USING SYSTEM PARTITION METHOD TO IMPROVE ARTERIAL SIGNAL COORDINATION

A Thesis

by

TAO ZHANG

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Chair of Committee,	Yunlong Zhang
Committee Members,	Clifford Spiegelman
	Luca Quadrifoglio
Head of Department,	John Niedzwecki

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ABSTRACT

A heuristic approach to the application of bandwidth-oriented signal coordination is proposed based on a system partition technique. The proposed approach divides a large signalized arterial into subsystems based on clustering results considering factors such as block distance and turning movements. Each subsystem is optimized to achieve the maximum bandwidth efficiency. Evaluation of the system includes two parts, THOS (through opportunity) comparison and simulation evaluation.

Two case studies are presented to illustrate how the proposed approach can be applied, and the influence of clustering method on signal coordination is presented with comparison of three scenarios, no partition, 2 clusters and 3 clusters. Evaluation of the case study shows that clustering method is beneficial in improving progression bandwidth, bandwidth efficiency, bandwidth attainability and THOS. Clustering is good for signal coordination in that either 2 clusters or 3 clusters will result in better performance measures that no partition. However, clustering is not always good for signal coordination in certain conditions. Though bandwidth and bandwidth efficiency of each sub-system can be improved after partition, control delay or number of stops for the corridor might be increased instead for certain conditions of the entire corridor. Whether or not clustering method can be used to partition a signalized system for the purpose of better signal coordination depends on specific traffic and geometric conditions of the corridor. When bandwidth capacity is exceeded by demand, bandwidth optimization should better give way to delay-based optimization strategies.

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NOMENCLATURE

LOS	Level of service
TSD	Time-space diagram
D_{ij}	Spacing between intersection i and j
V_{li}	Left turning volume of intersection i
V_{thi}	Through volume of intersection i
C_i	Cycle length of intersection i
THOS	Through opportunity
EB/WB/SB/NB	Eastbound/westbound/southbound/northbound
MOE	Measure of effectiveness

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1. INTRODUCTION

Signal systems can be divided into isolated intersection, arterial, and network. Minimizing delay is a common strategy for isolated signal timing plan development. This is because level of service (LOS) of an isolated intersection is determined by control delay. By minimizing delay, LOS and capacity will both be improved to optimum. However, for arterials and networks, there is a necessity for coordination especially when there are closely spaced intersections. The difficulties of coordination include need for a common cycle length, complicated intersection involving multiple phases, wide variability of traffic speeds, heavy turning movements, inadequate roadway capacity and so on. Over the past several decades, numerous studies have been conducted for the purpose of obtaining effective traffic signal coordination system and corresponding optimization timing plan. To get an optimized signal timing plan, four parameters need to be determined, i.e. cycle length, split, phase sequence, and offsets.

Existing signal optimization approaches can be classified into two main categories: to minimize delay and the number of stops, and to maximize progression bandwidth. The latter one is preferred by traffic engineers when developing arterial coordinated signal timing plan because a larger progression band implies that more vehicles can progress through without stops. In addition, a study conducted by Yang (2001) has indicated that bandwidth-oriented optimization generally outperform delay-oriented solutions based on several field studies.

One of the main issues of the bandwidth-based signal optimization is that when the number of signals increases (e.g., more than 10 signals), it becomes more and more difficult to maintain a good system progression bandwidth. It may not be a good practice to make use of a small progression bandwidth for an entire system. One of the problems is that when the through bandwidth is small and its capacity is lower than the through vehicle demand the coordination will be disturbed from the residual queue from the previous cycle and the effect of coordination will be severely reduced or even become useless. Therefore, there is a necessity of dividing a large system into several smaller subsystems before optimization, a technique called system partition. In that way, after optimization for subsystems, each subsystem is able to obtain a good progression bandwidth which in turn facilitates system coordination. System partition technique requires identifying critical intersections to be partitioning points. However, little work has been done of using system partition technique in signal optimization.

Another issue of bandwidth-based signal optimization is that volume is not an input parameter in some of the procedures. Even if the bandwidth capacity is quite good, when the traffic volume is larger than the bandwidth capacity, the coordination system will be severely influenced. There is a necessity to investigate the effect of different flow conditions on signal coordination.

A comprehensive investigation of using system partition method to facilitate signal coordination should be carried out. Several criteria of system partition based on cycle length, v/c ratio, spacing, and volume should be investigated, respectively. And since no theoretical research has been conducted to develop partition strategies, the researcher will investigate the applicability of using clustering statistical approach to partition intersections to improve coordination effects, in addition to practical driven considerations as those in the literature. A comparison of the performance between original system and partitioned system should be carried out in order for traffic engineers to recommend an appropriate system partition method for a specific system. The comparison can be done in two ways, manual calculation and simulation. In addition, a computer simulation gives us the flexibility to analyze the system partition method under different traffic conditions, which would not be practical in the field. Also, it is time and cost efficient. This research is designed to apply the system partition technique for signal coordination in real world conditions.

2. LITERATURE REVIEW

Among various signal optimization models, the most widely used ones make use of the following two approaches: (a) minimization of a disutility function such as delays and stops (b) maximization of progression bands.

Disutility-oriented signal timing may require minimizations in delay, number of stops, and queue length. SYNCHRO (Husch and Albeck, 2003) and TRANSYT-7F (Wallace and Courage, 1982) are the most popular macroscopic signal optimization models for arterial network that determine phase splits and offsets by minimizing a combination of delay, stop, and queue spill back. However, the models assume constant traffic flow. SCOOT (Martin and Hockaday, 1995) and SCATS (Grubba et al., 1993) are two widely used real-time signal optimization systems. However, SCOOT uses cruise speeds and saturation flow rate to predict queues, stops, and delays. In SCATS, free-flow speed and saturation flow rate are used to determine offsets.

Bandwidth-oriented signal timing strategies require optimization of basic signal timing parameters such as cycle length, green split, offset, and phase sequence. Morgan and Little (1964) developed the first optimization model used for arterial bandwidth maximization with a combinatorial optimization scheme. Little (1966) then proposed a more advanced model using mixed-integer linear programming (MILP). Later, MAXBAND was proposed by Little et al. (1981). In the MAXBAND program, signal cycle, offset, left-turn phase sequence, progression speed, and progression bandwidth can be optimized to maximize the weighted combination of the bandwidths in the two directions along the artery. Tsay and Lin (1988) proposed a modified version of the

MAXBAND model by defining queues as functions of arrival rates. Gartner et al. (1991), Stamatiadis and Gartner (1996), and Gartner and Stamatiadis (2002) used the maximum progression bandwidth and proposed a variable bandwidth (called multiband) for objective function and green time revision to adapt to different traffic conditions. Tian, Urbanik, Messer, Balke and Koonce (2003) proposed a new approach to the bandwidth-oriented signal-timing method based on a system partition technique. This method provides maximum progression for the peak direction, while still maintaining partial progression for the off-peak direction. Vasudevan and Chang (2006) presented an arterial signal control system that provides progression as well as optimizing signal timing plans at each intersection. The system was divided into two levels, i.e., progression control level which uses a modifies version of the multiband model, and intersection control level which optimizes signal timings by minimizing a weighted combination of queue length, control delay, and stops, subject to the bandwidth constraints generated at the progression control level. Lin et al. (2010) presented a new mixed-integer nonlinear programming (MINLP) model which is designed to optimize the bandwidths for successive signal intersections along an arterial. It was reported that this model can yield fewer stops, lower average delays, and higher average travel speeds. Lu et al. (2012) proposed a two-way bandwidth maximization model that maximizes the total bandwidth and introduced a bandwidth proration impact factor which allows the user to control the importance of satisfying the target bandwidth demand ratio.

Not much research has gone into the method of signal coordination through system partition. Tian and Urbanik (2007) proposed a heuristic approach to obtain bandwidth-oriented coordination based on system partition. In their proposed approach, a system was first divided into subsystems with each having three to five signals so that near 100% bandwidth attainability can be achieved. Then PASSER II was used to obtain the optimized bandwidth solution for each subsystem. The next step was to combine subsystems' progression band to form a system band for the peak-traffic direction. And for the off-peak direction, improvement can be achieved by making phasing adjustments (e.g., using a lead/lag phasing or switching the lead/lag sequence at partitioned signals). They concluded that bandwidth, bandwidth efficiency and bandwidth attainability can be significantly improved and average travel speed for through traffic can be increased by 15% through simulation evaluation. They also recommended that subsystem boundaries should be at intersections that have high v/c ratios which mean heavy traffic and where the spacing between contiguous intersections is large. Even though some recommendations were made based on their research, there is no systematic investigation of the effects of v/c ratio and spacing on system partition. In our research, not only v/c ratio and spacing, the researcher will also investigate the effect of volume and cycle length in order to make a comprehensive investigation.

Wu et al. (2012) also proposed a bandwidth-oriented optimization method based on group partition. They proposed an improved bandwidth optimization algorithm of calculating interference and offsets by specific conditions. Then a window program Bandwidth Optimization Time-Space Diagram (BOTSD) was developed to conduct group partition. For the process of group partition, they first investigated all possible combinations of subgroups (enumeration) and calculated arterial progression bandwidth for every combination. Based on their result, a method of partitioning arterial was developed based on traffic volumes. The principle was that intersections with minimum total traffic volumes of turning movement and maximum total traffic volumes of through movement were partitioning points. However, the principle they proposed was strange because in general, the intersection with maximum turning movement and minimum through movement is a master intersection which controls the maximum possible progression bandwidth and should be considered as potential partitioning points. Therefore, this research will focus on finding appropriate principles and recommendations of using system partition technique.

3. RESEARCH METHODOLOGY

The task of this research is to investigate the availability and applicability of arterial partition method in facilitating coordination. An automated process of arterial partition is enumeration which considers all possible combinations of subsystems. Then after optimization and coordination for each subsystem, we are able to evaluate all the possible combinations and recommend an optimal solution. However, with the number of signals increasing, the total number of enumeration will significantly increase. In other words, for an arterial with large number of signals, the automated process of partition may not be a good practice. On the other hand, there exist natural properties that can provide a guideline to select partitioning points. Specifically, the natural properties are closely related to parameters of traffic condition, i.e., spacing between contiguous intersections, left turning and through volume, the ratio of volume and capacity, and cycle length.

To investigate different partitioning methods for traffic signal coordinated control, several factors are considered as follows:

- To partition an arterial based on D_{ij} (contiguous spacing); specifically, a link with large spacing is a partitioning boundary. Large spacing has notable influence on progression bandwidth in that vehicles traveling on those links are more likely to fall outside of the progression band due to speed variation and platoon dispersion. For example, a platoon of vehicles are traveling on this kind of link with growing headway, then only a portion of this platoon can pass the next intersection during the green phase. Therefore, such criterion is to avoid platoon dispersion and queue spillback.

- To partition an arterial based on $V_{L,i}$ (left turning volume) and $V_{Th,i}$ (through volume); specifically, intersections with high left turning volume and low through volume are considered as partitioning points. Since through volume is relatively low to left turning volume, the through green time is relatively low (the intersection with the lowest through green time is called critical intersection). At such intersections, through traffic will be easily affected by both high volume of left turning vehicles and low through green time. Regrouping vehicles to start at the next progression band at such intersections has the advantage of avoiding queue spillback and facilitating coordination.
- To partition an arterial based on $(v/c)_i$ (the ratio of volume and capacity); specifically, intersections with high v/c ratios are considered as partitioning points. Such intersections normally have long queues. It is likely that progression traffic will be affected by the queues and thus may impede the progression band.
- To partition an arterial based on C_i (cycle length); specifically, intersections with different cycle length are partitioned to different subsystems. For the purpose of arterial coordination, the cycle length of each subsystem should be maintained the same.

Based on the scope of this research, the proposed signal coordination approach is outlined in the following steps:

3.1 Input parameters

For a given arterial, we can obtain parameters within the system, e.g., spacing between adjacent intersections, volumes of each intersection, speed at each link, and geometric conditions.

3.2 Matlab clustering

In this step, we apply the system partition method to our designate arterial. The partition method we use here is k-means clustering. K-means clustering method is a statistical approach which aims at partitioning n observations into k clusters, in which each of the n observations is contained in the cluster with the nearest mean (Mackay, 2003). In our study, n observations can be regarded as n intersections and k clusters can be considered as k subsystems. The problem is non-deterministic polynomial-time hard problem (NP-hard), but there exists several heuristic algorithms that can be used to obtain a local optimal solution. Moreover, k-means clustering has tendency to find clusters of comparable spatial extent (Chang el al., 1988). K-means clustering algorithm is introduced as follows.

The standard k-means algorithm uses an iterative refinement technique. Given an initial set of k means $m_1^{(1)}, m_2^{(1)}, \dots, m_k^{(1)}$, the algorithm proceeds by alternating between two steps (MacKay, 2003):

Assignment step: Assign each observation to the cluster with the closest mean.

$$S_i^{(t)} = \left\{x_p : \left\| x_p - m_i^{(t)} \right\| \le \left\| x_p - m_j^{(t)} \right\| \; \forall \, 1 \le j \le k \right\} \tag{1}$$

where each x_p goes into exactly one $S_i^{(t)}$, even if it could go in two of them.

Update step: Calculate the new means to be the centroid of the observations in the cluster.

$$m_i^{(t+1)} = \frac{1}{S_i^{(t)}} \sum_{x_j \in S_i^{(t)}} x_j \qquad (2)$$

The algorithm is deemed to have converged when the assignments no longer change between each other. Since it is a heuristic algorithm, it cannot be guaranteed that it will converge to the global optimal solution, and the result may depend on the initial clusters. As the algorithm is usually very fast, it is common to run it multiple times with different starting conditions.

An illustration of the standard k-means algorithm is shown in Figure 1. In step 1, k initial "means" (in this case k=3) are randomly generated (shown in color). And in step 2 (assignment step), k clusters are created by associating every observation with the nearest mean. Step 3 is the update step, the centroid of each of the k clusters becomes the new mean. In step 4, Steps 2 and 3 are repeated until convergence has been reached.

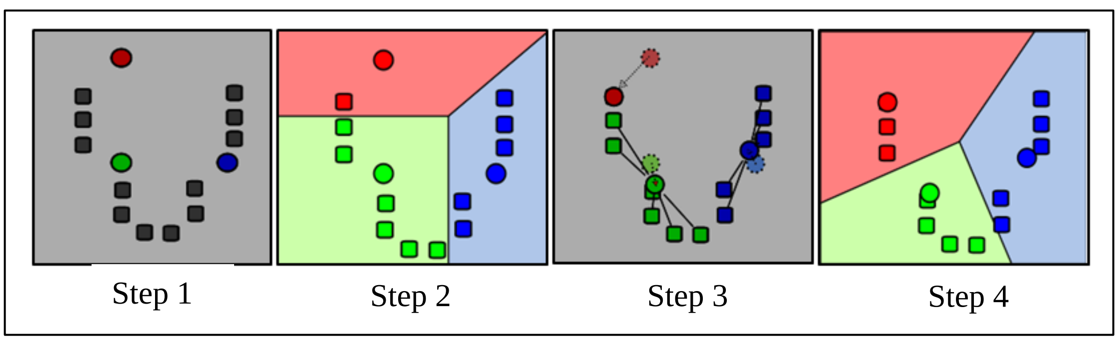

Figure 1 Illustration of k-means clustering algorithm

After investigating the applicability of k-means algorithm to partition *n* signals into *k* groups, we found that the main difficulty here is that in our signal system, adjacent intersections should be partitioned into the same subsystem. For example, for a signal system with 10 signals, even if 1st intersection and 8th intersection should be in the same cluster according to the k-means algorithm, they cannot just because they are not adjacent. Another example is that even if 3rd intersection and 4th intersection have great difference in parameters, they probably will have to be in the same cluster because they are adjacent and this difference is not as significant as that of other adjacent intersections. An easy way to overcome this difficulty is to add one more dimension, which is called location dimension. This location dimension is a set of numbers that start at zero and increase slightly more than the spacing between adjacent intersections. With this dimension existing, the clustering algorithm used in Matlab will ensure that adjacent intersections are partitioned into a same subsystem.

After clustering using Matlab, we are able to obtain clustering results that divide the whole arterial into several subsystems.

3.3 Signal coordination

In this step, we will perform signal optimization and coordination for each subsystem. We use Brook’s method and PASSER II to conduct signal coordination.

3.3.1 Brook’s method

Most bandwidth-oriented optimization approaches are based on the primary principles of bandwidth optimization algorithm developed by Brook and Little. Figure 2 illustrates the basic concept of Brook’s bandwidth optimization algorithm using simple three signals with two-phase operations. As seen in Figure 2, the intersection with minimum green split (the middle intersection in Figure 2), $\mathrm{G_{min}}$, is called the master intersection. This minimum green time determines the maximum possible progression bandwidth that can be achieved only if there is no interference. However, either an upper interference or a lower interference always occurs at each signal except the critical intersection. Then the final system bandwidth is determined by $\mathrm{G_{min}}$ minus the minimum possible combination of the upper interference and the lower interference, as shown in Eqs. (3).

$$\mathrm{B} = G_{min} - min\left\{\max_{\forall i}(I_{U,i}) + \max_{\forall j}(I_{L,j})\right\} \tag{3}$$

where: B= bandwidth (s); $\mathrm{I_{U,i}}$= upper interference at intersection *i* (s); $\mathrm{I_{L,j}}$= lower interference at intersection *j* (s); $\max_{\forall \mathrm{i}}(\mathrm{I_{U,i}})$= maximum value from all signals producing upper interference (s); $\max_{\forall j}(I_{L,j})$= maximum value from all signals producing lower interference (s).

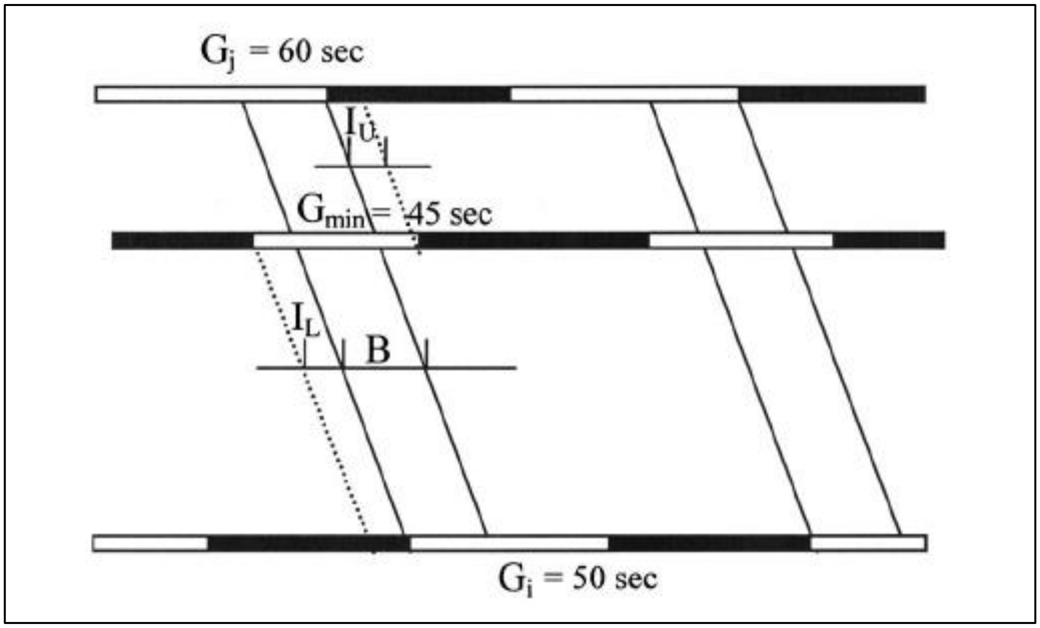

Figure 2 Illustration of Brook's algorithm (Tian and Urbanik, 2007)

To maximize the progression bandwidths for both directions, parameters such as the offset and phasing strategy of each intersection should be carefully determined. For each intersection, the interference for one direction is also related to the timing parameters for the other direction. Eqs. (4) and (5) show how the upper interference or the lower interference can be calculated for a direction.

$$I_{U,j}(p) = \left[G_{min} - T_{mj} + T_{jm} - O_m(n) + O_j(p) + G_j\right] mod\ C \quad (4)$$

$$I_{L,j}(p) = \left[T_{mj} + T_{jm} - O_m(n) + O_j(p) - S_j\right] mod\ C \quad (5)$$

where: $I_{U,j}(p)\ and\ I_{L,j}(p)$= upper interference and lower interference at intersection *j* with phase sequence *p* (only one phase sequence could occur) (s); T_{mj}, T_{jm}= travel times between intersections *m* and *j* (s); $O_m(n)$= relative offset between direction a green time and direction *b* green time at signal *m* with phase sequence *n* (s); $O_j(p)$= relative offset between direction a green time and direction b green time at signal j with phase sequence p (s); G_j= direction a green time at signal j (s); S_j= difference between green times of intersections j and m in direction b (s); and C= cycle length (s).

Eqs. (3)-(5) suggest that the interference is largely affected by T_{mj} and T_{jm}. With the increase of the number of intersections, the probability of having larger interference also increases. For example, there might be an intersection whose spacing may actually produce maximum interference, which equals to the green time of the master intersection. In this case, the bandwidth would be zero.

3.3.2 PASSER II method

In our research, another way of signal coordination is to use PASSER II option in PASSER V-03. The following is a basic introduction of PASSER II.

PASSER II is a bandwidth-based program for optimizing signal timing plans for signalized arterials (PASSER II-90 user's manual, 1990). Originally developed by TxDOT about 30 years ago, it is one of the most popular programs. The heuristic signal-timing optimization model of PASSER II is based on a Windows-based, user-friendly graphical technique, i.e. Time-space diagram (TSD), which is simple, efficient, and powerful. The program seeks to maximize two-way arterial progression and minimize signal delay. PASSER II can determine all four signal-timing variables. It selects the plan that maximizes arterial progression bandwidth, usually the one with largest bandwidth efficiency. PASSER II has passed the test of time and is known to produce good signal-timing plans, even when some level of congestion exists on an arterial. Because of its simplicity, it is also one of the most computationally efficient programs.

PASSER II performs comprehensive and exhaustive search over the range of cycle lengths provided by the user, at an increment of certain number defined by user. The program starts by calculating equal saturation splits using Webster's method. A brief introduction of Webster's method is as follows:

Webster's method

Webster's method is one of the most useful and prevalent methods that develop reasonable timing plans (Webster and Cobbe, 1966). It is based on minimizing intersection delay and calculates the optimal cycle length as a function of the lost time and critical flow ratios, as can be seen in Eqs. (6). Critical lane group is the lane group which has the highest volume/saturation flow ratio in each phase. Then cycle length typically is rounded up to the nearest 5 sec for values between 30 and 90 seconds. And it is rounded up to the nearest 10 sec for higher values. After the cycle length is determined, the distribution of green time is also determined based on volume/saturation flow ratio of critical lane group. Also note that minimum green time requirement should be satisfied.

$$C_o = \frac{1.5L+5}{1.0-\sum_{i=1}^{n} y_i} \tag{6}$$

where: C_o: optimal cycle length for minimizing delay (sec); L: Total lost time per cycle (sec); y_i: observed flow/saturation flow ratio for the critical lane group in each phase i.

After calculating the cycle length and corresponding allocation of green time, PASSER II applies a hill climbing approach to adjust splits and minimize delay. Finally, it applies a bandwidth optimization algorithm using the calculated green splits for a specific cycle length range. During the optimization period, it finds optimal offsets and phase sequences that produce maximum two-way progression. At this stage, PASSER first provides perfect one-way progression in the A direction. Then, it minimizes interference in the B (opposite) direction by adjusting phasing sequences and offsets. The maximum total band calculated by the program is as follows:

$$\text{Total Band} = G_A + G_B - I \qquad (7)$$

where: G_A = Minimum green in A-direction; G_B = Minimum green in B-direction; and I = Minimum possible band interference.

After achieving the best bandwidth (minimum interference) in the B direction, the program adjusts the two bands according to user-desired options for directional priority. Finally, the program calculates MOEs such as delays, bandwidth efficiency, and attainability.

Bandwidth efficiency for a direction is the percent of cycle used for progression. Bandwidth attainability is the percent of bandwidth in a direction in relation to the minimum green split in the same direction. Theoretically, the maximum bandwidth in a direction can be no more than the smallest through green split in that direction. PASSER II uses the following formulas to calculate combined efficiency and attainability for the two arterial directions:

$$\text{Progression Efficiency (\%)} = \frac{(Arterial\ Band_A + Arterial\ Band_B)}{2 * Cycle\ Length} * 100 \qquad (8)$$

$$\text{Progression Attainability (\%)} = \frac{(Arterial\ Band_A + Arterial\ Band_B)}{(Min.Green_A + Min.Green_B)} * 100 \qquad (9)$$

We should note that while bandwidth generally increases with an increase in cycle length, efficiency may increase, decrease, or remain constant.

3.4 Evaluation

In this step, we will evaluate the clustering results in two ways, through opportunity (THOS) comparison and simulation evaluation.

3.4.1 THOS evaluation

TRANSYT-7F has introduced a PROS (progression opportunity) measure in its optimization routine (Wallace and Courage, 1982). The PROS is a representative of partial progression band which has potential in reducing stops and delays for vehicles that travel outside the progression band.

THOS (Through opportunity) is similar to PROS but not the same. THOS describes a kind of availability of progression and is determined by multiplying the number of continuous through intersections by corresponding bandwidth, as shown in Eqs. (10).

$$\text{THOS} = \sum_{j=1}^{n} \sum_{i=1}^{2} [\frac{BW_{ji} * (N_j - 1)}{h} * \frac{3600}{C_j}] \qquad (10)$$

where: THOS= through opportunities; N_i= the number of intersections for subsystem *j*; BW_{ji}= progression bandwidth of subsystem *j* in i direction (sec); n= the total number of subsystems; h= saturation headway, 2 sec; C_j= cycle length of subsystem j (sec).

Generally, the larger THOS is, the smaller number of stops and the better progression we will obtain. Note that this comparison makes sense only if bandwidth capacity is greater than flow rate. Bandwidth capacity is the number of vehicles that can pass through a defined series of signals without stopping and is measured as shown in Eqs. (11):

$$c_{BW} = \frac{3600*BW*N}{C*h} \tag{11}$$

where: c_{BW}= bandwidth capacity (veh/h); BW= bandwidth (s); N= number of through lanes in the indicated direction; C= cycle length (s); h= saturation headway (s).

3.4.2 CORSIM simulation

Another way is to evaluate the effect of clustering on signal coordination by simulation. Though we get good results through PASSER V or Brook's method, in terms of bandwidth, bandwidth efficiency, bandwidth attainability, and PROS, it's still not comprehensive for traffic engineers to evaluate whether clustered signal coordination really helps.

Another significant reason that simulation evaluation should be performed is that in either Brook's method or PASSER II, speed at any link is assumed to be constant. However, in real world condition, speed is not a constant and varies often especially at links that have large spacing. Large spacing has notable influence on progression bandwidth in that vehicles traveling on those links are more likely to fall outside of the progression band due to speed variation and platoon dispersion. Taken into these considerations, simulation should be conducted.

The proposed approach of system partition is evaluated using the CORSIM (TSIS user's manual, 2003) microscopic simulation model. The outputs (e.g., delay and number of stops) from CORSIM can easily help us tell whether system partition is good for coordination.

3.5 Recommendations

Based on evaluation from two perspectives, we are able to make conclusions and recommendations. Several conclusions such as whether clustering method is good for signal coordination and which parameters are crucial to partition points should be included.

4. EXPERIMENTAL DESIGN

For the purpose of better understanding the scope of the research and investigating the effect on signal coordination of using system partition method, it is necessary to develop a comprehensive experimental design.

First, an arterial with 10 intersections is investigated and several scenarios including base scenario are developed. Parameters of an arterial might include spacing between adjacent intersections, volumes of each intersection, and signal timing plan of each intersection. However, if volumes of an intersection are known, then signal timing plan of the intersection is basically determined by using appropriate signal timing method. The most well know methods are Webster's method and HCM method. In our experimental design, we use Webster's method to develop signal timing plan for each intersection.

Second, for each scenario, we run clustering in Matlab and get the clustering results. Because in our experimental design, the arterial has 10 intersections, we only consider to partition the arterial once or twice, meaning that we will only have 2 clusters or 3 clusters of the arterial.

Third, based on the clustering results, both Brook's method and PASSER V are used to perform signal coordination. In Brook's method, we use Webster's equation to get cycle length and then assign green splits to each phase based on v/s (volume to saturation flow rate). Timing strategy is assumed to be three phase with left turn leading. After performing signal coordination, MOEs such as bandwidth, bandwidth efficiency, and bandwidth attainability are obtained.

Afterwards, we are able to evaluate the effect of system partition method on signal coordination based on the results from various scenarios.

Notice that evaluation of CORSIM simulation is not included in this experimental design. We put more emphasis on investigating the applicability and availability of clustering on signal coordination. The results may not be comprehensive in terms of performance measures (i.e. bandwidth, bandwidth efficiency, bandwidth attainability, and PROS), other performance measures such as delay, number of stops, and average speed can only be obtained from simulation. However, it's a good practice for us to run this experimental design before a real case study.

4.1 Base scenario

In our experimental design, only spacing and volumes are considered as variables. Also notice that the scope of the research includes investigating the influence of spacing, left turning volume and through volume of Major Street. Therefore, base scenario is shown in Table 1.Since the magnitude of volume is crucial in determining cycle length using Webster's method, the values in Table 1 were carefully chosen so that the calculated cycle length won't be too large or too small. We also assume that right turn volume of Major Street and all volumes of cross streets remain unchanged. Notice that in our base scenario, all parameters for each intersection are the same. For simplicity, we do not consider volume variations in two directions (i.e. EB/WB or NB/SB has symmetric volumes).

Table 1 Base scenario parameters

Intersection Number	Spacing (ft)	Volume of Major Street (EB/WB) (vph)			Volume of Cross Street (NB/SB) (vph)		
		Left Turn	Through	Right Turn	Left Turn	Through	Right Turn
1	0	300	900	60	80	300	30
2	1000	300	900	60	80	300	30
3	1000	300	900	60	80	300	30
4	1000	300	900	60	80	300	30
5	1000	300	900	60	80	300	30
6	1000	300	900	60	80	300	30
7	1000	300	900	60	80	300	30
8	1000	300	900	60	80	300	30
9	1000	300	900	60	80	300	30
10	1000	300	900	60	80	300	30

4.2 Scenario 1

In this scenario, we consider to change the values of spacing. Since the magnitude and location of the intersection whose spacing is changed might be critical to the clustering result, we develop three scenarios within this series.

4.2.1 Scenario 1.1

We change the spacing between intersection 4 and 5 from 1000 to 2000 feet in this scenario. Other parameters remain unchanged, as can be seen in Table 2.

Table 2 Parameters of scenario 1.1

Intersection Number	D_ij (ft)	V_Li (vph)	V_Thi (vph)
1		300	900
2	1000	300	900
3	1000	300	900
4	1000	300	900
5	2000	300	900
6	1000	300	900
7	1000	300	900
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering is shown in Table 3 and Table 4, meaning that if the system is clustered into 2 subsystems, then the first four intersections form one subsystem and the latter six construct the other. If the system is clustered into 3 subsystems, then the first four intersections constitute the first subsystem, the following three intersections form the second subsystem and the last three intersections make up the third subsystem. THOS of each subsystem and the total THOS are calculated and shown in Table 3 and Table 4. It can be seen that for Brook's method, THOS increases as the number of clusters increases. While for PASSER II, THOS decreases as the number of clusters increases. However, the magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. This is the result of different algorithms. For Brook's method, with more clusters exist, there are more chances for the algorithm to achieve larger bands. The bandwidth attainability of Brook's method is 9.8% and 28.3%, while PASSER II produces bandwidth attainability of nearly 100%. All these factors might suggest that PASSER II solution is more convincing for this scenario. Since the volumes at each intersection is the same, the best timing strategy here is to be developed without partition, which can produce eastbound and westbound bandwidth of 45 sec, bandwidth efficiency of 45% and bandwidth attainability of 93.75%. The resulting THOS is 14580, the highest among all three combinations in this scenario.

Table 3 Brook's signal coordination result of scenario 1.1

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	4	6	4	3	3
Cycle (sec)	80	80	80	80	80	80
TotalBand (sec)	6.28	18.1	6.28	18.1	18.1	18.1
EB Band (sec)	3.14	9.05	3.14	9.05	9.05	9.05
WB Band (sec)	3.14	9.05	3.14	9.05	9.05	9.05
TotalEff* (%)	3.9	11.3	3.9	11.3	11.3	11.3
EB Eff* (%)	3.9	11.3	3.9	11.3	11.3	11.3
WB Eff* (%)	3.9	11.3	3.9	11.3	11.3	11.3
Total Att* (%)	9.8	28.3	9.8	28.3	28.3	28.3
EB Attain* (%)	9.8	28.3	9.8	28.3	28.3	28.3
WB Attain* (%)	9.8	28.3	9.8	28.3	28.3	28.3
THOS_i	1272	1222	707	1222	815	815
THOS_total	1272	1928		2851		

Eff* represents efficiency; Att* and Attain* represent attainability.

Table 4 PASSER II signal coordination result of scenario 1.1

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	4	6	4	3	3
Cycle (sec)	100	105	105	105	105	105
TotalBand (sec)	90	99	99	99	102	102
EB Band (sec)	45	50	50	50	51	51
WB Band (sec)	45	49	49	49	51	51
TotalEff (%)	45	47.14	47.14	47.14	48.57	48.57
EB Eff (%)	45	47.62	47.62	47.62	48.57	48.57
WB Eff (%)	45	46.67	46.67	46.67	48.57	48.57
Total Att (%)	93.75	97.06	97.06	97.06	100	100
EB Attain (%)	93.75	98.04	98.04	98.04	100	100
WB Attain (%)	93.75	96.08	96.08	96.08	100	100
THOS_i	14580	5091	8486	5091	3497	3497
THOS_total	14580	13577		12086		

4.2.2 Scenario 1.2

In this scenario, on the basis of scenario 1.1, we change the spacing from intersection 7 and 8 from 1000 to 2000 feet. Other parameters remain unchanged, as can be seen in Table 5.

Table 5 Parameters of scenario 1.2

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	300	900
5	2000	300	900
6	1000	300	900
7	1000	300	900
8	2000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 6 and Table 7. It can be seen that the same result occurs as scenario 1.1 in that for Brook's method, THOS increases as the number of clusters increases. While for PASSER II, THOS decreases as the number of clusters increases. THOS of Brook's method without partition equals to zero. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. For Brook's method, with more clusters exist, there are more chances for the algorithm to achieve larger bands. Occasionally, the scenario of Brook's method with no partition produces no possible progression band. The bandwidth attainability of Brook's method is 0%, 11.9% and 28.3%, while PASSER II produces bandwidth attainability of nearly 100%. All these factors indicate that PASSER II solution is more convincing for this scenario. Since the volumes at each intersection is the same, the best timing strategy here is to be developed without partition, which can produce an eastbound bandwidth of 45 sec with bandwidth efficiency of 45% and bandwidth attainability of 93.75%, and a westbound bandwidth of 44 sec with bandwidth efficiency of 44% and bandwidth attainability of 91.67%. The resulting THOS is 14418, slightly greater than that of 2 clusters (13577) and much greater than that of 3 clusters (12086).

Table 6 Brook's signal coordination result of scenario 1.2

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	80	80	80	80	80	80
TotalBand (sec)	0	18.1	7.64	18.1	18.1	18.1
EB Band (sec)	0	9.05	3.82	9.05	9.05	9.05
WB Band (sec)	0	9.05	3.82	9.05	9.05	9.05
TotalEff (%)	0	11.3	4.8	11.3	11.3	11.3
EB Eff (%)	0	11.3	4.8	11.3	11.3	11.3
WB Eff (%)	0	11.3	4.8	11.3	11.3	11.3
Total Att (%)	0	28.3	11.9	28.3	28.3	28.3
EB Attain (%)	0	28.3	11.9	28.3	28.3	28.3
WB Attain (%)	0	28.3	11.9	28.3	28.3	28.3
THOS_i	0	1629	688	1222	815	815
THOS_total	0	2317		2851		

Table 7 PASSER II signal coordination result of scenario 1.2

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	100	105	105	105	105	105
TotalBand (sec)	89	99	99	99	102	102
EB Band (sec)	45	50	50	50	51	51
WB Band (sec)	44	49	49	49	51	51
TotalEff (%)	44.5	47.14	47.14	47.14	48.57	48.57
EB Eff (%)	45	47.62	47.62	47.62	48.57	48.57
WB Eff (%)	44	46.67	46.67	46.67	48.57	48.57
Total Att (%)	92.71	97.06	97.06	97.06	100	100
EB Attain (%)	93.75	98.04	98.04	98.04	100	100
WB Attain (%)	91.67	96.08	96.08	96.08	100	100
THOS_i	14418	6789	6789	5091	3497	3497
THOS_total	14418	13577		12086		

4.2.3 Scenario 1.3

In this scenario, on the basis of scenario 1.2, we change the spacing from intersection 7 and 8 from 2000 to 3000 feet. Other parameters remain unchanged, as can be seen in Table 8.

Table 8 Parameters of scenario 1.3

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	300	900
5	2000	300	900
6	1000	300	900
7	1000	300	900
8	3000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 9 and Table 10. It can be seen that the same result occurs as scenario 1.1 and 1.2 in that for Brook’s method, THOS increases as the number of clusters increases. While for PASSER II, THOS decreases as the number of clusters increases. THOS of Brook’s method without partition also equals to zero as scenario 1.2. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook’s method is much less than that in PASSER II. For Brook’s method, with more clusters exist, there are more chances for the algorithm to achieve larger bands. Occasionally, the scenario of Brook’s method with no partition produces no possible progression band. The bandwidth attainability of Brook’s method is 0%, 11.9% and 28.3%, while PASSER II produces bandwidth attainability of nearly 100%. All these factors indicate that PASSER II solution is more convincing for this scenario. Since the volumes at each intersection is the same, the best timing strategy here is to be developed without partition, which can produce an eastbound bandwidth of 44 sec with bandwidth efficiency of 44% and bandwidth attainability of 91.67%, and a westbound bandwidth of 44 sec with bandwidth efficiency of 44% and bandwidth attainability of 91.67%. The resulting THOS is 14256, slightly greater than that of 2 clusters (13371) and much greater than that of 3 clusters (12086).

Table 9 Brook's signal coordination result of scenario 1.3

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	4	3	3
Cycle (sec)	80	80	80	80	80	80
TotalBand (sec)	0	7.64	18.1	18.1	18.1	18.1
EB Band (sec)	0	3.82	9.05	9.05	9.05	9.05
WB Band (sec)	0	3.82	9.05	9.05	9.05	9.05
TotalEff (%)	0	4.8	11.3	11.3	11.3	11.3
EB Eff (%)	0	4.8	11.3	11.3	11.3	11.3
WB Eff (%)	0	4.8	11.3	11.3	11.3	11.3
Total Att (%)	0	11.9	28.3	28.3	28.3	28.3
EB Attain (%)	0	11.9	28.3	28.3	28.3	28.3
WB Attain (%)	0	11.9	28.3	28.3	28.3	28.3
THOS_i	0	860	1222	1222	815	815
THOS_total	0	2081		2851		

Table 10 PASSER II signal coordination result of scenario 1.3

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	4	3	3
Cycle (sec)	100	100	105	105	105	105
TotalBand (sec)	88	92	99	99	102	102
EB Band (sec)	44	46	50	50	51	51
WB Band (sec)	44	46	49	49	51	51
TotalEff (%)	44	46	47.14	47.14	48.57	48.57
EB Eff (%)	44	46	47.62	47.62	48.57	48.57
WB Eff (%)	44	46	46.67	46.67	48.57	48.57
Total Att (%)	91.67	95.83	97.06	97.06	100	100
EB Attain (%)	91.67	95.83	98.04	98.04	100	100
WB Attain (%)	91.67	95.83	96.08	96.08	100	100
THOS_i	14256	8280	5091	5091	3497	3497
THOS_total	14256	13371		12086		

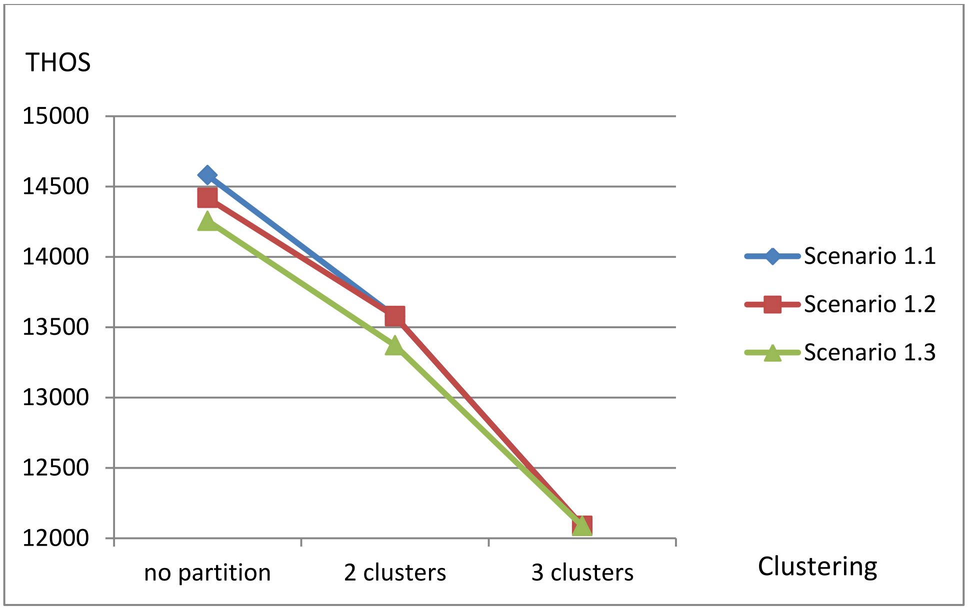

Figure 3 THOS for different clustering scenarios of scenario 1.1, 1.2, and 1.3

Figure 3 shows the total THOS of PASSER II for all clustering combinations of all scenarios in scenario 1. As can be seen, THOS decreases as the number of clusters increases, indicating that the best strategy is the scenario with no partition. It can also be seen that scenario 1.1 is the best while scenario 1.3 is the worst in terms of THOS. However, the difference between each scenario is slight, showing that spacing has influence to some extent on signal coordination.

4.3 Scenario 2

In this scenario, we consider to change the values of left turning and through volumes of major arterial. Since the magnitude and location of the intersection whose volumes are changed might be critical to the clustering result, we develop three scenarios within this series.

4.3.1 Scenario 2.1

In this scenario, we change the volume combination of intersection 4. Left turning volume is changed from 300 to 500 vph while through volume is decreased from 900 to 700 vph. The total of left turning volume and through volume remains 1200 vph. Other parameters remain unchanged as base scenario, as can be seen in Table 11.

Table 11 Parameters of scenario 2.1

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	500	700
5	1000	300	900
6	1000	300	900
7	1000	300	900
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 12 and Table 13. It can be seen that the result is different as compared to scenario 1. For Brook's method, though bandwidth, bandwidth efficiency and bandwidth efficiency are still pretty small, the trend differs from scenario 1 in that THOS of 3 clusters is the largest while THOS of 2 clusters is the smallest. While for PASSER II, there is slight difference between THOS of 3 scenarios. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. The scenario of Brook's method with no partition produces a total bandwidth of 12.36 sec. The bandwidth attainability of Brook's method is lower than 30%, while PASSER II produces bandwidth attainability of nearly 100%. It can also be seen that with the change of volume, the result of bandwidth significantly changes as compared to scenario 1. This scenario indicates that under certain traffic conditions, signal coordination is not affected too much.

Table 12 Brook's signal coordination result of scenario 2.1

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	3	4
Cycle (sec)	105	105	80	80	105	80
TotalBand (sec)	12.36	15.1	6.28	18.1	15.1	18.1
EB Band (sec)	6.18	7.55	3.14	9.05	7.55	9.05
WB Band (sec)	6.18	7.55	3.14	9.05	7.55	9.05
TotalEff (%)	5.9	7.2	3.9	11.3	7.2	11.3
EB Eff (%)	5.9	7.2	3.9	11.3	7.2	11.3
WB Eff (%)	5.9	7.2	3.9	11.3	7.2	11.3
Total Att (%)	19.9	24.3	9.8	28.3	24.3	28.3
EB Attain (%)	19.9	24.3	9.8	28.3	24.3	28.3
WB Attain (%)	19.9	24.3	9.8	28.3	24.3	28.3
THOS_i	1907	1035	565	815	518	1222
THOS_total	1907	1601		2554		

Table 13 PASSER II signal coordination result of scenario 2.1

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	3	4
Cycle (sec)	50	50	105	105	50	105
TotalBand (sec)	36	36	99	102	36	99
EB Band (sec)	18	18	50	51	18	50
WB Band (sec)	18	18	49	51	18	49
TotalEff (%)	36	36	47.14	48.57	36	47.14
EB Eff (%)	36	36	47.62	48.57	36	47.62
WB Eff (%)	36	36	46.67	48.57	36	46.67
Total Att (%)	100	100	97.06	100	100	97.06
EB Attain (%)	100	100	98.04	100	100	98.04
WB Attain (%)	100	100	96.08	100	100	96.08
THOS_i	11664	5184	6789	3497	2592	5091
THOS_total	11664	11973		11181		

4.3.2 Scenario 2.2

In this scenario, on the basis of scenario 2.1, we change the volume combination of intersection 7. Left turning volume is changed from 300 to 500 vph while through volume is decreased from 900 to 700 vph. The total of left turning volume and through volume remains 1200 vph. Other parameters remain unchanged as base scenario, as can be seen in Table 14.

Table 14 Parameters of scenario 2.2

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	500	700
5	1000	300	900
6	1000	300	900
7	1000	500	700
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 15 and Table 16. It can be seen for Brook's method, THOS increases as the number of clusters increases. While for PASSER II, THOS of no partition is the best (11016), 3.3% greater than THOS of 3 clusters and 6.3% greater than THOS of 2 clusters. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. The scenario of Brook's method with no partition produces a total bandwidth of 12.36 sec. The bandwidth attainability of Brook's method is lower than 30%, while PASSER II produces bandwidth attainability of nearly 100%. This scenario indicates that if two critical intersections (i.e. intersection 4 and 7 in this scenario) are clustered into the same subsystem, then the resulting signal coordination does not achieve improvement than the original system without partition.

Table 15 Brook's signal coordination result of scenario 2.2

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	4	3
Cycle (sec)	105	105	105	80	105	80
TotalBand (sec)	12.36	15.1	15.1	18.1	15.1	18.1
EB Band (sec)	6.18	7.55	7.55	9.05	7.55	9.05
WB Band (sec)	6.18	7.55	7.55	9.05	7.55	9.05
TotalEff (%)	5.9	7.2	7.2	11.3	7.2	11.3
EB Eff (%)	5.9	7.2	7.2	11.3	7.2	11.3
WB Eff (%)	5.9	7.2	7.2	11.3	7.2	11.3
Total Att (%)	19.9	24.3	24.3	28.3	24.3	28.3
EB Attain (%)	19.9	24.3	24.3	28.3	24.3	28.3
WB Attain (%)	19.9	24.3	24.3	28.3	24.3	28.3
THOS_i	1907	1035	1035	815	777	815
THOS_total	1907	2071		2406		

Table 16 PASSER II signal coordination result of scenario 2.2

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	4	3
Cycle (sec)	50	50	50	105	50	105
TotalBand (sec)	34	36	36	102	34	102
EB Band (sec)	17	18	18	51	17	51
WB Band (sec)	17	18	18	51	17	51
TotalEff (%)	34	36	36	48.57	34	48.57
EB Eff (%)	34	36	36	48.57	34	48.57
WB Eff (%)	34	36	36	48.57	34	48.57
Total Att (%)	94.44	100	100	100	94.44	100
EB Attain (%)	94.44	100	100	100	94.44	100
WB Attain (%)	94.44	100	100	100	94.44	100
THOS_i	11016	5184	5184	3497	3672	3497
THOS_total	11016	10368		10666		

4.3.3 Scenario 2.3

In this scenario, on the basis of scenario 2.2, we change the volume combination of intersection 7. Left turning volume is changed from 500 to 700 vph while through volume is decreased from 700 to 500 vph. The total of left turning volume and through volume remains 1200 vph. Other parameters remain unchanged as base scenario, as can be seen in Table 17.

Table 17 Parameters of scenario 2.3

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	500	700
5	1000	300	900
6	1000	300	900
7	1000	700	500
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 18 and Table 19. It can be seen for Brook's method, THOS increases as the number of clusters increases. Brook's method produces no possible bandwidth for the scenario of no partition. For PASSER II, the trend of THOS is the same as Brook's. THOS of 3 clusters (9819) is 8.8% greater than THOS of 2 clusters (9024) and 15.9% greater than THOS of no partition (8474). The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. The bandwidth attainability of Brook's method is lower than 30%, while PASSER II produces bandwidth attainability of all 100%. This scenario shows that the scenario with 3 clusters is the best strategy.

Table 18 Brook's signal coordination result of scenario 2.3

Brook's							
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	4	3
Cycle (sec)	150	105	150	80	150	80
TotalBand (sec)	0	15.1	13.18	18.1	13.18	18.1
EB Band (sec)	0	7.55	6.59	9.05	6.59	9.05
WB Band (sec)	0	7.55	6.59	9.05	6.59	9.05
TotalEff (%)	0	7.2	4.4	11.3	4.4	11.3
EB Eff (%)	0	7.2	4.4	11.3	4.4	11.3
WB Eff (%)	0	7.2	4.4	11.3	4.4	11.3
Total Att (%)	0	24.3	21.3	28.3	21.3	28.3
EB Attain (%)	0	24.3	21.3	28.3	21.3	28.3
WB Attain (%)	0	24.3	21.3	28.3	21.3	28.3
THOS_i	0	1035	633	815	474	815
THOS_total	0	1668		2103		

Table 19 PASSER II signal coordination result of scenario 2.3

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	3	4	3
Cycle (sec)	65	50	45	105	65	105
TotalBand (sec)	34	36	24	102	34	102
EB Band (sec)	17	18	12	51	17	51
WB Band (sec)	17	18	12	51	17	51
TotalEff (%)	26.15	36	26.67	48.57	26.15	48.57
EB Eff (%)	26.15	36	26.67	48.57	26.15	48.57
WB Eff (%)	26.15	36	26.67	48.57	26.15	48.57
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8474	5184	3840	3497	2825	3497
THOS_total	8474	9024		9819		

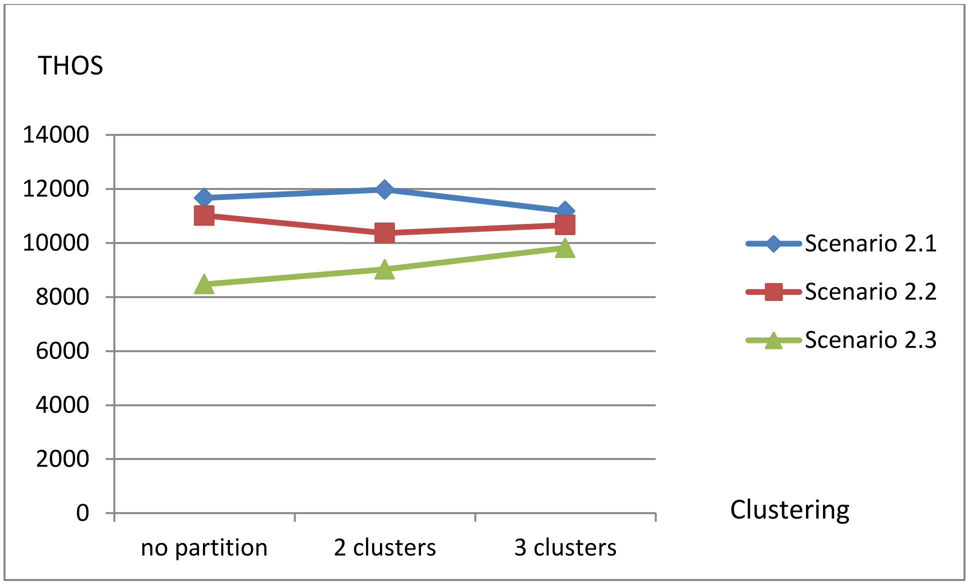

Figure 4 THOS for different clustering scenarios of scenario 2.1, 2.2, and 2.3

Figure 4 shows the total THOS of PASSER II for all clustering combinations of all scenarios in scenario 2. As can be seen, as the number of clusters increases, there is no certain trend that THOS will absolutely increase or decrease. We can infer from this series of scenario that signal coordination does not necessarily get better with the increase of clusters. Moreover, it can be seen from Figure 4 that the magnitude of THOS of scenario 2.1 is the greatest while that of scenario 2.3 is the least. This is as expected because the volume combination in scenario 2.3 has the greatest left turning volume (700 vph). It can be concluded that with the left turning volume increasing, the resulting bandwidth and bandwidth efficiency will be decreased.

4.4 Scenario 3

In this scenario, we consider to change both the values of spacing and volumes. Different combinations of spacing and volumes might have distinct influence on the clustering result and corresponding signal coordination. We develop six scenarios within this series.

For these six scenarios, we change the magnitude and location of the parameters of spacing and volume of critical intersection. The resulting THOS will definitely represent the influence of these two parameters.

4.4.1 Scenario 3.1

In this scenario, we first change the spacing between intersection 3 and 4 from 1000 to 2000 feet and the spacing between intersection 6 and 7 from 1000 to feet. Then we change the volume combination at intersection 4 and 7. After adjustment, intersection 4 has 500 vph of left turning volume and 700 vph of through volume. Intersection 7 has 700 vph of left turning volume and 500 vph of through volume. Other parameters remain unchanged as base scenario, as can be seen in Table 20.

Table 20 Parameters of scenario 3.1

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	2000	500	700
5	1000	300	900
6	1000	300	900
7	3000	700	500
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 21 and Table 22. It can be seen that for Brook's method, THOS increases as the number of clusters increases. While for PASSER II, THOS of 2 clusters is the greatest (9360), 4.4% greater than THOS of 3 clusters (8969) and 10.5% greater than THOS of no partition (8474). The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. The bandwidth attainability of Brook's method is less than 30%, while PASSER II produces bandwidth attainability of all 100%. All these factors indicate that PASSER II solution is more convincing for this scenario. It can be inferred that the best timing strategy here is 2 clusters, which can produce both westbound and eastbound bandwidth of 18 sec with bandwidth efficiency of 36% and bandwidth attainability of 100% for the first subsystem, and produce bandwidth of 12 sec, bandwidth efficiency of 26.67% and bandwidth attainability of 100% for the second subsystem. It can again be noticed that clustering does not guarantee the improvement of signal coordination. On the other hand, it depends on the real traffic conditions.

Table 21 Brook's signal coordination result of scenario 3.1

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	3	3	4
Cycle (sec)	150	105	150	80	105	150
TotalBand (sec)	12.1	12.36	13.18	18.1	15.1	13.18
EB Band (sec)	6.05	6.18	6.59	9.05	7.55	6.59
WB Band (sec)	6.05	6.18	6.59	9.05	7.55	6.59
TotalEff (%)	4	5.9	4.4	11.3	7.2	4.4
EB Eff (%)	4	5.9	4.4	11.3	7.2	4.4
WB Eff (%)	4	5.9	4.4	11.3	7.2	4.4
Total Att (%)	19.5	19.9	21.3	28.3	24.3	21.3
EB Attain (%)	19.5	19.9	21.3	28.3	24.3	21.3
WB Attain (%)	19.5	19.9	21.3	28.3	24.3	21.3
THOS_i	1307	1059	474	815	518	474
THOS_total	1307	1534		1807		

Table 22 PASSER II signal coordination result of scenario 3.1

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	3	3	4
Cycle (sec)	65	50	45	105	50	45
TotalBand (sec)	34	36	24	102	36	24
EB Band (sec)	17	18	12	51	18	12
WB Band (sec)	17	18	12	51	18	12
TotalEff (%)	26.15	36	26.67	48.57	36	26.67
EB Eff (%)	26.15	36	26.67	48.57	36	26.67
WB Eff (%)	26.15	36	26.67	48.57	36	26.67
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8474	6480	2880	3497	2592	2880
THOS_total	8474	9360		8969		

4.4.2 Scenario 3.2

In this scenario, on the basis of scenario 3.1, we switch the volume combination of intersection 4 and 7. Other parameters remain unchanged, as can be seen in Table 23.

Table 23 Parameters of scenario 3.2

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	2000	700	500
5	1000	300	900
6	1000	300	900
7	3000	500	700
8	1000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 24 and Table 25. It can be seen that for Brook's method, THOS increases as the number of clusters increases. For PASSER II, the same trend appears. THOS of 3 clusters is the greatest (9305), 7.1% greater than THOS of 2 clusters (8688) and 9.8% greater than THOS of no partition (8474). The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. All bandwidth attainability in PASSER II is 100%. It can be inferred that the best timing strategy here is 3 clusters, which can produce both westbound and eastbound bandwidth of 51 sec with bandwidth efficiency of 48.57% for the first subsystem, produce bandwidth of 12 sec with bandwidth efficiency of 26.67% for the second subsystem and produce bandwidth of 18 sec with bandwidth efficiency of 36% for the third subsystem. Notice that the result of no partition here is the same as scenario 3.1. This is because we only change the sequence of intersection 4 and 7 while the values are unchanged. THOS of 3 clusters in this scenario (9305) is also close to the greatest THOS in scenario 3.1 (9360). To some extent, volume plays an important role in determining signal timing and signal coordination.

Table 24 Brook's signal coordination result of scenario 3.2

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	3	3	4
Cycle (sec)	150	150	105	80	150	105
TotalBand (sec)	6.36	13.18	15.1	18.1	26.82	15.1
EB Band (sec)	3.18	6.59	7.55	9.05	13.41	7.55
WB Band (sec)	3.18	6.59	7.55	9.05	13.41	7.55
TotalEff (%)	2.1	4.4	7.2	11.3	8.9	7.2
EB Eff (%)	2.1	4.4	7.2	11.3	8.9	7.2
WB Eff (%)	2.1	4.4	7.2	11.3	8.9	7.2
Total Att (%)	10.3	21.3	24.3	28.3	43.3	24.3
EB Attain (%)	10.3	21.3	24.3	28.3	43.3	24.3
WB Attain (%)	10.3	21.3	24.3	28.3	43.3	24.3
THOS_i	687	791	777	815	644	777
THOS_total	687	1567		2235		

Table 25 PASSER II signal coordination result of scenario 3.2

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	6	4	3	3	4
Cycle (sec)	65	45	50	105	45	50
TotalBand (sec)	34	24	36	102	24	36
EB Band (sec)	17	12	18	51	12	18
WB Band (sec)	17	12	18	51	12	18
TotalEff (%)	26.15	26.67	36	48.57	26.67	36
EB Eff (%)	26.15	26.67	36	48.57	26.67	36
WB Eff (%)	26.15	26.67	36	48.57	26.67	36
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8474	4800	3888	3497	1920	3888
THOS_total	8474	8688		9305		

4.4.3 Scenario 3.3

In this scenario, we change the spacing between intersection 5 and 6 from 1000 to 2000 feet and we change the spacing between intersection 7 and 8 from 1000 to 3000 feet. Then we change the volume of intersection 4 to be 700 vph of left turning and 500 vph of through. Also we change the volume of intersection 6 to be 500 vph of left turning and 700 vph of through volume. Other parameters remain unchanged, as can be seen in Table 26.

Table 26 Parameters of scenario 3.3

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	700	500
5	1000	300	900
6	2000	500	700
7	1000	300	900
8	3000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 27 and Table 28. It can be seen that for Brook's method, THOS increases as the number of clusters increases. For PASSER II, THOS of 2 clusters is the greatest (9024), 0.6% greater than THOS of 3 clusters (8969) and 6.5% greater than THOS of no partition (8474). The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. All bandwidth attainability in PASSER II is 100%. There is slight difference between 2 clusters and 3 clusters. For 2 clusters, the first five intersections are within the first subsystem, which includes intersection 4. And the second subsystem includes intersection 6. For 3 clusters, the first subsystem consists of the first four intersections, which also includes intersection 4. The second subsystem is the following three intersections, which includes intersection 6. The last three intersections form the third subsystem. Since spacing itself won't affect signal coordination much according to the results and discussions in scenario 1 and critical volumes of intersection 4 and 6 are clustered into different subsystems for both 2 clusters and 3 clusters, this explains why THOS of 2 clusters and 3 clusters are close to each other.

Table 27 Brook's signal coordination result of scenario 3.3

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	150	150	105	150	105	80
TotalBand (sec)	14.54	13.18	15.1	13.18	37.18	18.1
EB Band (sec)	7.27	6.59	7.55	6.59	18.59	9.05
WB Band (sec)	7.27	6.59	7.55	6.59	18.59	9.05
TotalEff (%)	4.8	4.4	7.2	4.4	17.7	11.3
EB Eff (%)	4.8	4.4	7.2	4.4	17.7	11.3
WB Eff (%)	4.8	4.4	7.2	4.4	17.7	11.3
Total Att (%)	23.5	21.3	24.3	21.3	60	28.3
EB Attain (%)	23.5	21.3	24.3	21.3	60	28.3
WB Attain (%)	23.5	21.3	24.3	21.3	60	28.3
THOS_i	1570	633	1035	474	1275	815
THOS_total	1570	1668		2564		

Table 28 PASSER II signal coordination result of scenario 3.3

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	65	45	50	45	50	105
TotalBand (sec)	34	24	36	24	36	102
EB Band (sec)	17	12	18	12	18	51
WB Band (sec)	17	12	18	12	18	51
TotalEff (%)	26.15	26.67	36	26.67	36	48.57
EB Eff (%)	26.15	26.67	36	26.67	36	48.57
WB Eff (%)	26.15	26.67	36	26.67	36	48.57
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8474	3840	5184	2880	2592	3497
THOS_total	8474	9024		8969		

4.4.4 Scenario 3.4

In this scenario, on the basis of scenario 3.3, we switch the volume combination at intersection 4 and 6. Other parameters remain unchanged, as can be seen in Table 29.

Table 29 Parameters of scenario 3.4

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	500	700
5	1000	300	900
6	2000	700	500
7	1000	300	900
8	3000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 30 and Table 31. It can be seen that for Brook's method, THOS of no partition is zero, THOS of 2 clusters is 2978, 34.9% greater than THOS of 3 clusters. For PASSER II, THOS increases as the number of clusters increases. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. All bandwidth attainability in PASSER II is 100%. For this scenario, the best strategy is to have 3 clusters.

Table 30 Brook's signal coordination result of scenario 3.4

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	150	105	150	105	150	80
TotalBand (sec)	0	15.1	40.46	15.1	25.72	18.1
EB Band (sec)	0	7.55	20.23	7.55	12.86	9.05
WB Band (sec)	0	7.55	20.23	7.55	12.86	9.05
TotalEff (%)	0	7.2	13.5	7.2	8.6	11.3
EB Eff (%)	0	7.2	13.5	7.2	8.6	11.3
WB Eff (%)	0	7.2	13.5	7.2	8.6	11.3
Total Att (%)	0	24.3	65.2	24.3	41.5	28.3
EB Attain (%)	0	24.3	65.2	24.3	41.5	28.3
WB Attain (%)	0	24.3	65.2	24.3	41.5	28.3
THOS_i	0	1035	1942	777	617	815
THOS_total	0	2978		2208		

Table 31 PASSER II signal coordination result of scenario 3.4

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	4	3	3
Cycle (sec)	65	50	45	50	45	105
TotalBand (sec)	34	36	24	36	24	102
EB Band (sec)	17	18	12	18	12	51
WB Band (sec)	17	18	12	18	12	51
TotalEff (%)	26.15	36	26.67	36	26.67	48.57
EB Eff (%)	26.15	36	26.67	36	26.67	48.57
WB Eff (%)	26.15	36	26.67	36	26.67	48.57
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8474	5184	3840	3888	1920	3497
THOS_total	8474	9024		9305		

4.4.5 Scenario 3.5

In this scenario, on the basis of scenario 3.4, we switch the spacing of D_{56} and D_{78}. Other parameters remain unchanged, as can be seen in Table 32.

Table 32 Parameters of scenario 3.5

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	500	700
5	1000	300	900
6	3000	700	500
7	1000	300	900
8	2000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 33 and Table 34. It can be seen that for Brook's method, THOS of 2 clusters (3305) is 28.1% greater than THOS of 3 clusters (2581), and 61.9% greater than THOS of no partition. For PASSER II, THOS increases as the number of clusters increases. The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. All bandwidth attainability in PASSER II is 100%. For this scenario, the best strategy is to have 3 clusters (THOS=9641), 6.8% better than 2 clusters (THOS=9024) and 11.6% better than no partition (THOS=8640).

Table 33 Brook's signal coordination result of scenario 3.5

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	5	2	3
Cycle (sec)	150	105	150	105	150	80
TotalBand (sec)	18.9	15.1	47.28	15.1	60.9	18.1
EB Band (sec)	9.45	7.55	23.64	7.55	30.45	9.05
WB Band (sec)	9.45	7.55	23.64	7.55	30.45	9.05
TotalEff (%)	6.3	7.2	15.8	7.2	20.3	11.3
EB Eff (%)	6.3	7.2	15.8	7.2	20.3	11.3
WB Eff (%)	6.3	7.2	15.8	7.2	20.3	11.3
Total Att (%)	30.5	24.3	76.2	24.3	98.2	28.3
EB Attain (%)	30.5	24.3	76.2	24.3	98.2	28.3
WB Attain (%)	30.5	24.3	76.2	24.3	98.2	28.3
THOS_i	2041	1035	2269	1035	731	815
THOS_total	2041	3305		2581		

Table 34 PASSER II signal coordination result of scenario 3.5

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	5	2	3
Cycle (sec)	45	50	45	50	45	105
TotalBand (sec)	24	36	24	36	24	102
EB Band (sec)	12	18	12	18	12	51
WB Band (sec)	12	18	12	18	12	51
TotalEff (%)	26.67	36	26.67	36	26.67	48.57
EB Eff (%)	26.67	36	26.67	36	26.67	48.57
WB Eff (%)	26.67	36	26.67	36	26.67	48.57
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8640	5184	3840	5184	960	3497
THOS_total	8640	9024		9641		

4.4.6 Scenario 3.6

In this scenario, on the basis of scenario 3.5, we switch the volume combination of intersection 4 and 6. Other parameters remain unchanged, as can be seen in Table 35.

Table 35 Parameters of scenario 3.6

Intersection Number	D_ij	V_Li	V_Thi
1	0	300	900
2	1000	300	900
3	1000	300	900
4	1000	700	500
5	1000	300	900
6	3000	500	700
7	1000	300	900
8	2000	300	900
9	1000	300	900
10	1000	300	900

The results of clustering, MOEs and THOS of each subsystem and the total THOS are calculated and shown in Table 36 and Table 37. It can be seen that for Brook's method, THOS of 3 clusters (3170) is 55.3% greater than THOS of no partition (2041), and 90.4% greater than THOS of 2 clusters (1668). For PASSER II, THOS of 2 clusters (9024) is 1.9% greater than THOS of 3 clusters (8853), and 4.4% greater than THOS of no partition (8640). The magnitude of bandwidth, bandwidth efficiency, bandwidth attainability and THOS in Brook's method is much less than that in PASSER II. All bandwidth attainability in PASSER II is 100%. For this scenario, the best strategy is to have 2 clusters.

Table 36 Brook's signal coordination result of scenario 3.6

Brook's						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	2	3	5
Cycle (sec)	150	150	105	80	150	105
TotalBand (sec)	18.9	13.18	15.1	29.9	60.9	15.1
EB Band (sec)	9.45	6.59	7.55	14.95	30.45	7.55
WB Band (sec)	9.45	6.59	7.55	14.95	30.45	7.55
TotalEff (%)	6.3	4.4	7.2	18.7	20.3	7.2
EB Eff (%)	6.3	4.4	7.2	18.7	20.3	7.2
WB Eff (%)	6.3	4.4	7.2	18.7	20.3	7.2
Total Att (%)	30.5	21.3	24.3	46.7	98.2	24.3
EB Attain (%)	30.5	21.3	24.3	46.7	98.2	24.3
WB Attain (%)	30.5	21.3	24.3	46.7	98.2	24.3
THOS_i	2041	633	1035	673	1462	1035
THOS_total	2041	1668		3170		

Table 37 PASSER II signal coordination result of scenario 3.6

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	10	5	5	2	3	5
Cycle (sec)	45	45	50	105	45	50
TotalBand (sec)	24	24	36	102	24	36
EB Band (sec)	12	12	18	51	12	18
WB Band (sec)	12	12	18	51	12	18
TotalEff (%)	26.67	26.67	36	48.57	26.67	36
EB Eff (%)	26.67	26.67	36	48.57	26.67	36
WB Eff (%)	26.67	26.67	36	48.57	26.67	36
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8640	3840	5184	1749	1920	5184
THOS_total	8640	9024		8853		

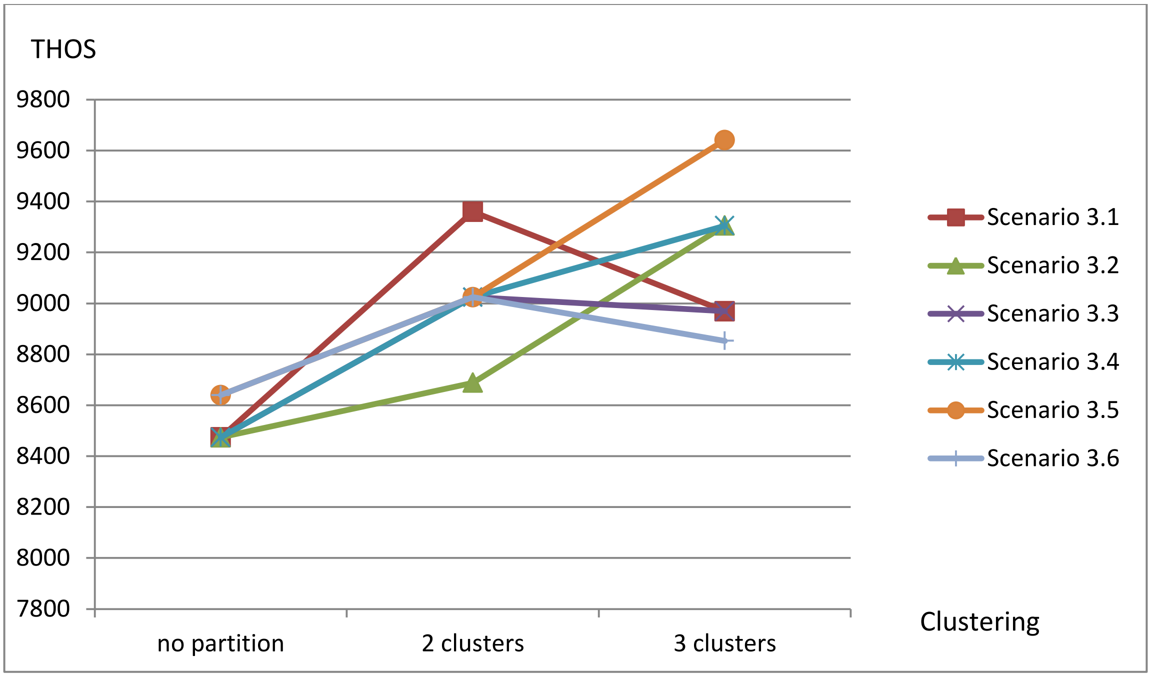

Figure 5 THOS for different clustering scenarios of scenario 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6

Figure 5 shows the total THOS of PASSER II for all clustering combinations of all scenarios in scenario 3. As can be seen, as the number of clusters increases, there is no certain trend that THOS will absolutely increase or decrease. We can infer from this series of scenario that signal coordination does not necessarily get better with the increase of clusters. Moreover, it can be seen from Figure 5 that the magnitude of THOS varies from 8474 to 9641. We should notice that THOS with no partition is either less than THOS of 2 clusters or THOS of 3 clusters, indicating that clustering is promising in improving signal coordination, as long as traffic conditions are suitable to the clustering result. The most common way that large THOS can be obtained is to divide the critical intersections into different subsystems.

It can be concluded from the experimental design that clustering method is beneficial in improving bandwidth, bandwidth efficiency, bandwidth attainability and THOS. PASSER II provides optimal bandwidth for one direction and maximum possible bandwidth for the other direction. Brook's method with assumed phasing strategy does not provide optimal bandwidth solution as PASSER II. Therefore, phasing strategy is an important factor in signal coordination.

Partition points are found to be at locations with critical volumes and spacing. Large left turning volume plays an important role in the corresponding signal coordination. With the increase of spacing, bandwidth efficiency and THOS of the subsystem will be slightly decreased. The influence of spacing on signal coordination is not as great as that of volume.

5. CASE STUDY

5.1 Site description

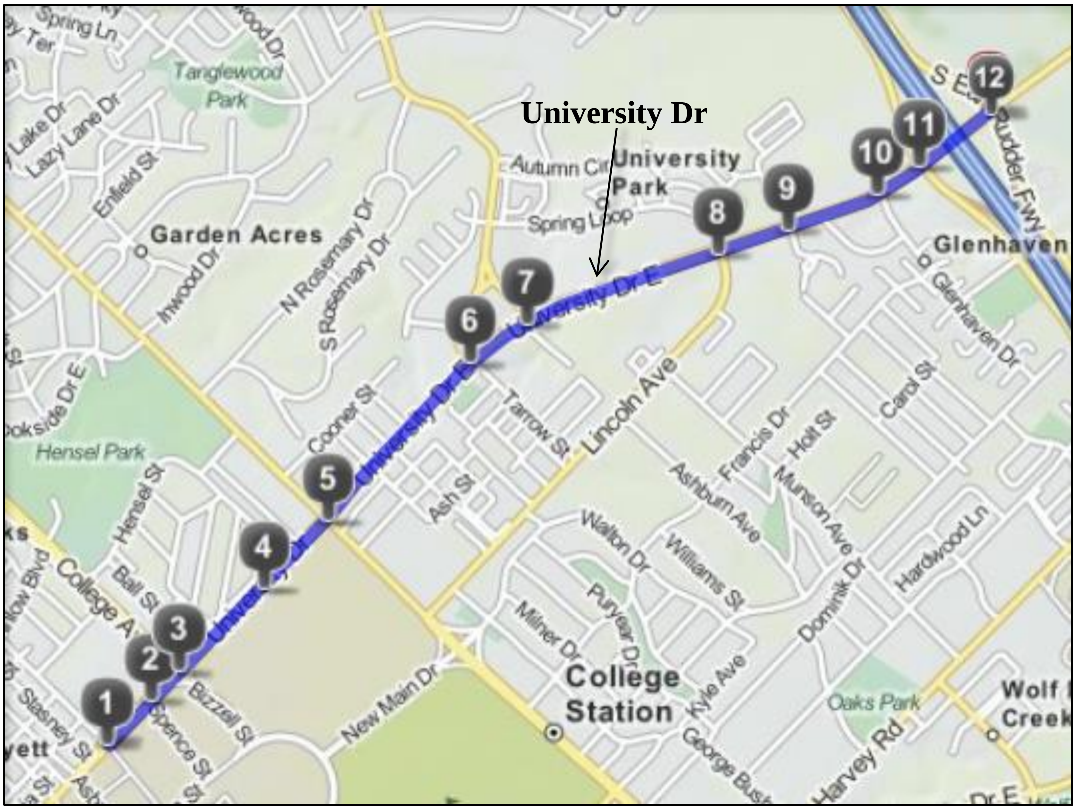

Figure 6 Signal system map of University Dr (University Dr, College Station, 2013)

Two case studies are presented in this section to illustrate the proposed signal timing approach using different volume combinations. The test site is *University Drive* in College Station, TX. Figure 6 shows part of University Dr and highlights the successive 12 intersections along the arterial that will be investigated. University Drive is a major west/east arterial serving traffic generated majorly by business center of City of College Station and Texas A&M University. The signal system has 12 signals, and Table 38 summarizes traffic characteristics such as speed and spacing of each link. The speed of cross streets is 30 mph.

Table 38 Summary of traffic characteristics

Intersection Number	Cross Street Name	Spacing (feet)	Westbound speed (mph)	Eastbound speed (mph)
1	Ireland St.	—	35	35
2	Spence St.	683	35	35
3	College Ave.	453	35	35
4	Polo Rd.	1492	40	40
5	S Texas Ave.	1140	40	40
6	Tarrow W	2638	45	45
7	Tarrow E	823	50	50
8	Spring Loop	2537	50	50
9	Forest Dr.	885	50	50
10	Glenhaven Dr.	1185	50	50
11	TX-6 Frontage W	666	50	50
12	TX-6 Frontage E	1093	50	50

In order to perform a comprehensive case study, the traffic volumes we used for developing timing strategy are derived based on p.m. peak hour and off peak period. During the p.m. peak period, the eastbound traffic is the peak direction. Heavy left turning movements coming from or going to the cross streets happen at several locations, i.e. S Texas Ave, TX-6 Frontage W and TX-6 Frontage E. During off peak period, westbound has slightly more traffic than that in p.m. peak hour and eastbound volume is more than westbound volume.

Based on two different volume combinations, two case studies (p.m. peak and off peak case) are conducted and shown as follows:

5.2 P.M. peak case

The p.m. peak case has huge eastbound volume and relatively small westbound volume. Cross street volumes are also large at several locations, i.e. S Texas Ave, TX-6 Frontage W and TX-6 Frontage E. The proposed approach is applied to the arterial.

5.2.1 K-means clustering

According to our experimental design, which shows that clustering is promising in benefiting signal coordination, University Dr in our case study is also clustered using Matlab clustering function. The system is clustered into 2 subsystems or 3 subsystems. The clustering result is shown in Table 39.

Table 39 Clustering result of the arterial (p.m. peak case)

Clustering	# of intersections
no partition	12
2 clusters	5
	7
3 clusters	3
	4
	5

5.2.2 PASSER II optimization solution

Although several bandwidth-based software packages can be used in the study, we select PASSER II option in PASSER V-03 as the primary tool because of its popularity and availability. After creating an arterial with 12 intersections, input parameters including volume, spacing, speed, and lane assignment are coded into the software. Notice that for lane assignment, there is a limitation of PASSER V-03, i.e. no more than 1 left turning lane can be assigned to each intersection. However, there are intersections that have 2 left turning lanes in real world condition. Therefore, we do the following workaround: for those intersections with 2 left turning lanes, reduce left turn volume by 50% and use 1 left turning lane. This workaround will not affect the bandwidth. Several other system parameters include ideal saturation flow rate of 1900 vph. And cycle length range that will be used in PASSER II option is from 40 to 150 sec at an increment of 5.

Table 40 PASSER II signal coordination result (p.m. peak case)

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	12	5	7	3	4	5
Cycle (sec)	100	95	90	145	135	95
TotalBand (sec)	44	42	55	106	61	59
EB Band (sec)	34	32	43	86	49	47
WB Band (sec)	10	10	12	20	12	12
TotalEff (%)	22	22.11	30.56	36.55	22.59	31.05
EB Eff (%)	34	33.68	47.78	59.31	36.3	49.47
WB Eff (%)	10	10.53	13.33	13.79	8.89	12.63
Total Att (%)	100	100	100	100	100	100
EB Attain (%)	100	100	100	100	100	100
WB Attain (%)	100	100	100	100	100	100
THOS_i	8712	3183	6600	2632	2440	4472
THOS_total	8712	9783		9543		

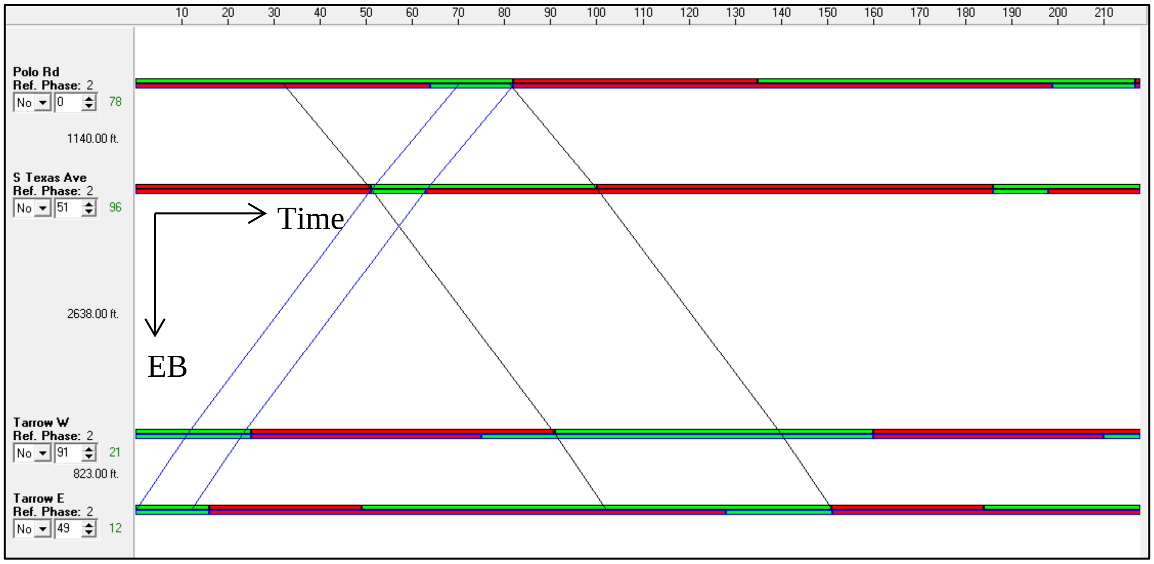

Figure 7 Time-space diagram of subsystem 3.2

Based on the clustering result in Table 39, we create corresponding subsystems in PASER V-03. The resulting PASSER II solution is shown in Table 40. For the scenario with no partition, the PASSER II solution produces an eastbound bandwidth of 34 sec with an attainability of 100%, and a westbound bandwidth of 10 sec with an attainability of 100%. The total bandwidth efficiency is 22% and the calculated THOS is 8712. For the scenario with 2 clusters, the first subsystem consists of the first five intersections and the PASSER II solution produces an eastbound bandwidth of 32 sec with an attainability of 100%, and a westbound bandwidth of 10 sec with an attainability of 100%. The total bandwidth efficiency is 22.11% and the calculated THOS is 3183. The second subsystem consists of the last seven intersections and the PASSER II solution produces an eastbound bandwidth of 43 sec with an attainability of 100%, and a westbound bandwidth of 12 sec with an attainability of 100%. The total bandwidth efficiency is 30.56% and the calculated THOS is 6600. The total THOS of two subsystems is 9783. For the scenario with 3 clusters, the first subsystem includes the first three intersections and the PASSER II solution produces an eastbound bandwidth of 86 sec with an attainability of 100%, and a westbound bandwidth of 20 sec with an attainability of 100%. The total bandwidth efficiency is 36.55% and the calculated THOS is 2632. As can be seen in Figure 7, the second subsystem consists of the following four intersections and the PASSER II solution produces an eastbound bandwidth of 49 sec with an attainability of 100%, and a westbound bandwidth of 12 sec with an attainability of 100%. The total bandwidth efficiency is 22.59% and the calculated THOS is 2440. The third subsystem consists of the last five intersections and the PASSER II solution produces an eastbound bandwidth of 47 sec with an attainability of 100%, and a westbound bandwidth of 12 sec with an attainability of 100%. The total bandwidth efficiency is 31.05% and the calculated THOS is 4472. The total THOS is 9543.

As can be seen from the results, although cycle length is increased after partition, the bandwidth efficiency still increases after partition due to a remarkable increase of the bandwidth. Also it can be noticed that the bandwidth attainability of 100% for both eastbound and westbound approaches is obtained. Overall, the total THOS for the whole arterial increases by 12.3% and 9.5%, respectively for the scenario with 2 clusters and 3 clusters. This implies that more vehicles can progress without stops. The increase in all of the MOEs shows that clustering method is promising in improving signal coordination.

It should be noted that bandwidth capacity exceeds volume, indicating that THOS comparison is meaningful for our study.

5.2.3 Simulation evaluation

Though we get good results through PASSER V in terms of bandwidth, bandwidth efficiency, bandwidth attainability, and THOS, it’s still not comprehensive for traffic engineers to evaluate whether clustered signal coordination really helps.

Another way of evaluation is performed in simulation, which is an effective and available way to represent the real world condition. CORSIM microscopic simulation model is used in this study. CORSIM models the movements of individual vehicles and take into account factors such as car following model and lane changing model, which are generally not considered in other traffic simulation models.

In CORSIM, an arterial with 12 intersections is created entirely based on the real world condition. Input parameters including volume, speed, link length, lane configuration and assignment are all coded into CORSIM. For eastbound and westbound approach, the speed varies from 35 to 50 mph while the speed of cross streets is 30 mph. Other parameters such as mean start up lost time and mean discharge time are kept unchanged, using the default values of 2 sec and 1.8 sec.

Then, the PASSER II optimization timing plans are coded into CORSIM, respectively for three scenarios. Basically, if a master controller exists at a signal location (i.e. all offsets are referenced to that intersection), the offsets of all the intersections within the same subsystem need not be changed; only the offsets of intersections in other subsystems need to be adjusted. However, in our case study, we should notice that for the scenarios with 2 clusters and 3 clusters, they have different cycle length (i.e. 90 and 95 sec for 2 clusters, 95, 135 and 145 sec for 3 clusters). For our simulation, relative offsets can be any number since it will not affect the result. So the relative offsets between subsystems are set to be zero since relative offset functions for only one cycle.

The time of simulation is 900 sec (15 min) for each scenario. This is because the volumes in p.m. peak case are particularly large that severe queue spillback will occur if we keep running the simulation after 15 minutes. Severe queue spillback will definitely influence the arterial traffic significantly and should be avoided in order to get meaningful outputs.

Because of the stochastic nature of CORSIM, it is necessary to run each case multiple times varying the random number seeds to obtain an accurate reflection of performance measures. In our case study, we run 10 times for each scenario.

Several MOEs (measure of effectiveness) are collected for all EB and WB links, i.e. total number of trips, through trips, control delay for through movement, control delay for all movements, the number of stops in percent (CORSIM does not specify the number of stops based on different movements). The results are shown in the following:

Table 41 Control delay for through movement (p.m. peak case)

Control delay (through movement)	no partition	2 clusters	3 clusters
EB (sec/veh)	9.68 ±0.20	9.88 ±0.12	9.92 ±0.24
WB (sec/veh)	110.38 ±0.93	98.21 ±1.23	117.79 ±1.08
Total average (sec/veh)	37.21 ±0.25	34.52 ±0.67	38.41 ±0.49

Table 41 shows the result of control delay for through movement. The numbers are mean values with 95% confidence interval. It can be seen that for both scenarios of 2 clusters and 3 clusters, EB control delay increased slightly as compared to no partition. For westbound approach, scenario of 3 clusters suffers greater control delay than that of no partition. However, for westbound approach, scenario of 2 clusters has significant improvement in control delay. Overall, the average control delay for through movement of the arterial system decreases from no partition to 2 clusters while increases from no partition to 3 clusters.

Table 42 Control delay for all movements (p.m. peak case)

Control delay (all movements)	no partition	2 clusters	3 clusters
EB (sec/veh)	10.20 ±0.15	10.42 ±0.12	10.67 ±0.18
WB (sec/veh)	103.52 ±0.84	93.01 ±1.08	111.83 ±1.04
Total average (sec/veh)	35.37 ±0.15	33.24 ±0.52	36.72 ±0.32

Table 42 shows the result of control delay for all movements. It can be seen that for both scenarios of 2 clusters and 3 clusters, EB control delay increased slightly as compared to no partition. For westbound approach, scenario of 3 clusters suffers greater control delay than that of no partition. However, for westbound approach, scenario of 2 clusters has significant improvement in control delay. Overall, the average control delay for all movements of the arterial system decreases from no partition to 2 clusters while increases from no partition to 3 clusters. This result is consistent with the result of control delay for through movement.

Table 43 Number of stops (p.m. peak case)

Number of stops (all movements)	no partition	2 clusters	3 clusters
EB (veh/15 min)	1919 ±60	2004 ±23	1960 ±22
WB (veh/15 min)	1592 ±82	1600 ±71	1659 ±69
Total (veh/15 min)	3511 ±49	3604 ±58	3619 ±40

Table 43 shows the number of stops for all scenarios. It can be seen that both scenarios of 2 clusters and 3 clusters suffer greater number of stops for eastbound approach. However, for westbound approach, the number of stops is almost the same for three scenarios. We notice that THOS is consistent with the number of stops in that our peak directions is EB approach and with the bandwidth-based timing strategy, the number of stops for EB decreases and THOS increases.

In this case study, scenario of 2 clusters has an increased THOS, a decreased control delay and an increased number of stops than scenario of no partition. Scenario of 3 clusters has an increased THOS, an increased control delay and an increased number of stops than scenario of no partition.

The evaluation from two perspectives (THOS and simulation) provides us comprehensive information. Clustering is able to improve bandwidth, bandwidth efficiency and corresponding THOS, which can be obtained from THOS evaluation. Clustering method results in improvement of control delay for scenario of 2 clusters. But both 2 clusters and 3 clusters lead to higher number of stops. This inconsistency of delay optimum and stops optimum is particularly true for high volume situations.

5.3 Off peak case

Another case using off peak volume combinations is presented in this section.

5.3.1 K-means clustering

The system is clustered into 2 subsystems or 3 subsystems. The clustering result is shown in Table 44.

Table 44 Clustering result of the arterial (off peak case)

Clustering	# of intersections
no partition	12
2 clusters	5
	7
3 clusters	4
	3
	5

5.3.2 PASSER II optimization solution

Using PASSER II, the result of optimization solution is shown and discussed in the following.

Table 45 PASSER II signal coordination result (off peak case)

PASSER II						
Clustering	no partition	2 clusters		3 clusters		
# of intersections	12	5	7	4	3	5
Cycle (sec)	80	100	65	120	60	55
TotalBand (sec)	24	39	29	91	24	29
EB Band (sec)	14	23	16	53	14	16
WB Band (sec)	10	16	13	38	10	13
TotalEff (%)	15	19.5	22.31	37.92	20	26.36
EB Eff (%)	17.5	23	24.62	44.17	23.33	29.09
WB Eff (%)	12.5	16	20	31.67	16.67	23.64
Total Att (%)	75	100	76.32	100	100	90.63
EB Attain (%)	73.68	100	76.19	100	100	88.89
WB Attain (%)	76.92	100	76.47	100	100	92.86
THOS_i	5940	2808	4818	4095	1440	3796
THOS_total	5940	7626		9331		

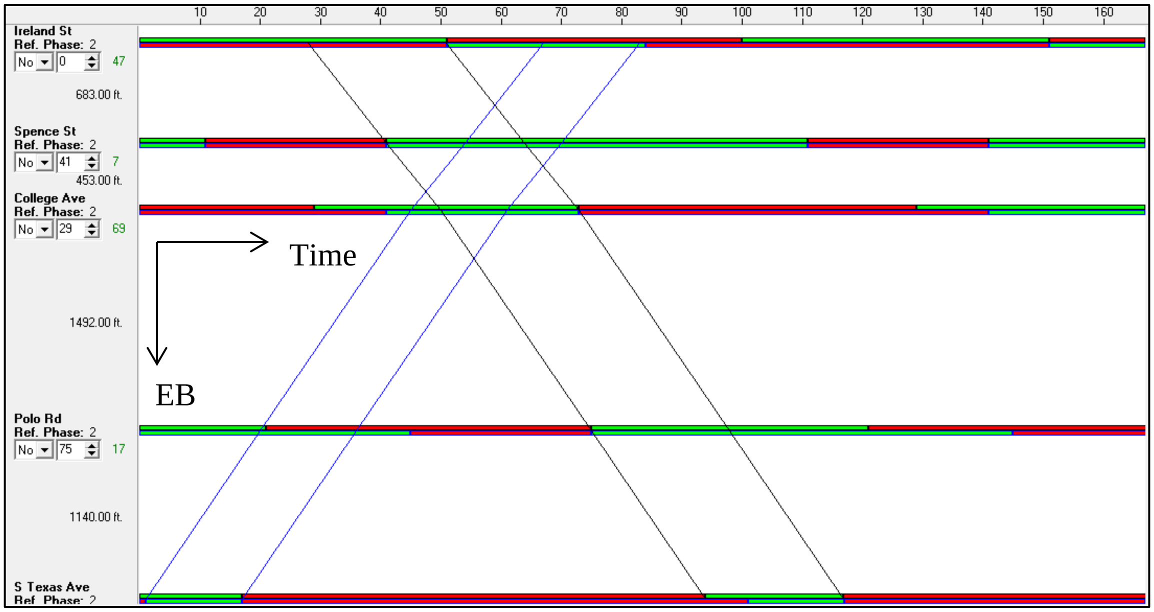

Figure 8 Time-space diagram of subsystem 2.1

Based on the clustering result in Table 44, we create corresponding subsystems in PASER V-03. The resulting PASSER II solution is shown in Table 45. For the scenario with no partition, the PASSER II solution produces an eastbound bandwidth of 14 sec with an attainability of 73.68%, and a westbound bandwidth of 10 sec with an attainability of 76.92%. The total bandwidth efficiency is 15% and the calculated THOS is 5940. For the scenario with 2 clusters, the first subsystem consists of the first five intersections and the corresponding time-space diagram is shown in Figure 8. The PASSER II solution produces an eastbound bandwidth of 23 sec with an attainability of 100%, and a westbound bandwidth of 16 sec with an attainability of 100%. The total bandwidth efficiency is 19.5% and the calculated THOS is 2808. The second subsystem consists of the last seven intersections and the PASSER II solution produces an eastbound bandwidth of 16 sec with an attainability of 76.19%, and a westbound bandwidth of 13 sec with an attainability of 76.47%. The total bandwidth efficiency is 22.31% and the calculated THOS is 4818. The total THOS of two subsystems is 7626. For the scenario with 3 clusters, the first subsystem includes the first four intersections and the PASSER II solution produces an eastbound bandwidth of 53 sec with an attainability of 100%, and a westbound bandwidth of 38 sec with an attainability of 100%. The total bandwidth efficiency is 37.92% and the calculated THOS is 4095. The second subsystem consists of the following three intersections and the PASSER II solution produces an eastbound bandwidth of 14 sec with an attainability of 100%, and a westbound bandwidth of 10 sec with an attainability of 100%. The total bandwidth efficiency is 20% and the calculated THOS is 1440. The third subsystem consists of the last five intersections and the PASSER II solution produces an eastbound bandwidth of 16 sec with an attainability of 88.89%, and a westbound bandwidth of 13 sec with an attainability of 92.86%. The total bandwidth efficiency is 26.36% and the calculated THOS is 3796. The total THOS is 9331.

As can be seen from the results, bandwidth efficiency increases after partition due to a remarkable increase of the bandwidth. Also it can be noticed that the bandwidth attainability of 100% is obtained for several subsystems. Overall, the total THOS for the whole arterial increases by 28.4% and 57.1%, respectively for the scenario with 2 clusters and 3 clusters. This implies that more vehicles can progress without stops. The increase in all of the MOEs shows that clustering method makes sense from THOS comparison. It should be noted that bandwidth capacity exceeds volume, indicating that THOS comparison is meaningful for our study.

5.3.3 Simulation evaluation

For this case, the time of simulation is set to be 1800 sec (30 min) for each scenario. Off peak volume is much less than p.m. peak volume. Spillback does not occur in the 30 min simulation. The number of runs is also 10 for each scenario.

Several MOEs (measure of effectiveness) are collected for all EB and WB links, i.e. total number of trips, through trips, control delay for through movement, control delay for all movements, the number of stops. The results are shown in the following:

Table 46 Control delay for through movement (off peak case)

Control delay (through movement)	no partition	2 clusters	3 clusters
EB (sec/veh)	11.72±0.19	10.74±0.14	12.52±0.14
WB (sec/veh)	27.71±0.85	28.96±1.11	22.63±0.92
Total average (sec/veh)	21.44±0.14	21.49±0.43	18.07±0.35

Table 46 shows the result of control delay for through movement. It can be seen that for the scenario of 2 clusters, EB control delay decreases but WB control delay increases. The average control delay increases slightly from the scenario of no partition. For the scenario of 3 clusters, though EB control delay increases slightly than no partition, WB control delay gets significant improvement. The average control delay also improves from the scenario of no partition.

Table 47 Control delay for all movements (off peak case)

Control delay (all movements)	no partition	2 clusters	3 clusters
EB (sec/veh)	12.71 ±0.19	11.75 ±0.12	12.89 ±0.15
WB (sec/veh)	29.01 ±0.84	30.37 ±1.00	23.23 ±0.94
Total average (sec/veh)	22.34 ±0.15	22.48 ±0.48	18.25 ±0.25

Table 47 shows the result of control delay for all movements. The result is consistent with the result of control delay for through movement. For the scenario of 2 clusters, EB control delay decreases but WB control delay increases. The average control delay increases slightly from the scenario of no partition. For the scenario of 3 clusters, EB control delay is the same as that of no partition, WB control delay gets significant improvement. The average control delay also improves from the scenario of no partition.

Table 48 Number of stops (off peak case)

Number of stops (all movements)	no partition	2 clusters	3 clusters
EB (veh/30 min)	2217 ±70	2148 ±17	2658 ±22
WB (veh/30 min)	4011 ±118	3992 ±73	4003 ±64
Total (veh/30 min)	6228 ±49	6140 ±56	6661 ±37

Table 48 shows the number of stops for all scenarios. It should be noted that since the simulation time is doubled from p.m. peak case to off peak case, the magnitude of the number of stops should definitely increase, as compared to the numbers in Table

43. It can be seen that the scenario of 2 clusters result in fewer number of stops in both EB and WB approaches. However, for the scenario of 3 clusters, the number of stops is more than those of other 2 scenarios.

After all, scenario of 3 clusters has an increased THOS, a decreased control delay and an increased number of stops than scenario of no partition. Scenario of 2 clusters has an increased THOS, a slightly increased control delay and a decreased number of stops than scenario of no partition.

The evaluation from two perspectives (THOS and simulation) provides us comprehensive information. Clustering method is beneficial in improving bandwidth, bandwidth efficiency, bandwidth attainability, and THOS. Clustering method results in either better control delay as can be seen from the scenario of 3 clusters, or better number of stops as can be seen from the scenario of 2 clusters. Delay optimum and stops optimum are not always consistent. We also notice that THOS is consistent with the number of stops. THOS of EB is greater than THOS of WB. Correspondingly, the number of stops of EB is smaller than that of WB.

6. CONCLUSIONS AND RECOMMENDATIONS

The following is a summary of the major conclusions and recommendations:

- Partition points are found to be at locations with critical volumes and spacing. Large left turning volume plays an important role in the corresponding signal coordination. With the increase of spacing, bandwidth efficiency and THOS of the subsystem will be slightly decreased. The influence of spacing on signal coordination is not as great as that of volume.
- Clustering method is promising and beneficial in improving progression bandwidth, bandwidth efficiency, bandwidth attainability and THOS.
- Based on results from case study, clustering method makes sense since at least one partition provides better control delay and stops.
- Delay optimal and stops optimum are not always consistent. This is particularly true for high volume situations.
- Clustering is not always good for signal coordination. Though bandwidth and bandwidth efficiency for each subsystem can be improved after partition, control delay or number of stops for the corridor might increase instead.
- Whether or not clustering method can be used to partition a signalized system for the purpose of better signal coordination depends on specific traffic and geometric conditions of the corridor.
- When demand is higher, bandwidth solutions will lead to large delay. When bandwidth capacity is exceeded by demand, bandwidth optimization should better give way to delay-based optimization strategies.

For future research, more case studies and volume combinations should be considered. The p.m. peak case we investigated is for a heavily traveled corridor during the afternoon peak period so the demand for the corridor is particularly high.

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