time ratio algorithm has caused the highest decrease of 37% in queue length. The queue speed ratio algorithm has decreased the queue length by 30%. Queue time ratio algorithm has caused the highest decrease in queue length ratio of the whole network.

The highlighted cells in the Table 6, indicate an increase in comparison to the previous situation.

As can be concluded from the above tables in saturated and over saturated conditions, queue time ratio algorithm shows the best results because it has resulted in decrease of delay, density and queue length ratio in one hand and, it has caused an increase in vehicle flow speed of the whole network in other hand. This is because queue time ratio algorithm leads to a balanced dispersal of the flow throughout the network and that is why the inbound flow to the network increases.

In non-saturated situation, due to less density, network experiences a higher entrance flow. As seen from the tables, each of three algorithms bring better conditions for the network. Because all of them have caused delay times and density of the network is decreased but the speeds of vehicles are increased.

Queue length ratio and queue time ratio has decreased the entrance flow rate but queue speed ratio has caused a confinement in flow directed to the network. This is because in this situation, network is in non-saturated condition and could undertake more traffic values. This is the reason why algorithms did not affect the confinement of flow entered in the network.

7. Conclusion

The metering policies could be applied by entering approaches. But to undertake this control, some parameters should be considered. The parameters that in this paper has considered as network controller consist of: position, time and speed. Because long queues in arterials and then blockage happen in one of the following situations:

1- The length of queue formed is very excessive and has made a spill-back to the downstream intersection
2- The queue discharge is not happening at an appropriate time and causes some unduly long delays
3- The queue discharge rate is so low that the awaiting vehicles do not discharge the queue in time and this causes blockage in the network.

In this paper, an imaginary network of 9 intersections and an artificial traffic load was considered. In other instances, at a same condition queue time, length and speed ratio algorithms were simulated in the network. The delay, blockage and travel times as well as flow, density, etc. where calculated for before and after simulation of algorithms. These algorithms were applied to the network under three conditions of 1) non-saturated, saturated and oversaturated conditions.

The queue length, time and speed ratio algorithms have been applied to traffic network with different entrance flows which each has caused different discharges. In non-saturated condition, queue length and time ratio algorithms caused an increase in incoming flow and decrease in delay, density of queue length ratio in the routes. Queue speed ratio algorithm has caused a decrease in incoming flow, delay, density and increase in vehicles flow speed.

In saturated condition, by applying queue length ratio algorithm the inbound flow has been reduced much and the queue length of the routes reached to a reasonable level. The queue speed ratio algorithm has caused reducing inbound flow as well as delay and lengthening the queues. Considering these results, it is inevitable that queue time ratio algorithm causes a more appropriate timing of traffic signals within the network because more demand as compared to base case situation has been handled and the density in this algorithm, compared to other algorithms, has been better-distributed within the network. Due to the relationships between place, time and speed, speed control has resulted in an intermediate outcome compared to queue length and time control.

In oversaturated condition, applying queue length ratio algorithm, the entering flow and delay time are reduced and queue length in routes have reached a reasonable level. Applying queue time ratio has led to increase in the inbound flow as well as reduction of delay and density within network. The queue length as well has been reduced substantially. Queue speed ratio in the whole network has increased the entered flow and resulted in delay and lengthening of the queues.

With comparing outcomes of each algorithm application on the network by three different flows, it was determined that network traffic has different behaviors under each non-saturated and two other flows. In non-saturated condition, by increasing the flow and flow, a substantial decrease in delays and density takes place. This is because the network could pass higher flow rates till it reaches saturation.

Considering different effects of algorithms on traffic networks, it is suggested if we need to control the incoming traffic in an oversaturated network, the queue speed ratio algorithm and if there is a necessity to increase the entering flow as well as reducing delay and queue length, the queue length ratio algorithm is used. In non-saturated traffic network, speed control makes the
incoming flow restricted and queue length and time ratio algorithms are capable of passing more flow with less delay and less queue length.

References

## Appendix

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>Arterial approach length</td>
</tr>
<tr>
<td>$h$</td>
<td>Mean queue discharge headway, sec/veh.</td>
</tr>
<tr>
<td>$(LN)_{C1,C2}$</td>
<td>Number of lanes on the cross street approaches 1, 2, respectively</td>
</tr>
<tr>
<td>$N_{C1,C2}$</td>
<td>Average number of cross street vehicles per-lane seeking service in one cycle for cross-street approaches 1 and 2 respectively</td>
</tr>
<tr>
<td>$L'$</td>
<td>Average vehicle spacing within a standing queue.</td>
</tr>
<tr>
<td>$s$</td>
<td>Lost time per green phase, sec</td>
</tr>
<tr>
<td>$F$</td>
<td>Safety factor to guard against spill-back.</td>
</tr>
<tr>
<td>$P_{C1,C2}$</td>
<td>Proportion of total traffic on the cross street approaches 1 and 2 respectively, that turns onto arterial link.</td>
</tr>
<tr>
<td>$C$</td>
<td>Cycle length, sec.</td>
</tr>
<tr>
<td>$V_L$</td>
<td>Average vehicle spacing within a standing queue.</td>
</tr>
<tr>
<td>$2, 1$</td>
<td>Number of lanes on the cross street approaches 1, 2, respectively</td>
</tr>
<tr>
<td>$2, 1$</td>
<td>Number of lanes in intersection i and approach j</td>
</tr>
<tr>
<td>$S^l$</td>
<td>Average vehicle discharge rate, veh/sec.</td>
</tr>
<tr>
<td>$P_{l-1}$</td>
<td>Percent of turners from arterial feeder approach</td>
</tr>
<tr>
<td>$X_{C1,C2}$</td>
<td>Percent saturation on cross street 1 and 2</td>
</tr>
<tr>
<td>$\left[\hat{q}<em>{0,j,i}\right]</em>{\text{est}}$</td>
<td>Optimum standing queue length ratio in intersection i and approach j</td>
</tr>
<tr>
<td>$\left[\hat{q}<em>{0,j,i}\right]</em>{\text{min}}$</td>
<td>Minimum queue length ratio in intersection i and approach j</td>
</tr>
<tr>
<td>$\left[\hat{q}<em>{0,j,i}\right]</em>{\text{max}}$</td>
<td>Maximum queue length ratio (q/L) in intersection i and approach j</td>
</tr>
<tr>
<td>$T_v$</td>
<td>Vehicles travel time in congested situations, assumed as delay</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Vehicles travel time in free situations</td>
</tr>
<tr>
<td>$V$</td>
<td>Vehicles speed based on density of the link</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of vehicles in each time period</td>
</tr>
<tr>
<td>$\hat{m}_{0,i,j}$</td>
<td>Optimum queue time ratio in intersection i and approach j</td>
</tr>
<tr>
<td>$\left[m_{0,i,j}\right]_{\text{max}}$</td>
<td>Maximum queue time ratio in intersection i and approach j</td>
</tr>
<tr>
<td>$\left[m_{0,i,j}\right]_{\text{min}}$</td>
<td>Minimum queue time ratio in intersection i and approach j</td>
</tr>
<tr>
<td>$\hat{v}_i$</td>
<td>Mean speed of the lead vehicle of the incoming platoon, assumed 6 m/sec</td>
</tr>
<tr>
<td>$\Delta m_0$</td>
<td>Change in queue time ratio</td>
</tr>
<tr>
<td>$\hat{v}$</td>
<td>Discharge wave speed, assumed 10 m/sec</td>
</tr>
<tr>
<td>$\hat{u}$</td>
<td>Discharge wave speed, assumed 10 m/sec</td>
</tr>
<tr>
<td>$w$</td>
<td>Shock wave speed, assumed 8 m/sec</td>
</tr>
</tbody>
</table>