DYNAMIC LANE-USE MANAGEMENT AT ISOLATED INTERSECTIONS WITH DEMAND RESPONSIVE SIGNAL CONTROL

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ABSTRACT

In urban areas, the fluctuation of traffic demand at peak hours usually results in traffic congestions, especially at signalized intersections. However, it seems that this kind of congestions can be avoided because only a few directions are oversaturated at the intersection, and others are usually far from saturated. When the fluctuation is small, the problem can be solved by using a demand responsive signal control strategy. But sometimes when the fluctuation is big, only changing the signal control strategy will not work as well as expected. In this paper, a new solution that combines the dynamic lane-use and demand responsive signal control strategy of an isolated intersection is proposed to decrease the risk of traffic congestion and make better use of the capacity of road facilities. A programmable integrative model of lane-use and signal timing is built and solved. A case study is given with microscopic simulation to validate the model. The simulation results show that the proposed model is effective, especially for some "tide traffic" cases whose traffic operation will have little improvement by only modifying the signal timings.

Keywords: traffic management, traffic control, dynamic lane-use management, demand responsive signal

INTRODUCTION

During peak hours, it is easy to see a "tide traffic" phenomenon in urban road networks: there are long queues waiting in some approaches of intersections, while the lanes of other approaches are rarely used. A heavy "tide traffic" often causes traffic congestions and simultaneously, wastes the capacity of road facilities. In essence, the problem lies on the contradiction between dynamic traffic demand and static road facilities. Usually, not all the approaches at the intersection that suffers from the “tide traffic” are oversaturated. It means that the total traffic demand is still smaller than the total capacity and the road resources are not fully used. Signal control is helpful in relieving the contradiction by assigning green time to different traffic flows dynamically. However, the role of signal control is more or less limited because the traffic space is fixed by the static lane-use assignment (or lane markers) and it may restrict the effects of signal control under certain circumstances, such as the “tide traffic”. In these cases, only modifying the signal timing is not enough to stop the queue accumulating. So there comes the concept of dynamic lane-use management, which adjusts the lane-use pattern of an intersection dynamically to make full use of its capacity and avoid the “unnecessary” congestion.

In previous studies, there were a number of researchers that had investigated the design and optimization of lane-use assignment at signalized intersections. Lam built an integrated model for lane-use assignment and signal control with mixed linear integer planning(Lam et al., 1997). The objective of his model was minimizing the sum of the flow ratio of all the phases and the results were compared with TRANSYT-7F. Wong reported a lane-based optimization method isolated signalized intersections. The method integrated the design of lane-use assignment and signal control. He built two types of models: one was a binary mix integer linear program that can maximize the capacity or minimize the cycle length. It was solved by the branch and bound algorithm(Wong and Wong, 2003b). The other was a binary mix integer non-linear program that can minimize the delay of the intersection. It was solved by the cutting plane algorithm and a heuristic linear search algorithm(Wong and Wong, 2003a). Lam and Wong’s models are more theoretical but relatively lack of consideration of application issues, such as the reduction of capacity under two-phase control. Q. Wang gave a three-step method for lane-use assignment at signalized intersections(Wang, 2003). J. Y. Wang went further on it and built a computing model(Wang and Wang, 2007). Both of them did not give empirical examples.

To sum up, we find that: 1) when discussing lane-use at signalized intersections, signal control was always discussed simultaneously in the previous studies; 2) most of the studies focused on the static design of lane-use pattern and the dynamic lane-use management was less addressed; 3) the previous studies provided important foundations and have good value of reference for us to discuss the dynamic lane-use management.

In the paper, the combined optimization problem of dynamic lane-use management and demand responsive signal control at an isolated intersection are discussed. What should be pointed out is that the dynamic lane-use management mentioned here is not the real-time modification of the lane markers at the intersection. Instead, the lane markers will only be changed by time of day according to the traffic demand. For example, there may be different lane markers at morning peak hours, evening peak hours and off-peak hours. Similarly, the demand responsive signal control here is time of day based, too.

The paper is organized as follows: firstly, the space-time relation at isolated signalized intersections is discussed, which is the foundation of this research; secondly, the dynamic lane-use management model is formulated; thirdly, the solution space of the model is analyzed and the solution procedures are introduced; and finally, the model is validated with micro-simulation in a case study with three different scenarios.

SPACE-TIME RELATION ANALYSIS AT ISOLATED SIGNALIZED INTERSECTIONS

Assume the cycle length is fixed, and the saturation degree of a single traffic flow (movement) at an intersection approach can be described as (1)

$$x_i = \frac{q_i}{\lambda_i s_i n_i}, 0 < \lambda_i < 1 \tag{1}$$

Where, $i = 1,2,3 \dots \dots, K$(an integer larger than 1) is the serial number of traffic movements; x_i is the saturation degree; q_i is the volume (veh/h); λ_i is the green ratio, s_i is the average saturation flow (veh/h/lane), n_i is the number of usable lanes.

This simple function reflects the space-time relation of traffic movements at an approach of a signalized intersection. It is not hard to notice that these two kinds of resources, space and time, can transform into each other, and they also have mutual constraints. To decrease x_i, there are two ways, either increase λ_i or n_i. At a given intersection, because the sum of green ratio of all phases and the total lane number are fixed, there will always be a certain lane-use assignment to ensure the saturation degree of every movement is lower than the upper limit and achieve a minimum total green time, as long as the ratio of total volume of flow and total capacity is lower than its upper limit. In other words, there is a combined optimal lane-use and signal timing plan that makes best use of the capacity of the intersection. Ma gave a numerical analysis on the space-time relation of an approach at signalized intersections and proved this statement(Ma, 2007). It is the theoretical basis for integrated optimization of lane-use and signal control.

MODEL FORMULATION

In this section, we give the formulation of the dynamic lane-use management model with demand responsive signal control, taking a four-leg intersection as example. The proposed model is applicable for different types of at-grade four-leg intersections, because the crossing angle of an intersection has little relation to the model formulation. It is also usable for intersections with three legs or more than four legs by adjusting some detailed settings.

Notation

Lane-use Patterns

There are many different lane-use patterns for an intersection, composed by different lanes, such as left lanes and right lanes. Including shared lanes, the number of lanes for an intersection depends on the topology of it. For example, four-leg intersection has six types of lanes and three-leg one has three (U-turn lanes are not included here). Figure 1 shows the six different types of lanes as well as two different lane-use patterns for a four-lane approach and three different lane-use patterns for a two-lane approach.

Use $\mathbf{u} = \{\mathbf{u}_{\boldsymbol{\alpha}}\}$ to describe the lane-use patterns of an intersection. Where a may equal to the integer of 1 to 4, representing the four approaches sequentially: east, south, west and north. Use $\mathbf{u}_{\boldsymbol{a}} = \{u_{ab}\}$ to describe the lane-use patterns of an approach. Where b may equal to the integer of 1 to 6, representing the six lane types sequentially: exclusive left lane, left-through shared lane, exclusive through lane, right-through shared lane, exclusive right lane and left-right-through shared lane; u_{ab} is the quantity of the corresponding lane. N_a is the total quantity of lanes at approach a while K_a is the total quantity of lanes at exit a.

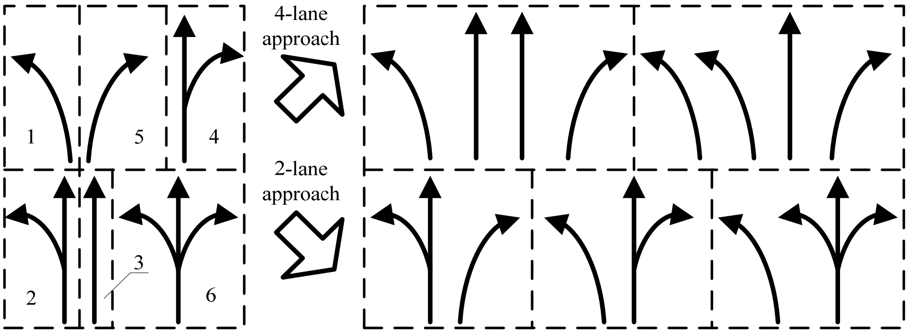

Figure 1 – Illustration of Different Lane-use Patterns

Signal Control Policy

The signal control policy proposed by Webster(Webster, 1958), or called equisaturation policy was chosen as the basic signal timing method in this study. The Webster's method is one of the most widely used control policy for urban intersections in the world. From a theoretical point of view, it is more attractive to investigate the existence and optimal solution. However, from a practical point of view, these assumptions may make the problem further from reality and it is also important to find an applicable solution. So it is necessary to describe the problem in a simple way without change the essence of it. To achieve a good combination of the two views, we presented some settings on signal control considerations.

Table 1 – Typical Signal Phase Plans

a	Number of Phases	Phases Description[a, b]			
		Phase 1	Phase 2	Phase 3	Phase 4
1	2	EB+WB	NB+SB	/	/
2	3	EB-T(R)+ WB-T(R)	EB-L+ WB-L	NB+SB	/
3	3	EB+WB	NB-T(R)+ SB-T(R)	NB-L+ SB-L	/
4	3	EB+WB	NB	SB	/
5	3	EB	WB	NB+SB	/
6	4	EB-T(R)+ WB-T(R)	EB-L+ WB-L	NB-T(R)+ SB-T(R)	NB-L+ SB-L
7	4	EB	WB	NB	SB
8	4	EB	WB	NB-T(R)+ SB-T(R)	NB-L+ SB-L
9	4	EB-T(R)+ WB-T(R)	EB-L+ WB-L	NB	SB
a. T denotes through; L denotes left-turn; R denotes right-turn b. EB, WB, NB and SB denote east, west, north and south bound					

Generally, the number of commonly used signal phase plans is limited. For simplicity, we considered nine typical signal phase plans (Table 1), which can cover most of conditions used in practice. If necessary, other plans can be easily added up. Define $q \in Q$ as the serial number of a signal phase plan, while Q is the set of feasible signal phase plans, which may include all or a part of the nine signal phase plans based on the condition of the intersections, such as traffic demand and geometric features. In this study, the signal phase plan will be decided with the lane-use patterns. After that, the detailed signal timing plan including cycle length and green time will be generated.

Movements and Right-of-way

Define the vehicles which enter and leave the intersection from the same approach and exit as a movement and ignore the u-turn movements. Right-of-way refers the right of one movement to move during a certain signal phase, described by $\mathbf{R} = \{r_{jad}\}$, where d may equal to the integer of 1 to 4, representing the four exits sequentially: east, south, west and north; $r_{jad} = 1$ means the movement which enters the intersection from approach a and leave from exit d has right-of-way during phase j, otherwise $r_{jad} = 0$.

Objective

The dynamic lane-use management is to improve the total efficiency of traffic operation at the intersection and avoid traffic congestions. The total delay of vehicles crossing through the intersection is an important indicator of traffic efficiency at intersections. Therefore, the objective of this model is to minimize the total delay at the intersection.
According to the problem addressed in this paper, we use the signal delay model in HCM2000 to calculate the total delay at intersections(TRB, 2000). The HCM2000 delay model of the signalized intersection, which was improved based on Akcelik's model(Akcelik, 1988), is widely used and applicable on both unsaturated and oversaturated conditions.
The general delay model of HCM2000 for each lane group(TRB, 2000) at signalized intersection is shown in (2) and (3), and (3) is the detailed expression of (2).

$$d = d_1(PF) + d_2 + d_3 \quad (2)$$

$$d = \frac{0.5C\left(1-\frac{g}{C}\right)^2(PF)}{1-\left[min(1,X)\frac{g}{C}\right]} + 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right] + d_3 \quad (3)$$

Where, d is signal control delay (s/veh); d_1 is uniform delay (s/veh); PF is progression adjustment factor; d_2 is incremental delay (s/veh); d_3 is initial queue delay (s/veh); C is signal cycle length (s); g is effective green time for the lane group (s); X is volume to capacity (v/c) ratio or saturation degree for the lane group; T is analysis time period (h); k is incremental delay factor that is dependent on controller settings; I is upstream filtering/metering adjustment factor; and c is lane group capacity (veh/h).
In our case, we deal with isolated intersections and do not consider oversaturated conditions. So, PF and I equal to 1, d_3 equals to 0, and k equals to 0.5.
Moreover, the HCM2000 model is a lane group based delay model. In order to get the total delay, a parameter which describes the relationship between movements and lane groups is introduced. As a result, the objective function is shown as (4).

$$\min \Omega = \sum_i d_i v_i = \sum_i \left(d_i \sum_m \gamma_{im} v_m \right) \tag{4}$$

Where, Ω is the total delay of the intersection (s); i is the quantity of lane groups; v_i is the flow rate in lane group i (veh/h); m is the number of movements; γ_{im} equals to 1 if movement m belongs to lane group i, otherwise 0.

There are two categories of constraints for the model: lane constraints and signal phase constraints. The details of them will be discussed in the following section.

Constraints

Lane Constraints

The lane constraints ensure the compatibility of different types of lanes in a certain lane-use pattern. Two constraints are considered when assign the lane-use at an approach of one intersection.

Lane number constraints: The summation of number of each type of lanes equals to the total lane number at an approach, shown as (5).

$$\sum_b u_{ab} = N_{\boldsymbol{a}} \tag{5}$$

Shared lane constraints: There should be no more than one lane of each type of shared lane at an approach, and if there is a left-right-through shared lane, there cannot be a left-through shared lane or a right-through shared lane or exclusive through lanes at the same time. The constraints are shown as (6) and (7).

$$u_{ab} \leq 1,\ \forall a;\ \forall b = 2,4,6 \tag{6}$$

$$u_{a2} = u_{a3} = u_{a4} = 0, \text{if } u_{a6} = 1;\ \forall a \tag{7}$$

Signal Phase Constraints

The signal phase constraints ensure the compatibility of lane-use patterns and signal phase plan. Three constraints are considered when combining the lane-use assignment and signal control.

Lane matching constraints: Ensure that the total lane number at each exit are more or the same as the necessary quantity of lanes when different movements are released simultaneously, shown as (8).

$$\mathbf{r}_{\boldsymbol{d}} \cdot \mathbf{u}_{\boldsymbol{d}} \leq K_d \tag{8}$$

Where, $\mathbf{r}_{\boldsymbol{d}}$ is the vector of right-of-way of the movements from other approaches to exit d; $\mathbf{u}_{\boldsymbol{d}}$ is the vector of lanes of them; K_d is the quantity of lanes at exit d.

Signal constraints for movements on shared lanes: Ensure that the different movements which share a same lane are always released simultaneously, shown as (9) to (11).

$$r_{jab} = r_{jac}, \text{ if } u_{a2} = 1; \forall j, a \tag{9}$$

$$r_{jad} = r_{jac}, \text{ if } u_{a4} = 1; \forall j, a \tag{10}$$

$$r_{jab} = r_{jac} = r_{jad}, \text{ if } u_{a6} = 1; \forall j, a \tag{11}$$

Protected left-turn phase constraints: When the volume of left-turn vehicles and opposite through vehicles reach a certain level, they should be released separately for safety and efficiency. The constraints in HCM2000, which gives a full description of the conditions to set up a protected left-turn phase, are adopted in this study.

SOLUTION AND VALIDATION

Solution Space Analysis

According to the model formulation, it is not hard to know that its solution space is discrete and finite. Namely, it has finite solutions as well as the optimal solution(s). This property is good when we try to find an optimal solution. For a four-leg intersection, there are 25 decision variables in the model, 24 from the lane-use patterns $\mathbf{u}$ and the rest from signal phase plan q. However, if the values of these 25 variables are chosen randomly in the process of solution, there will be a large number of inappropriate plans that violate the constraints mentioned above and bring a lot of unnecessary computation. So it is possible and necessary to narrow the solution space before solve the model.

There are two steps which correspond to the two categories of constraints in narrowing the solution space. Firstly, consider the lane constraints and generate all feasible lane-use patterns, described as $\mathbf{w} = \{w_1, w_2, \dots, w_\beta\}$, denoting the feasible lane-use patterns of an intersection. Where, β is the quantity of approaches. The second step is to check the signal phase constraints and it further narrows the feasible solution space of the problem.

The solution space can be sharply narrowed after these two steps. Taking a four-leg intersection as an example, assume there are 5 lanes at each approaches, 3 lanes at each exits, no forbidden turnings, and no more than 2 exclusive right lanes at each approaches. There will be 23 feasible lane-use patterns for an approach before considering the compatibility with the signal phase plan. It is easy to find the original space is $6^5 = 7776$. The solution space is narrowed by 338 times, for only one approach!

Moreover, the variables are reduced from 25 to 5 (4 for the lane-use patterns of the 4 approaches, the rest for signal phase plan) and guarantees the validity of all the alternative lane-use patterns. Now the solution space, notated as E, is shown as (12).

$$E = w_1 w_2 w_3 w_4 q \tag{12}$$

Solution Procedures

Programs were developed to solve the model and find the combined optimal solution of lane-use pattern and signal timing plan. The signal timing plan includes the signal phase plan, the cycle length and the green time for every traffic movements. The optimal plans will change with the inputted traffic demand dynamically.

The solution procedures can be described as follows:

STEP 1: Initialization. Input all the data (traffic demand, geometric features, etc.) of the objective intersection and set up the parameters of the model;

STEP 2: Plan generation. First generate the feasible lane-use patterns under the lane constraints one by one approach, then generate the feasible combined plans E from the feasible lane-use patterns $\mathbf{w}$ and signal phase plan Q for the intersection under the signal phase constraints;

STEP 3: Optimization. Find the optimal plan that leads to a minimum total delay Ω_{MIN} from E output it;

STEP 4: Modification. When the traffic demand changes dramatically, go to STEP 1 and update the solution.

The flowchart of the solution procedures is shown as Figure 2.

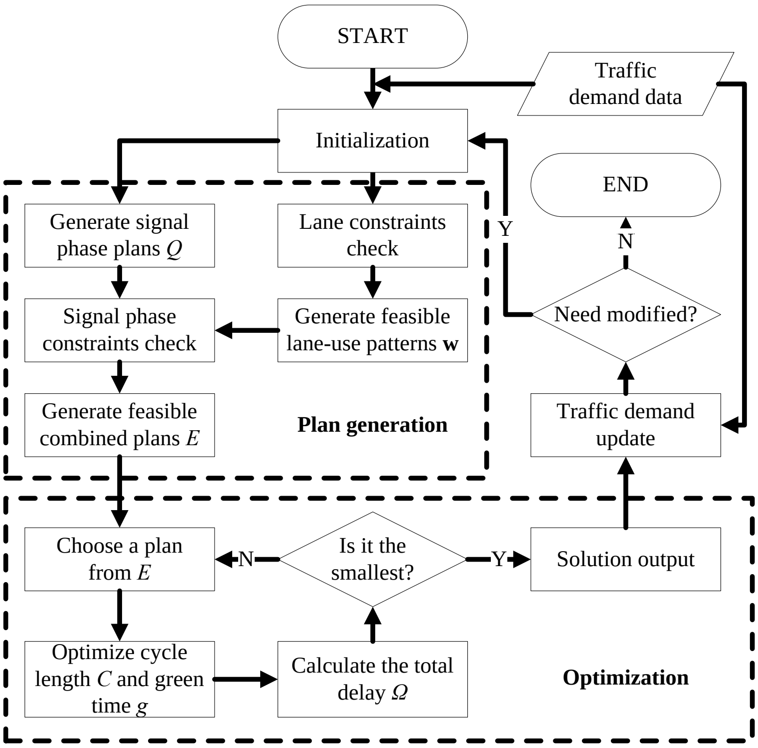

Figure 2 – The Flowchart of Solution Procedures

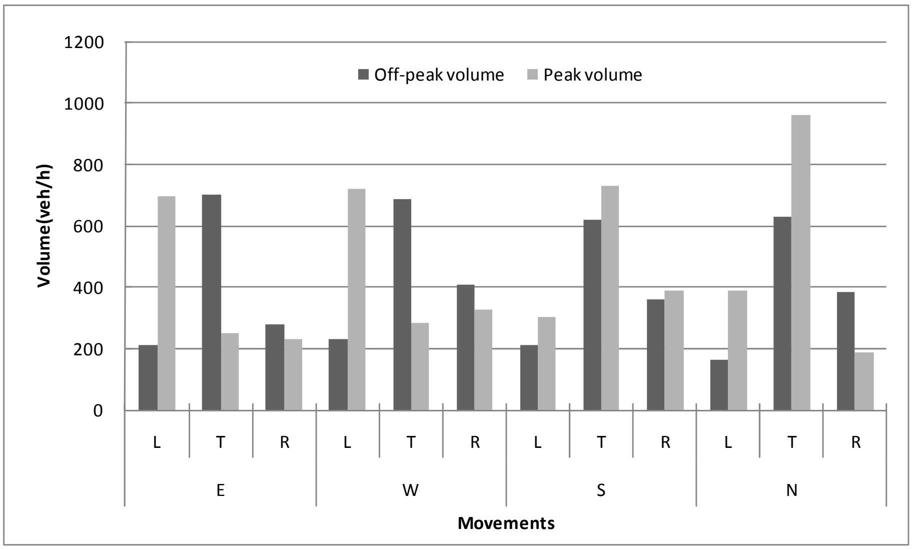

Figure 3 – Two Different Flow Pattern for Input

Model Validation

Description of the Case Study

Micro-simulation is used for model validation. A four-leg at-grade intersection is simulated as a case study in VISSIM, a widely used simulation tool in road traffic system. The intersection has a four-lane approach and a three-lane exit at each leg. Figure 3 shows two different flow patterns, peak hours and off-peak hours. The total volume in off-peak hours is 4881veh/h and it increases to 5457veh/h in peak hours, by 11.8%. The total volume does not increase very much, but the direction of the movements changes dramatically.

Calculation Analysis

There are four different scenarios in this case study.
Scenario 1: Apply the proposed model on the off-peak hour case and get an optimal solution of the lane-use assignment and signal timing. This solution is named as S_1.
Scenario 2: In the peak hour case, keep lane-use assignment and phase plan of S_1 unchanged, and improve the cycle length and green ratio with Webster's control policy.
Scenario 3: Optimize the phase plan as well as the cycle length and green ratio based on Scenario 2.
Scenario 4: Apply the proposed model on the peak hour case and get an optimal solution of the lane-use assignment and signal timing. This solution is named as S_2.
Before simulation, we first calculated the sum of the flow ratio of all the phases (denoted by Y here) for the four scenarios. This Y value reflects the balance of traffic demand and supply to a certain extent(Wang, 2002). The bigger Y is, the more prominent the contradiction. By calculation, Y is 0.63 in Scenario 1, while it becomes 1.01 in Scenario 2, increased by 60.3%. It shows that if we only adjust the signal control slightly, the "tide traffic" may cause traffic congestion. In Scenario 3, Y reduces to 0.98, by 3%, and it reduces to 0.79, by 21.8% in Scenario 4. The results show that there will be little improvement if only modifying the signal control in this case and it will be helpful if modifying both the lane-use assignment and signal timing. The solution S_1 and S_2 are shown in Figure 4 and Figure 5.

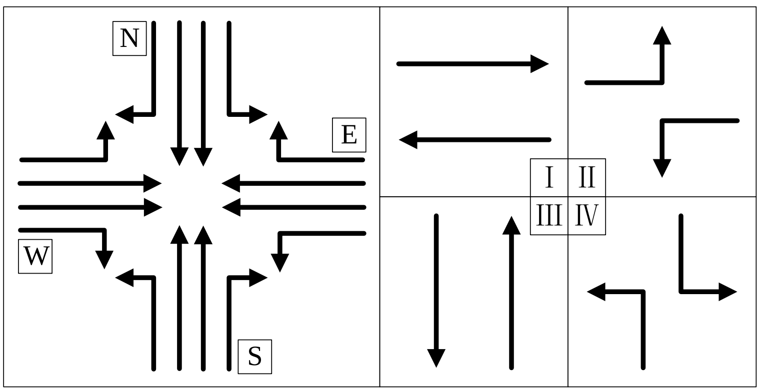

Figure 4 – The Optimal Solution for the Off-peak Hour Case

It is found that the traffic states of Scenario 2 and Scenario 3 are similar to each other and both close to saturation. To further validate the model, we simulate Scenario 1, 3 and 4 with VISSIM and get the microscopic indicators for traffic operation.

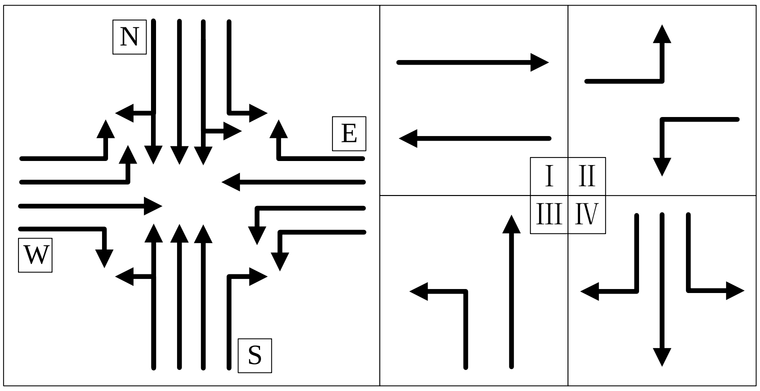

Figure 5 – The Optimal Solution for the Peak Hour Case

Simulation Results Analysis

According to the simulation results, the total delay of Scenario 3 increased by 54.1% compared to Scenario 1, while Scenario 4 increased by 34.3%. Figure 6, Figure 7 and Figure 8 sequentially show the comparison of average delay (AD), average queue length (AQ) and maximum queue length (MQ) from the simulation outputs. It is found that:

- Although the total volume increased only by 11.8% in peak hours, the queue of some movements spilled over the road section in Scenario 3. Compared to Scenario 1, the AD, AQ and MQ increased by 23.8%, 280.8% and 82.8%.
- Compared to Scenario 1, the AD, AQ and MQ of Scenario 4 increased by 7%, 72.1% and 36.3%;
- Compared to Scenario 3, the AD, AQ and MQ of Scenario 4 decreased by 9.4%, 18.4% and 16.2%.

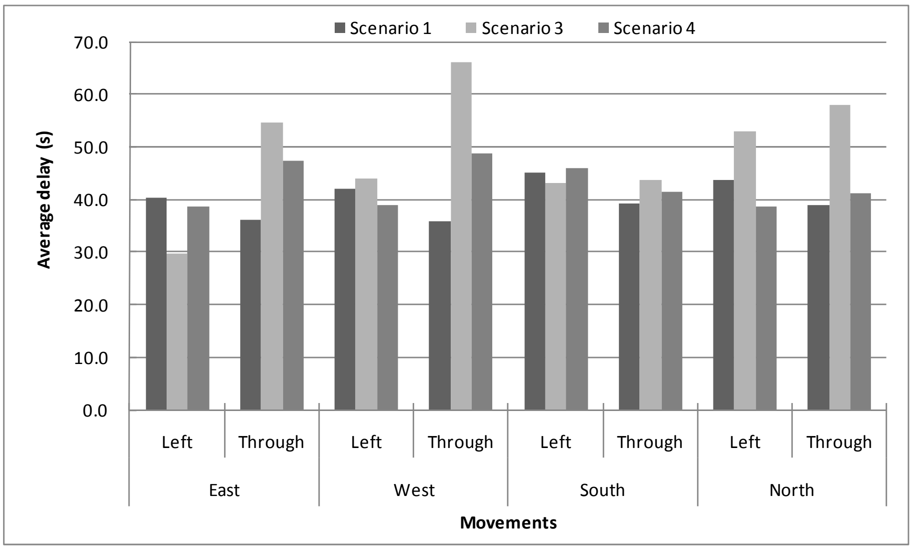

Figure 6 – Simulation Results Comparison: Average Delay

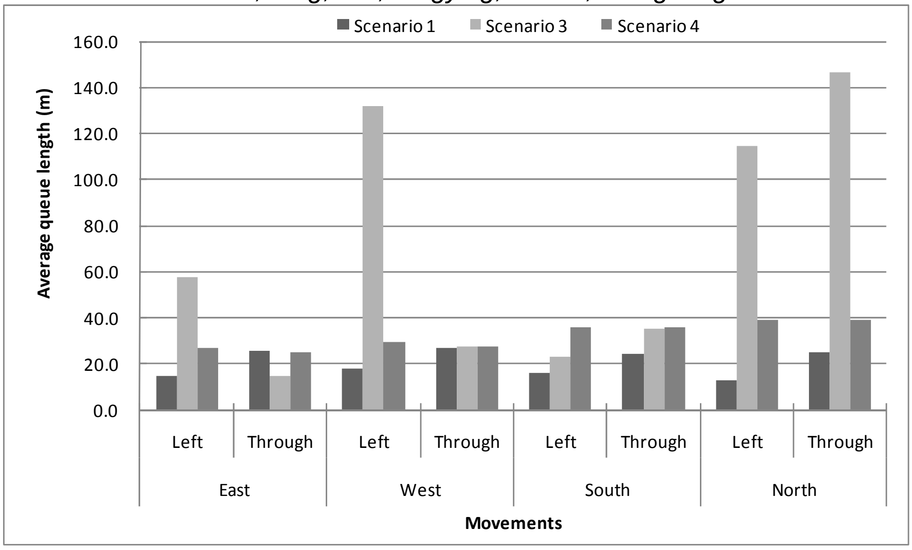

Figure 7 – Simulation Results Comparison: Average Queue Length

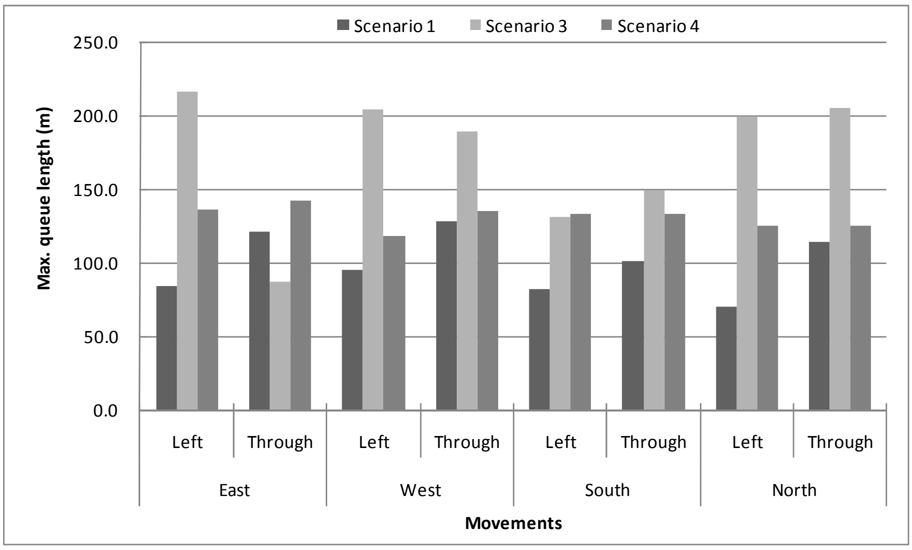

Figure 8 – Simulation Results Comparison: Maximum Queue Length

Discussion

According to the analysis of both theoretical calculation and micro-simulation, we find that:

- Not only the increase of traffic demand will cause traffic congestion at intersections, the change of the OD (origin-destination) of movements can also be an important reason, such as “tide traffic”;
- There are synergistic effects between lane-use assignment and signal control at intersections. In some cases, modifications on signal timing may not be helpful without improving the lane-use assignment together;
- It is proved that the dynamic lane-use management with demand responsive signal control is an effective method to prevent traffic congestions caused by the flow fluctuation as “tide traffic”.

CONCLUSIONS

In this paper, the problem of dynamic lane-use management at isolated intersections with demand responsive signal control is discussed. A programmable integrative model of lane-use assignment and signal timing is formulated and validated using micro-simulation. It is proved that the efficiency of traffic operation at intersections can be further improved by combining lane-use assignment and signal timing. The dynamic lane-use management, which changes the lane-use assignment at intersections according to the traffic demand by time of day, is especially suitable for the traffic congestions caused by dramatic traffic demand fluctuation such as the “tide traffic”.

The methodology proposed in this paper provides a new idea for traffic management under the background of ITS. However, there are still a lot of works to do before applications. For example, how to deal with the safety issues when changing the lane markers (e.g. between peak hour plan and off-peak hour plan) and whether a buffering plan is needed for transition? These problems will be interesting and worthy of being discussed in the further works.

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