Applied Mechanics and Materials Vols. 543-547 (2014) pp 1417-1422
Online available since 2014/Mar/24 at www.scientific.net
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doi:10.4028/www.scientific.net/AMM.543-547.1417

# Modeling and Simulation of Urban Arterial Traffic Signal Coordinated Control

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**Keywords:** Traffic Signal, Coordinated Control, Offset Model.

**Abstract.** Traffic congestion is a major concern for many cities throughout the world. Developing a sophisticated traffic monitoring and control system would result in an effective solution to this problem. In order to reduce traffic delay, a novel urban arterial traffic signal coordinated control method is presented. The total delay of downstream and upstream vehicles is considered and the function describing the relationship between vehicles delay and signal offset among intersections is established. Finally, comparing the performance of traffic signal under method proposed in this paper with the traditional isolated traffic signal control method, the microscopic simulation results show that the method proposed in this paper has better performance in the aspect of reducing the vehicles delay. The offset model is tested in a simulation environment consisting of a core area of three intersections. It can be concluded that the proposed method is much more effective in relieving oversaturation in a network than the isolated intersection control strategy.

## Introduction

Traffic signals are common features of urban areas throughout the world, controlling vehicles' traveling through intersections. They are used to improve the traffic safety, maximizing the capacity and minimizing the delays at the intersection. Thus careful design of the traffic signal control would result in increasing the efficiency of the road network to yield economical and environmental benefits. In a conventional traffic signal controller, the traffic lights under control change at a constant cycle without considering the traffic status of adjacent intersections. This isolated control method cannot maximize the traffic capacity of the intersection. Arterial traffic signal coordinated control is proved a effective method to reduce vehicles delay and number of stops at intersections [1].

A considerable amount of work has been done on the problem of modeling and controlling several traffic junctions in the arterial. Reference [2] proposed a green-wave signal control model based on minimum delay; in reference [3], a two-way green wave band control was presented, but this traffic condition is rare in reality and limited to its application; the coordinated control method put forward in reference [4] only focused on the vehicle delay at an isolated intersection without considering the total delay while driving through the arterial. Based on the previous work, in this paper, vehicles delay through the arterial is considered. The delay of the downstream and upstream vehicles at intersections is analyzed. An offset model is proposed to solve the traffic signal timing control problem for unsaturated traffic arterial, the aim is to relieve the traffic congestion. The paper is organized as follows: Section II gives a brief introduction about arterial control system. Section III discusses the offset model of arterial traffic signal control system in details. Section IV discusses the simulation result and draws a conclusion question.

## Description of arterial control system

Transportation system is an extremely complex system with a strong randomness, fuzziness and uncertainty, the internal mechanism and accurate mathematical model of which is difficult to understand and build [5]. Thus, the vehicles delay model is based on the assumptions as follows:

1. Turning traffic at intersections is neglected;
2. Stochastic errors caused by stochastic oversaturation are not considered;
3. The traffic flow is stable in a signal cycle and unsaturated;
4. The delay of external approach is not considered.

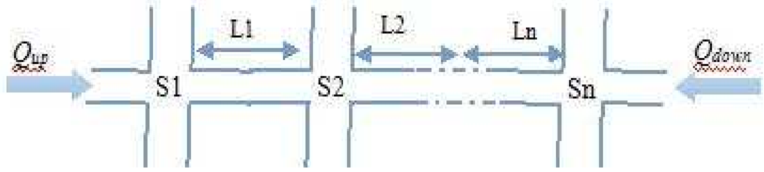


Fig. 1 Urban arterial adjacent intersections

Fig. 1 shows that the urban arterial under control is composed of several adjacent intersections such as $S_1, S_2, S_3 ... S_n$. The distance between adjacent intersections is $L_1, L_2, L_3 ... L_n$ (m) respectively. The upstream traffic is donated as $Q_{up}(pcu/s)$ and the downstream traffic as $Q_{down}(pcu/s)$. Let the driving speed in upstream direction be $V_{up}(m/s)$ and be $V_{down}(m/s)$ in downstream direction. The arterial signal cycle and split are determined by traditional methods [6].

**Model of arterial traffic signal control system**

The total delay time of motorcade while driving through the arterial is the sum of delay time at each intersection. It includes two cases: the upstream vehicles delay and the downstream vehicles delay. In order to maximize the intersections capacity, the total delay time which is donated as $D$ should be minimized. Variable $D$ can be expressed as,

$$D = \sum_{i=1}^{n} D_i \tag{1}$$

Where variable $D_i$ represents the sum of the upstream and downstream motorcade's delay time at $i'th(1 \le i \le n)$ intersection.

**Delay model of downstream vehicles**

It can be calculated that the average time from intersection Si to Si+1 is $L_i / V_{down}$. Assuming that the offset between intersection $S_i$ and $S_{i+1}$ is $\varphi_{i,i+1}$. There are two conditions of vehicles delay while driving from intersection $S_i$ to $S_{i+1}$ [7]. They are as follows:

(1) When the first vehicle of motorcade arrives at the intersection $S_{i+1}$, the red light at the intersection $S_{i+1}$ just lights up then vehicles delay happens. This condition is called Motorcade Front Delay Model (or MFDM, for short).

(2) The first vehicle of motorcade drives through $S_{i+1}$ successfully, however, when vehicles at the end of motorcade are ready to cross intersection $S_{i+1}$, the red light at $S_{i+1}$ lights up then vehicles delay happens. This condition is called Motorcade End Delay Model (or MEDM, for short).

**Downstream Motorcade Front Delay Model.** Assuming that $Q_{max}$ represents maximum traffic capacity of intersection during green time; $T_{red}$ represents red time during one signal cycle T; $T_{green}$ represents green time during one signal cycle; $T_q$ represents vehicles queuing time; $\varphi_{i,i+1}$ represents the offset between the intersection $S_i$ and $S_{i+1}$. Then,

$$\varphi_{i+1,i} = \left[ \frac{L_i}{V_{down}} \right] (\bmod T) + T_{red} \tag{2}$$

Let $T_d$ be the vehicles dispersing time. During $T_d$ after signal turns green, then,

$$Q_{down} * (T_{red} + T_d) = Q_{max} * T_d \tag{3}$$

The total delay formulation in this situation is as follows.

$$D^1_{(i+1)down} = 0.5 * T_{red} * Q_{down} * (T_{red} + T_d) \tag{4}$$

Variable $T_{red}$ and $T_d$ can be found by solving equations (2) and (3) respectively. By putting $T_{red}$ and $T_d$ into equation (4), a delay model at the $(i+1)'th$ intersection $S_{i+1}$ can be established.

$$D^1_{(i+1)down} = \frac{Q_{down} Q_{max} \left\{ \varphi_{i+1,i} - \left[ \frac{L_i}{V_{down}} \right] (\mathrm{mod} T) \right\}^2}{2(Q_{max} - Q_{down})} \tag{5}$$

**Downstream Motorcade End Delay Mode.** When the end of motorcade arrives at the intersection $S_{i+1}$, signal turns red. Let $T_{ed}$ be the time gap between the first vehicle in motorcade stops at the intersection $S_{i+1}$ and the last vehicle in motorcade leaves $S_{i+1}$. Then,

$$T_{ed} = \left[ \frac{L_i}{V_{down}} \right] (\mathrm{mod} T) - \varphi_{i+1,i} \tag{6}$$

Let $T_d$ be the vehicles dispersing time. During $T_d$ after signal turns green, then,

$$Q_{max} * T_d = Q_{down} * T_{ed} \tag{7}$$

The total delay formulation in this situation is as follows.

$$D^2_{(i+1)down} = 0.5 Q_{down} T^2_{ed} + Q_{down} T_{ed} (T_d - T_{ed}) + 0.5 T_d Q_{down} T_{ed} \tag{8}$$

Variable $T_{red}$ and $T_d$ can be found by solving equations (5) and (6) respectively. By putting $T_{ed}$ and $T_d$ into equation (7), a delay model at the $(i+1)'th$ intersection can be established.

$$D^2_{(i+1)down} = \frac{Q^2_{max} T^2_{ed}}{2Q_{down}} + Q_{down} T^2_{ed} \left( \frac{Q_{max}}{Q_{down}} - 1 \right) + \frac{Q^2_{down} T^2_{ed}}{2Q_{max}} \tag{9}$$

Considering the above two cases, let $D_d$ be the total delay time of downstream motorcade at intersection $S_{i+1}$. Then $D_d$ can be expressed as:

$$D_d = \sum_{i=2}^{n} \left[ \alpha_i D^1_{(i+1)down} + (1-\alpha_i) D^2_{(i+1)down} \right], \alpha_i \in [0,1] \tag{10}$$

**Delay Model of Upstream Vehicles**

Let $L_i/V_{up}$ be the vehicle travel time from $S_{i+1}$ to $S_i$ and $\varphi_{i,i+1}$ be the offset between $S_i$ and $S_{i+1}$. The same as vehicles in downstream direction, the delay time of upstream vehicles also includes two conditions: (1) when a vehicle arrives at the intersection $S_i$, the red light just lights up; (2) when a vehicle arrives at the intersection $S_i$, the red light has already lighted up.

**Upstream Motorcade Front Delay Model.** Let $Q_{max}$ be the maximum traffic capacity of intersection during green time and $T_q$ be queuing time. When a vehicle arrives at the intersection $S_i$, the red light just lights up. Then,

$$\varphi_{i,i+1} = \left[\frac{l_i}{V_{up}}\right](\mathrm{mod}\,T) + T_r \tag{11}$$

Let $T_d$ be the dispersing time. During $T_d$ after signal turns green, then,

$$Q_{up}(T_r + T_d) = Q_{max} T_d \tag{12}$$

The total delay formulation in this situation is as follows.

$$D^1_{(i)up} = 0.5 T_r Q_{up}(T_r + T_d) \tag{13}$$

Variable $T_r$ and $T_d$ can be found by solving equations (11) and (12) respectively. By putting $T_r$ and $T_d$ into equation (13), a delay model at the $i'th$ intersection can be established.

$$D^1_{(i)up} = \frac{Q_{max} Q_{up} \left\{\varphi_{i,i+1} - \left[\frac{L_i}{V_{up}}\right](\mathrm{mod}\,T)\right\}^2}{2(Q_{max} - Q_{up})} \tag{14}$$

**Upstream Motorcade End Delay Mode.** When the end of motorcade arrives at the intersection $S_i$, the signal turns red. Let $T_{ed}$ be the time gap between the first vehicle in motorcade stops at the intersection $S_i$ and the last vehicle in motorcade leaves $S_i$. Then,

$$\left[\frac{L_i}{V_{up}}\right](\mathrm{mod}\,T) - T_{ed} = \varphi_{i,i+1} \tag{15}$$

The total delay formulation in this situation is as follows.

$$D^2_{(i)up} = Q_{up} T_r T_{ed} - 0.5 Q_{up} T^2_{ed} + \frac{0.5 Q^2_{up} T^2_{ed}}{Q_{max}} \tag{16}$$

Considering the above two cases, let $D_u$ be the total delay time of upstream motorcade at intersection $S_i$. Then $D_u$ can be expressed as:

$$D_u = \sum_{i=2}^{n} \left[\beta_i D^1_{(i)up} + (1-\beta_i) D^2_{(i)up}\right], \beta_i \in [0,1] \tag{17}$$

Assuming that D is the total vehicles delay in the arterial, considering the downstream and upstream vehicles delay, D can be expressed as:

$$D = D_d + D_u = \sum_{i=2}^{n}\left[\alpha_i D^1_{(i+1)down} + (1-\alpha_i) D^2_{(i+1)down}\right] + \sum_{i=2}^{n}\left[\beta_i D^1_{(i)up} + (1-\beta_i) D^2_{(i)up}\right] \tag{18}$$

## Simulation and Analysis

An arterial road with three intersections, S1, S2, S3, is built; each intersection includes two-way six lanes at east-west direction and two-way four lanes at south-north direction. Table 1 shows saturation flow at above three intersections. The traffic data of the intersections is acquired by traffic radar installed at each intersection. The signal cycle and green time of each intersection is determined according to flow rate [8].

Table 1 Traffic flow and Saturation flow of each intersection (unit: veh/h)

| Intersection | | North Entry | South Entry | East Entry | West Entry |
|---|---|---|---|---|---|
| #1 | Traffic flow | 538 | 643 | 1731 | 1617 |
| | Saturation flow | 3000 | 3000 | 4500 | 4500 |
| #2 | Traffic flow | 783 | 650 | 1631 | 1738 |
| | Saturation flow | 3000 | 3000 | 4500 | 4500 |
| #3 | Traffic flow | 635 | 681 | 1849 | 1965 |
| | Saturation flow | 3000 | 3000 | 4500 | 4500 |

Table 2 Signal cycle and green time of each intersection (unit: s)

| Intersection | Signal Cycle | Green Time | Signal Offset |
|---|---|---|---|
| #1 | 65 | 34 | 17 |
| #2 | 74 | 36 | 24 |
| #3 | 79 | 43 | 22 |

Table 2 shows the signal cycle and green time of each intersection. The simulation platform MATLAB is used to analyze the benefit of offset models proposed in this paper. To analyze the adaptability of the offset model, a considerable amount of experiments have been done. Table 3 shows the comparison results of three intersections with coordinated control method and with isolated control method respectively.

Table 3 Comparison of delay time under two different control methods (unit: s)

| | Coordinated control method | | | Isolated control method |
|---|---|---|---|---|
| Cycle | $\Phi_{1,2}$ | $\Phi_{2,3}$ | Delay | Delay |
| #1 | 38.2 | 39.5 | 78.3 | 126.7 |
| #2 | 40.3 | 42.8 | 105.2 | 166.1 |
| #3 | 35.5 | 39.2 | 113.6 | 182.2 |
| #4 | 46.8 | 40.7 | 120.5 | 193.4 |
| #5 | 43.6 | 38.5 | 124.5 | 205.4 |
| #6 | 38.9 | 46.8 | 127.5 | 207.4 |
| #7 | 42.1 | 26.8 | 137.0 | 209.8 |
| #8 | 40.6 | 42.7 | 137.9 | 213.1 |
| #9 | 39.9 | 37.5 | 138.8 | 214.4 |
| #10 | 37.4 | 41.5 | 136.3 | 215.9 |

$\Phi_{1,2}$ in Table 3 represents the signal offset between the intersection S1 and intersection S2.Likely, $\Phi_{2,3}$ is the offset between S2 and S3. The simulation experiments have been done in successive ten signal cycles. The simulation results in Table 3 show that traffic signals under coordinated control method have better performance than those under isolated control in the aspect of reducing arterial vehicles delay.

## Summary

Signal offset optimization model is established in this paper by considering the downstream and upstream vehicles delay in the arterial. The function describing the relationship between the vehicles and offset among intersections is set, which provides a basis for optimizing signal offset through artificial intelligent algorithms in future work. The simulation results show that the performance of the offset optimization model is better than signal under no coordination, which proves that the signal offset model is effective.

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10.4028/www.scientific.net/AMM.543-547

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10.4028/www.scientific.net/AMM.543-547.1417