PERFORMANCE OF TRAFFIC SIGNAL CONTROL IN SATURATED TRAFFIC CONDITIONS

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Abstract: This paper summarizes the traffic signal control performances during the period of traffic saturation. The efficiency of traffic operations in various traffic conditions and signal control methods are investigated. The study focuses on two types of saturated traffic demand; constant and time-dependent. The study also explores various traffic control strategies for congested conditions. They range from fixed time to real-time adaptive control. The analyses are mainly conducted using CORSIM simulation. The impacts of the control on delay, queue, fuel consumption, and other indicators are assessed. The results of each control are compared and the control that yields the highest performance in each traffic scenario is disclosed. The results of the research will lead to the better traffic control and operations which accounts for congested conditions.

Key Words: Signal Control, Saturated condition, Performance

1. INTRODUCTION

Signal control is a common practice in the management of traffic in urban areas. The traffic control has an advantage on its adaptability to current traffic conditions. Many of existing traffic control systems are designed to cope with variable traffic conditions, from low flow to high flow level as well as varying traffic volume. Nonetheless, few of them exclusively deal with saturated traffic conditions. Many cities experience the situation where the demand for traffic passing through a road link exceeds its capacity during considerable time period in a day. This saturated traffic condition makes aggravating traffic congestion that lasts for expansive time.

The attempts to yield more efficient signal control methods are dated back 30 years ago by several researchers. The review is summarized in Organisation of Economic Co-operation and Development, OECD (1981). There have been many traffic signal control techniques available to cope with a variety of traffic conditions. Some researchers have worked on the theoretical solutions while the practitioners have adopted those findings into many commercial signal control systems. It is noted that many systems lack the signal control determination exclusively for saturated traffic conditions. Moreover, there is no comparative study on the effectiveness of each signal control method in a traffic control condition. In addition, there is no investigation of the performance over the range of the traffic volumes.

This paper addresses the testing and comparative study of various traffic signal control methods under diverse traffic conditions. The focus aims at the signal control in saturated conditions, both constant and time-varying traffic levels.

2. THEORETICAL BACKGROUND

Many theoretical researches of optimal signal control have been done for many decades. The early examination was conducted by rigorous mathematical formulation and analysis. Webster was the first who extensively investigated signal performance and signal setting method for undersaturated traffic flow condition. The examination on traffic signal control in undersaturated (or low flow) condition is now more or less well researched. The signal control policy is to yield the maximum efficient use and minimize travel time loss. The implicit assumption of the signal control is that the interference between intersections is negligible. This control policy is adopted in many commercial signal control systems, such as

TRANSYT, SYNCHRO™, and SCOOT. Most of them recommend the signal setting with a method similar to Webster's calculation and by means of an optimization method.

The traffic signal control near or in saturated conditions has also long been studied. These signal control methods are reviewed by OECD (1981) and Shepherd (1992). The controls in these traffic conditions are somewhat more difficult than the low flow conditions since they require much of real-time traffic information and more adaptive signal setting. Some special control procedures are required to deal with the effect of queues that interact adjacent intersections. The concept of queue management is suggested to replace the delay minimization policy, although this is not directly applied in most commercial signal control software. Quinn (1992) suggested that the queue length should determine the signal control policy during saturated traffic condition. Figure 1 shows that once the queue length is permanently developed at intersection approaches, the control method should shift from delay minimization to capacity maximization. When the queues extend to fill the approaches (or the queue storages are full), then the signal should be adjusted so that the intersection blockage is prevented. After the oversaturation is over, the signal is set to fasten the release of the queues.

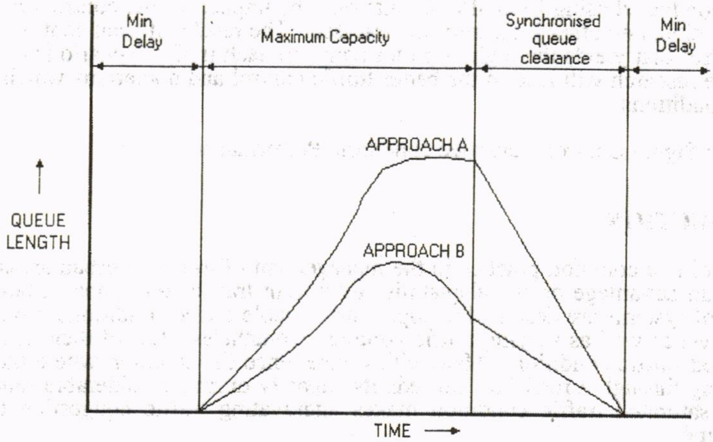


Figure 1. Signal control by queue management technique (Quinn, 1992)

Although several concepts of signal control in saturated conditions are recommended, there are only few work that explicitly investigate the performance and practicality of these techniques.

Two major limitations of the application of the signal control policy in saturated conditions are (1) when and how fast the control methods should be implemented and (2) the amount of traffic information for signal control should be obtained. Most commercial signal control systems have "sluggishness" factor that prevents the signal from sudden change. This may be a major limitation since the timings during the queue-growing period require fast adaptation. Yielding more advanced control requires also an amount of traffic data, real-time and more frequent. Not only traffic volume in each movement but also queue length or another queue information is requested for signal control determination. This means more investment on traffic data gathering effort and more accuracy.

3. RESEARCH METHODOLOGY

The study is designed to compare the performance of signal control methods under various traffic conditions.

As it is impossible to experiment the control across geometric configuration, a hypothetical network is selected to be a test bed for this study. A road network consists of a five-intersection corridor whose the middle intersection intersects with another major street. The layout of the test network is shown in Figure 2. It is noted that the construction of the network does not mean to represent any real-world road network but builds the reference level for comparison. The dimension of the test network is associated with the duration of study (simulation time) and tested traffic volumes.

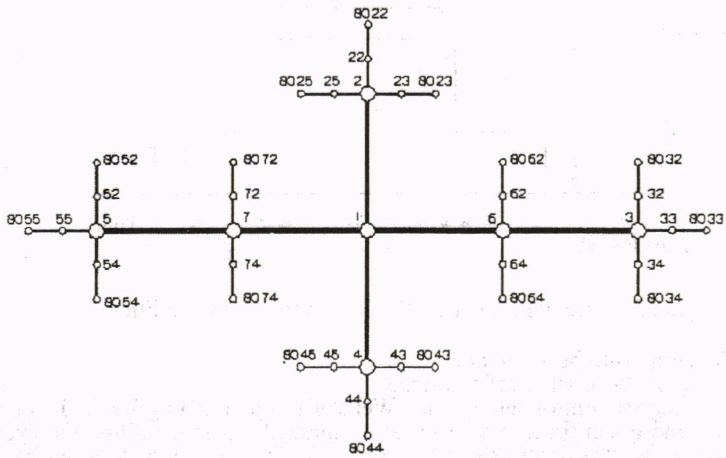


Figure 2. Network for testing signal control

Two types of traffic are examined: constant and time-dependent conditions. The constant traffic conditions are the traffic operation where the levels of traffic volumes entering the network are assumed constant throughout the simulation period, although the actual simulated volumes may slightly vary due to stochastic nature of simulation. The time-dependent traffic conditions are the traffic operation where the volumes of entering volumes vary over time. This represents the peak duration in the real world. The peak duration can be the rush-hour peak period or the surge of traffic due to abnormal high/low flow such as the traffic from special events.

The levels of traffic volumes and the duration of study are arranged to cover the low-flow and high-flow traffic conditions. At the higher flow, traffic may be saturated and queue accumulation may take place. The test environment (road network, traffic volume, and simulation period) is established to depict a variety of traffic conditions, from undersaturation to oversaturation, with and without queue spillback.

To supply various traffic conditions, the traffic is loaded on this network so that the degree of saturation (DS) of traffic at the critical intersection (bottleneck) is at 0.4, 0.6, 0.8, 1.0, and 1.2. The traffic conditions are then classified into two main categories: undersaturated (DS $\leq$ 0.8) and saturated conditions (DS $\geq$1.0).

At the undersaturated traffic level, two traffic factors are varied; proportion of traffic on main and cross streets, and the level of traffic demand (or volume/capacity ratio). Some of the traffic conditions are partially tested to understand the trend and the consequences of the control.

Table 1. Design of experiment on traffic levels to be tested in constant traffic conditions

Traffic Level (V/C)	Proportion of traffic on main and cross streets (main street : cross street)							
	1:1	1.33:1	1.5:1	1.67:1	2:1	2.67:1	3:1	4:1
0.4	X							
0.6	X				X			
0.8	X			X			X	
1.0	X		X			X		X
1.2	X	X			X			

Special attention is paid to the undersaturated and saturated conditions where traffic levels are time-dependent. The schematic representation of varying traffic flow in saturated conditions is illustrated in Figure 3, to see the whole effect of oversaturation.

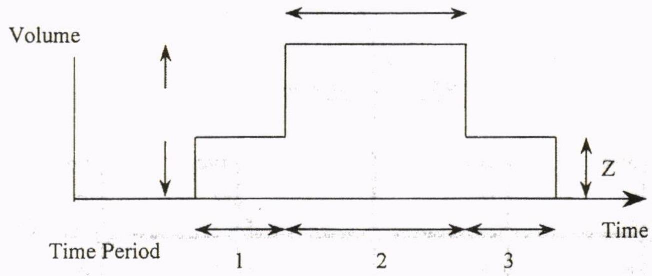


Figure 3. Time-dependent traffic flow in saturated condition

The signal control methods to be tested are:

Method 1 – Using the historical traffic volume

This traffic signal control setting uses Webster's signal setting method to calculate cycle time and green time. However, at a saturated traffic condition the cycle time will be set at the maximum value (240 seconds). The cycle time does not have to be set identical for each intersection in the network. In other words, each intersection will operate individually. There is no attempt to adjust the signal according to the critical intersection. There is no offset setting for this method. During varying volume conditions, the volume of traffic is assumed to be known (from historical volume pattern) and the signal setting is adjusted right away according to the estimated volumes. This method represents an individual signal operation.

Method 2 – Consider progression on the main road

This method pays attention on the progression on the main flow movements. The cycle time and offset on the main road are synchronized. The cycle time is determined from a critical intersection (where the highest intersection degree of saturation takes place). The green time is allocated as the proportion of traffic volume in each direction. The offset in the low flow condition is set to minimize stops or maximize the green band on the main roads. In a constant saturated traffic condition, the negative offset is set to synchronize the movement of queue on the road link and the traffic entering from upstream intersection. The procedure follows Pignataro *et.al.* (1978). In the time-dependent flow situation, the signal setting is adjusted according to estimated traffic volume as in the method 1. This method represents a conventional fixed time signal setting as area traffic control in which all intersections in the region (network) are coordinated.

Method 3 – Using an average historical traffic volume

This method will be used only in the time-dependent traffic condition. The method averages the volume of traffic during the entire range of study duration and adjusts the cycle time and green time using Webster's technique. The procedure is similar to the method 1, each intersection operates individually and no offset setting. This control method represents the decentralized fixed time control at each intersection when traffic data is aggregated and no real-time data is available.

Method 4 – Using real-time actual counts

This method utilizes the real-time traffic data measured at each intersection approaches. The traffic counts are then used to modify cycle time and green time for each individual intersection. The offset is not set for this method. This method represents an adaptive signal control using real-time traffic information at each intersection. It implies an adaptive decentralized traffic control with no linkage between intersections.

Method 5 – Using a storage management concept

This method is used only when a road link is filled by a traffic queue, basically at oversaturated traffic situations. The signal control is calculated using queue storage concept to prevent a queue blockage at an upstream intersection. Since this method is used in saturated condition, the cycle time is set at the maximum of 240 seconds. Green time is allocated due to the spaces on the downstream links. There is no offset setting for this method.

The simulation is used to test the signal control methods. Two candidates of simulation programs are TRANSYT-7F and CORSIM. In 1999, Federal Highway Administration in the United States has released the version 8 of TRANSYT-7F simulation software. Although traffic is macroscopically modeled, the software is claimed the capability of simulating oversaturated traffic condition. However, from the early investigation, it is found that there is a significant restriction on the TRANSYT-7F in that it could accurately report the results only when the queues are not accumulating up to two consecutive cycles. If the queues accumulate beyond the program limit, then the program outputs would wrongly reported. It is plausible to accept only the results in only undersaturated traffic conditions.

The CORSIM is a microscopic simulation model that could be used without the above problem. The program has been validated by many agencies in the United States and accepted for all traffic projects. The model can convincingly replicate the oversaturated traffic conditions where a traffic queue extends from one intersection to another. The program is flexible in altering the signal timings. The outputs of the programs are measures of effectiveness (MOEs) that indicate the performance of the signal operations. The indicators used for this study are:

Average delay per vehicle
Queue time (or waiting time)
Fuel consumption
Carbonmonoxide level (as a measure of environmental impact)
Throughput

4. FINDINGS

4.1. Signal Control Performance in Constant Undersaturated Traffic Conditions

The traffic condition allows the signal control a wide range of setting and, thus, most of signal control methods are determined and compared. The signal control performances can be found for two types of traffic volumes; constant and variable volume during the study duration. For constant traffic volumes, the results are illustrated in Figure 4.

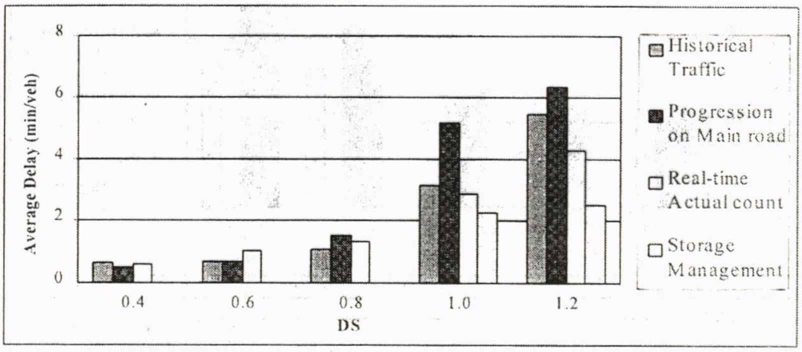


Figure 4. Performances of signal control in undersaturated conditions

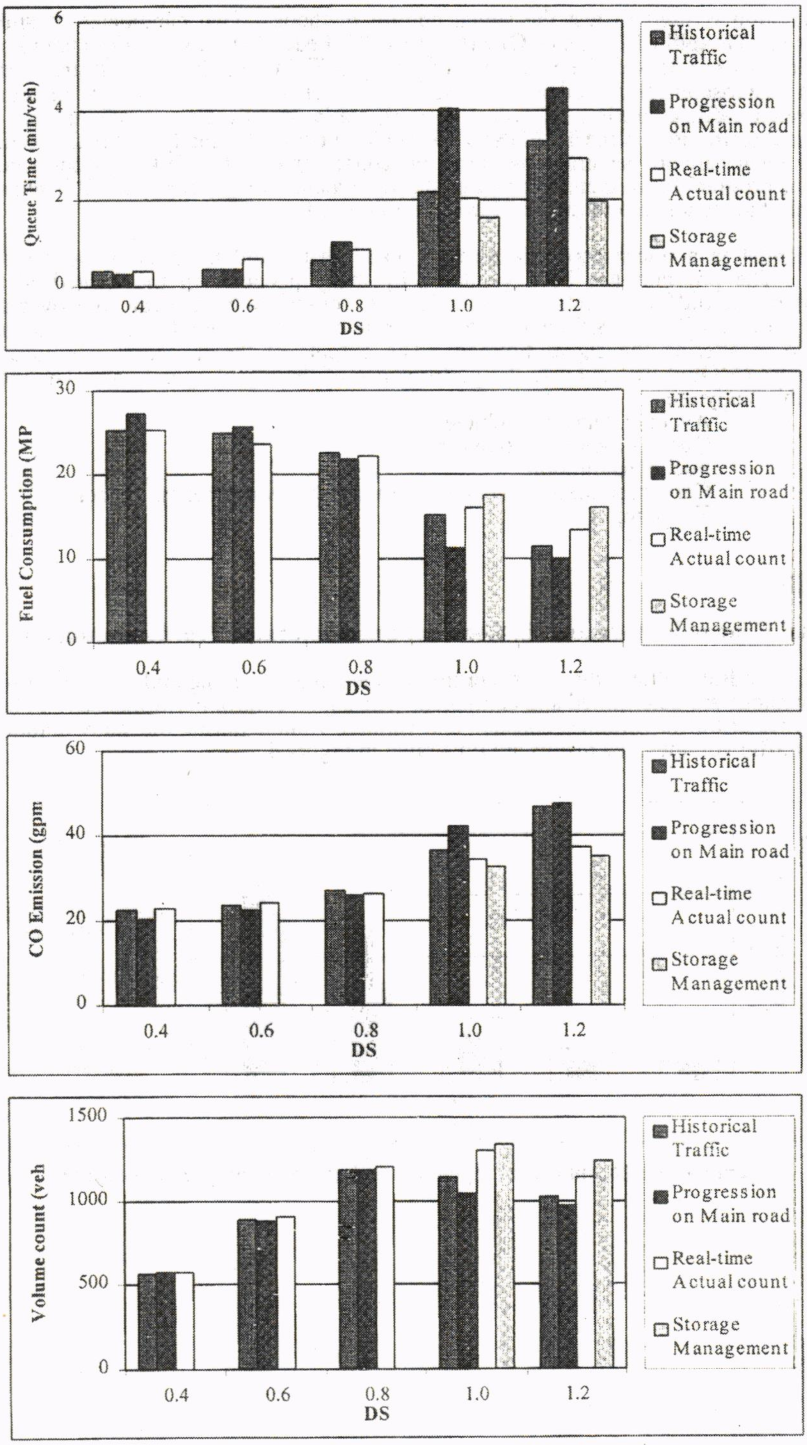


Figure 4. Performances of signal control in undersaturated conditions (Cont'd)

The following section will compare the individual intersection delay optimization (method 1), provision of progression (method 2), and the split real-time adaptation (method 4). At the same traffic volume patterns (main street : cross street = 1:1), traffic control method 2, provision of progression on the main street, brings about the lowest delay in the low flow condition (v/c = 0.4 and 0.6). The method 1 yields slight lower delay than the method 4. It implies that the modification of traffic split using real-time information does give better benefits when the constant flow is undersaturated. Nonetheless, when the flow is heavier (v/c is 0.8 and above), the real-time signal setting becomes more advantageous. The setting to favor progression results gives the highest delay among the three methods. Considering fuel consumption and queue time, the conclusions are similar to the delay deliberation, the signal setting for progression results in the highest performance in the low flow conditions, while the real-time split setting is the most efficient in the saturated conditions. However, at the near-saturated condition or v/c =0.8, the three indicators draw a slight different conclusion. At this traffic conditions, the signal setting to yield minimum intersection delay does not give the lower average network vehicular delay than the setting for progression. Nevertheless, it gives lower fuel consumption and queue time. It is scrutinized that the progression gives lower percent stop and this may contribute to lower travel time and thus overall delay (percent stop by method 1 is 145% while percent stop by method 2 is 118%).

4.2. Signal Control Performance in Constant Saturated Traffic Conditions

From the experiments on the signal control in constant saturated traffic conditions, the method 5, the queue storage concept, produces the highest performance in terms of delay, fuel consumption, emission, and throughput (Figure 4). This signal control method filters excess amount of traffic entering the critical intersection. Thus, the degree of saturation at to-be-critical intersection is maintained at a certain level, while the approaching intersections cumulate the metered traffic and may turn a new oversaturated intersection.

It is mentioned that the control method 5 creates a wide area of congestion. The control attempts to prevent the intersection blockage by giving green time to uncongested (unaffected) movements. The traffic entering the congested area is thus given shorter green time at the upstream intersections. Then, as time goes by, the surrounded intersections to the (first) critical intersection possess long queues. Thus, the congestion (and queue) is spread further from the first critical intersection.

4.3. Signal Control Performance in Time-dependent Saturated Traffic Conditions

This section shows the degree of effectiveness that each signal control method provides when there is a surge of traffic demand. Five control techniques are studied; the intersection delay minimization (method 1), progression (method 2), delay minimization using historical traffic data (method 3), adaptive split setting using real-time volume (method 4), and queue control (method 5). The testing is conducted on various levels of the traffic demand and two periods of peak; 10 and 20 minutes. The difference between the two periods is that the 10-minute traffic surge does not produce the spillback (upstream intersection blockage) while the 20-minute traffic surge will produce the blockage.

4.3.1. When traffic volume peak period is 10 minutes

The traffic conditions in this consideration are further categorized into 2 groups: the surge is below the capacity of the intersections and the surge is above the capacity of the intersections.

When the traffic demand does not exceed capacity in the peak period, the signal control is aimed at properly adapting signal to yield better efficiency, in addition to make better the measures of effectiveness. Since there are a wide variety of traffic volume levels at each movement, the findings are compared to illustrate the performances of the signal control in various matters.

Comparing the control methods at different traffic level during peak duration, it is found that the control method 3, using historical data to set the signal timings, generates the highest performances in most categories. The exception is at the low traffic level where the progression still performs better. This may be because at the changing traffic level it is more efficient to preset the signal to the anticipated traffic, rather than being reactive as in the control method 4. It is also worth noting that the queue control performs very badly in a low-level surge traffic condition and it performs relatively well (the second highest performance) when the surge traffic is heavier.

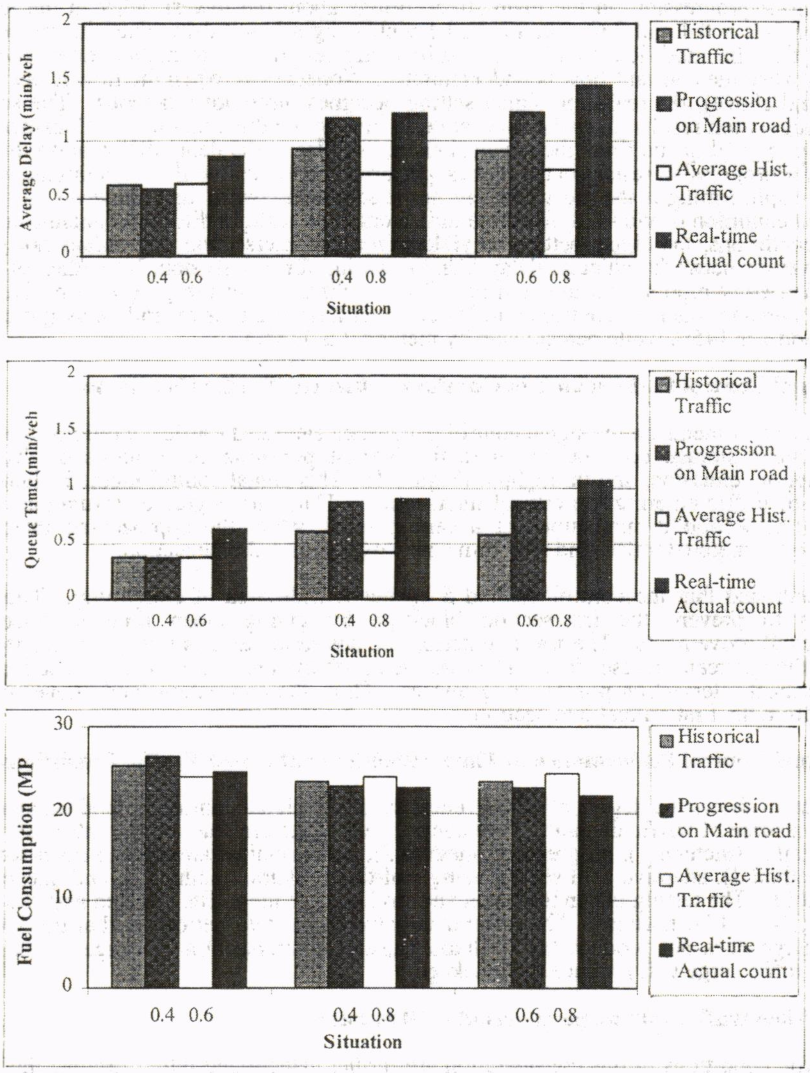


Figure 5. Performances of traffic signal control in saturated conditions (no spillback)
The surge is below the capacity of the intersections

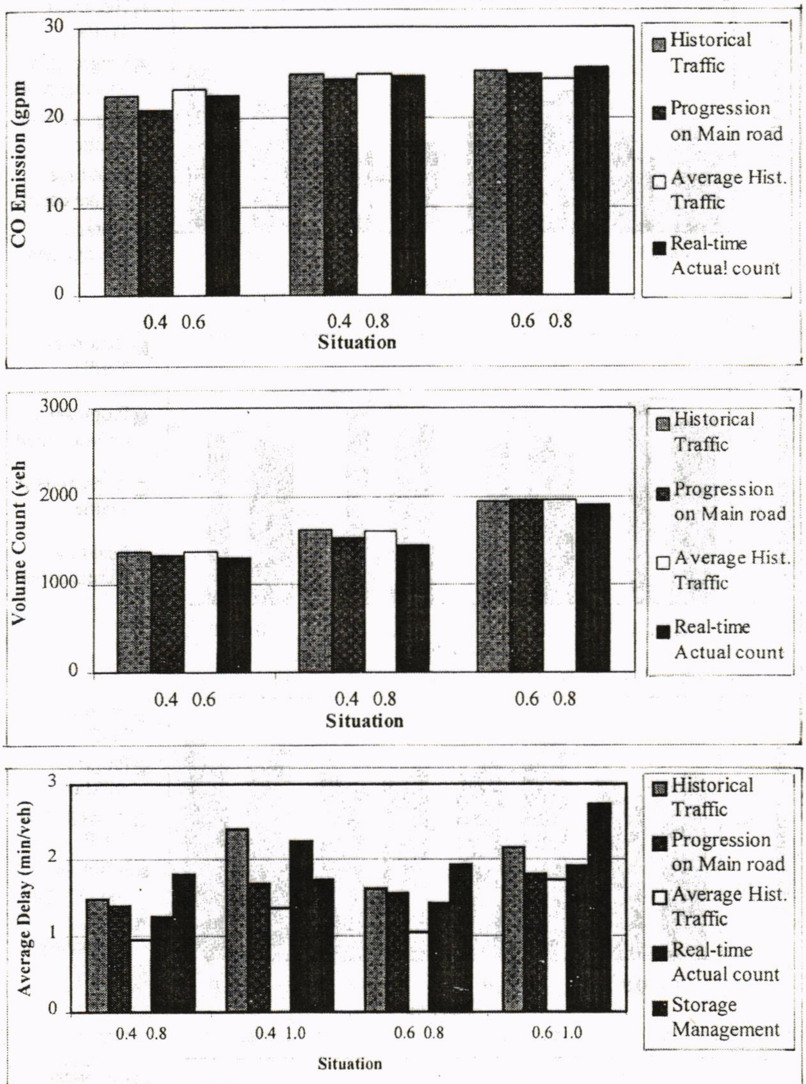


Figure 5. Performances of traffic signal control in saturated conditions (no spillback)
The surge is below the capacity of the intersections (Cont'd)

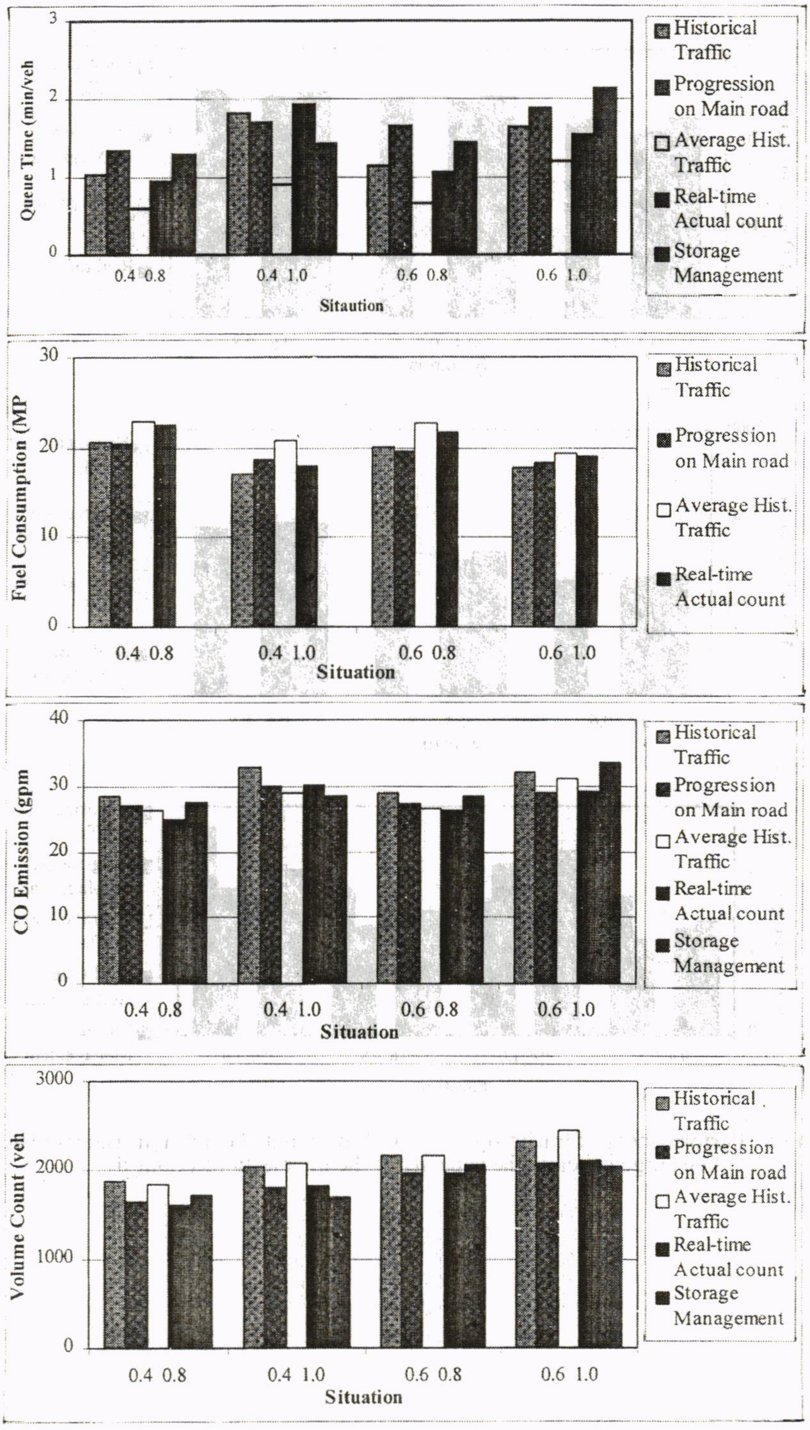


Figure 6. Performances of traffic signal control in saturated conditions (no spillback)
The surge is above the capacity of the intersections.

4.3.2. When traffic volume peak period is 20 minutes

The traffic in this condition is simulated to examine the effectiveness of signal control when the traffic level during peak period is oversaturated. At this traffic level, there will be a blockage at the upstream intersections. The performances of signal control methods are displayed in Figure 7.

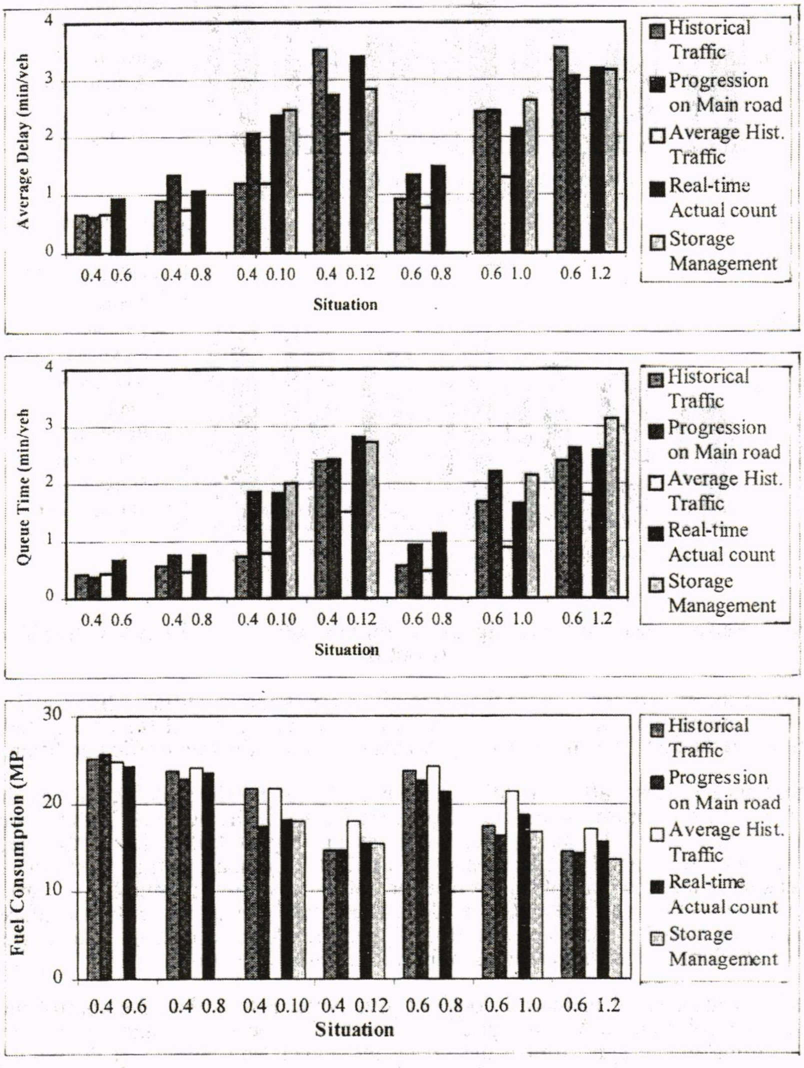
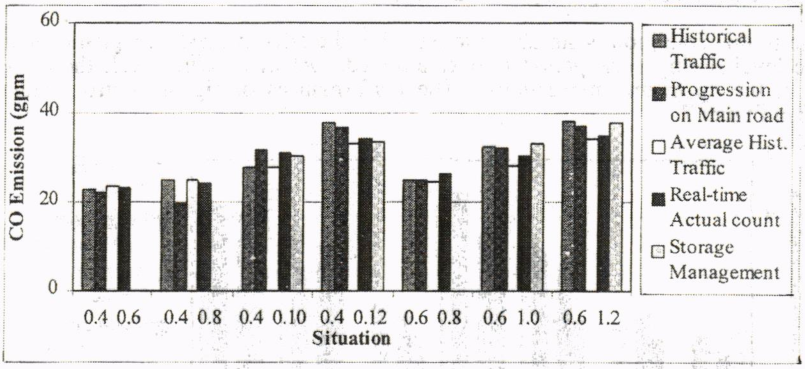


Figure 7. Performances of traffic signal control in saturated conditions (with spillback)



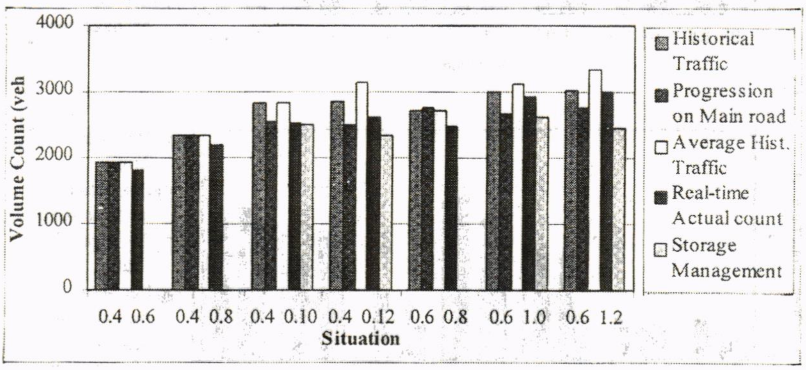


Figure 7. Performances of traffic signal control in saturated conditions (with spillback) (Cont'd)

The results of the experiments show the same direction as the condition when traffic volume peak of 10 minutes. The presetting of signal timing using historical (or anticipated) traffic data (control method 3) gives the highest performance except the low traffic condition.

The performance in this traffic condition can be explained by the throughput. At the lower traffic flow level, the control method 3 releases traffic out of the network in the amount very close to control method 1 and 2. However, at the higher traffic level, the throughput effectiveness of the method 3 becomes more evident. Comparing the 10-minute and 20-minute peak situation, the controls at the heavier traffic can allow less number of traffic out of the critical intersection and the network. This is because the queue spillback places more restriction to the signal control and therefore forces the signal to operate at a shorter cycle. This creates the longer start-up lost time to the entire traffic operation.

It is noted that the control method 5 does not give better results than the control method 3. Despite the control method 5 is designed to prevent the queue blockage and set the signal timing according to the synchronize the queue movement and storage, it does not provide lower delay nor the total queue time of the road network. This may be because the control focuses on the management of queue and thus the traffic moves at a lower speed and is subject to lost time due to the starts and stops. Unlike the control method 3 that has "internal" metering at the upstream intersections, the control method 5 attempts to fill the approaches of the critical intersection and thus prolongs the saturation at the critical intersection.

4.4 Comparison of signal control methods at different volume levels

In time-dependent traffic environments, one traffic signal control technique will yield different performances at different traffic levels. This section compares the performances of the signal controls in various traffic levels. Figure 8 shows the comparison of signal control performances in two time-dependent traffic levels; when the peak traffic levels are undersaturated (degrees of saturation are 0.6 and 0.8) and the peak periods are 10 and 20 minutes. The figure exhibits that in the case of the saturation level of 0.6, most signal control methods would perform similarly, as indicated by the similar percentage of increase in the average total delay. In the higher traffic level, it is found that the signal setting to favor progression will have a discernable increase in the delay. Therefore, although the signal setting for progression yields the highest performance in many of low flow conditions (as displayed in Figure 9), the performance of this control method is relatively worse when the flow is higher and varying.

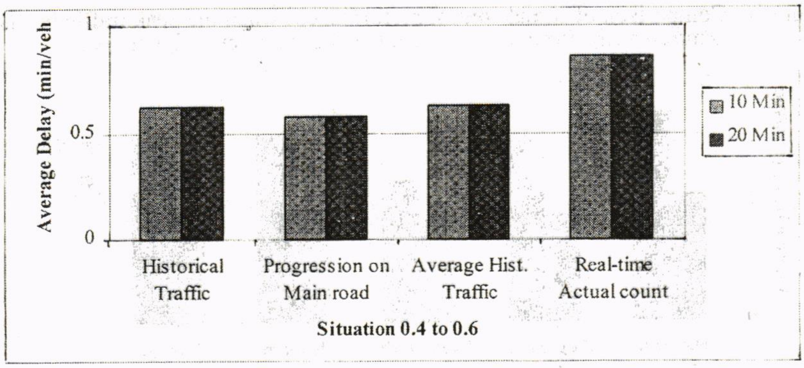


Figure 8. Comparison of signal control performances when the peak traffic levels are undersaturated (degrees of saturation is 0.6) and the peak periods are 10 and 20 minutes

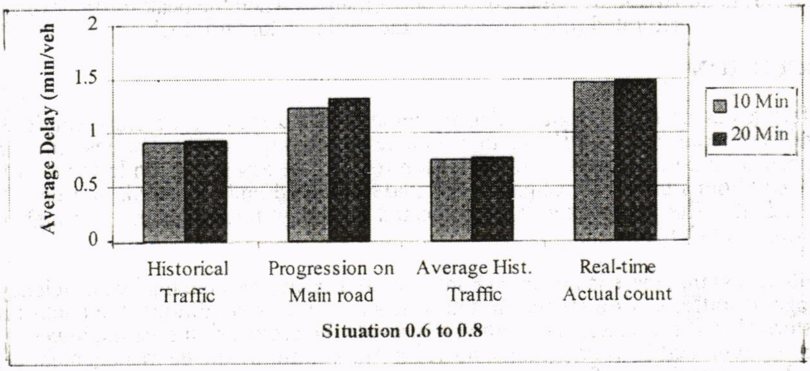


Figure 9. Comparison of signal control performances when the peak traffic levels are undersaturated (degrees of saturation is 0.8) and the peak periods are 10 and 20 minutes

When the flow is higher up to the saturation during the peak period, the conditions can be classified as (1) the flow does not produce the intersection blockage, and (2) the flow creates the spillback and gridlock. Figure 10 and Figure 11 show the performances of traffic control techniques in both conditions.

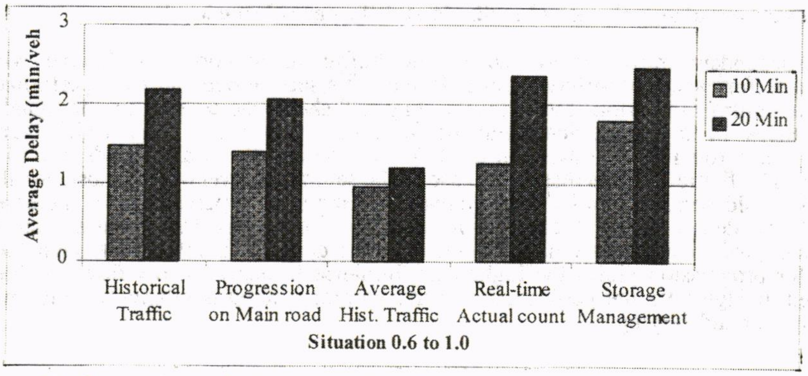


Figure 10. Comparison of signal control performances when the peak traffic levels are saturated (the flow does not produce the intersection blockage)

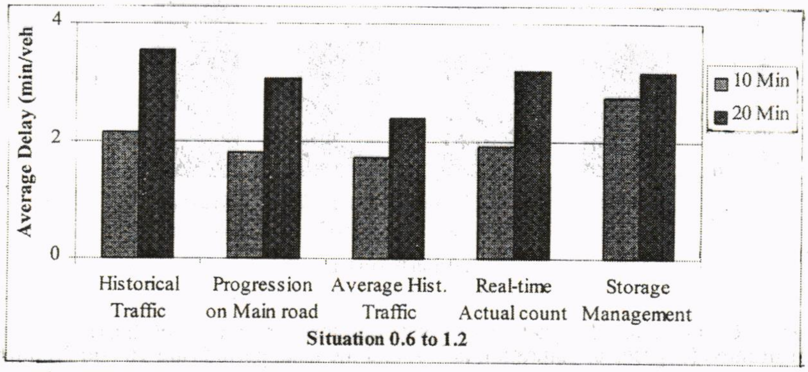


Figure 11. Comparison of signal control performances when the peak traffic levels are saturated (the flow creates the spillback and gridlock)

5. CONCLUSION

The performances of traffic signal control methods, at various traffic flow conditions, are tested and compared using CORSIM microscopic simulation model. The test environments are designed so that the effectiveness of the controls can be assess in a wide variety of flows. The flow conditions under investigation are undersaturated and saturated, and constant and time-dependent. The performances are indicated by delay, time in queue, throughput, fuel consumption, and CO_2 emission.

The results reveal that there is no single control method that gives the highest efficiency in the entire range of traffic environments. In the constant low flow conditions, the control method using historical traffic data and the method to provide the progression give the lowest network delay. In the saturated flow conditions, however, the control by queue management performs the best. In the varying traffic volume conditions, the setting using average historical traffic data gives the lowest delay. The other measures of effectiveness indicate similar conclusions, although there may be slight alteration in the comparison.

Although the control method using average historical traffic data yields good performance in time-dependent conditions, this control method creates a spread of congestion to the wider area, since it makes the spillback of queue to the surrounded intersections (to the critical one).

From the experiments in this study, it is found that the signal should have various control policies. At lower flow, the signal should employ a control to favor progression or control using the historical traffic data to yield low delay. When the traffic is heavier, the queue control should take place.

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