Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia - Social and Behavioral Sciences 43 (2012) 232 – 244

Procedia
Social and Behavioral Sciences

8th International Conference on Traffic and Transportation Studies
Changsha, China, August 1–3, 2012

Bandwidth Optimization of Coordinated Arterials Based on Group Partition Method

Xianyu Wu[a,*], Zong Tian[b], Peifeng Hu[b], Zhenzhou Yuan[a]

[a] *MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China, 100044*
[b] *Center for Advanced Transportation Education and Research (CATER), University of Nevada, Reno, MS 258, Reno, NV 89557,USA*

Abstract

An approach to the application of bandwidth-oriented signal timing has been proposed based on a group partition method for coordinated arterials. Firstly, the approach is an improved and detailed bandwidth optimization method, including detail steps to calculate upper/lower influences and relative offset for intersections, with different conditions. A window program BOTSD (Bandwidth Optimization and Time-Space Diagram) was developed to obtain optimal progression bandwidth and draw time-space diagram for an arterial. Secondly, a group partition method of coordinated arterials to get optimal bandwidth has been developed. In the case study, after calculating valid and optimal bandwidth for every possible subgroup, arterial progression bandwidth for every combination of possible subgroups can be obtained using the improved bandwidth optimization and group partition method. The results of intersection control delay and progression bandwidth for every combination of possible subgroups show that bandwidth-based solutions generally outperform delay-based solutions. Meanwhile, the signal timing plan from improved bandwidth optimization and group partition method is much better than the result from Synchro 6.0 optimization function and Messer's method.

Keywords: Signal coordination; Arterial; Progression bandwidth; Group partition

---

[*] Corresponding author. Tel.: +86-10-51687147; Phone: +86-13811093957
E-mail address: xianyu0104@gmail.com.

doi:10.1016/j.sbspro.2012.04.096

1. Introduction

The growth of the number of automobiles on urban roads has put a higher demand on traffic signal control system to efficiently reduce congestion. Signal coordination in urban network has attracted numerous studies over the past several decades. Procedures for determining optimal signal timings have been developed and continuously improved, especially about signal optimization, including the phase sequence of signals and partition method for arterials to achieve the optimal progression bandwidth.

Signal optimization. Existing traffic signal optimization approaches can be classified into two categories: those to minimize delay and stops such as TRANSYT-7F and SIGOP, and those to maximize arterial progression bandwidth such as PASSER II and MAXBAND. The basic limitation of existing bandwidth maximization programs is that progression bands do not reflect the actual traffic flow on arterials. Despite the various shortcomings of bandwidth-based signal timing, maximizing progression bandwidth is still a primary objective when developing coordinated signal timing plans. A larger progression bandwidth implies that more traffic on an arterial can progress through the signals without stops. Furthermore, bandwidth-based signal timing is preferred because it meets drivers' expectations. A signal timing solution, no matter how well it may minimize system delays and stops, may not be acceptable to traffic engineers if the timing solution does not have a good progression band. A study conducted by Yang has indicated that bandwidth-based solutions generally outperform delay-based solutions based on several field studies. To get the optimal traffic signals for arterials or road network, there are four parameters, including cycle length, split, phase sequence and offset. As a prerequisite, the splits for every phase are treated as given. This paper focuses on optimizing the phase sequence and offset of every intersection to get the optimal progression bandwidth for an arterial. The bandwidth optimization algorithm developed by Brook and Little, for two-phase signals, establishes the primary principles of bandwidth optimization. Most bandwidth-based software packages adopted these principles. For example, Messer et al enhanced the original algorithm to handle multiphase signals. Although the effectiveness of using lead–lag phasing has been realized by scholars and engineers for maximizing progression bandwidth, no quantitative assessment has been made on when lead–lag phasing can improve bandwidth over other phasing sequences, or how much bandwidth improvement can be achieved. A related issue is how bandwidth is affected by the number of signals in a system. Tian has provided such quantitative evaluations.

Partition of arterials. Progression bandwidth or bandwidth efficiency is one of the major criteria for judging the quality of a coordinated signal timing plan. However, when the number of signals in a system increases, it becomes more difficult to obtain a good bandwidth solution. In fact, attempting to use a small progression band for an entire arterial system may not be a good practice in signal timing and coordination. For example, traffic entering an arterial may not go through the entire system to fully utilize a system progression band. Traffic engineers and researchers have recognized the necessity of dividing a large system into smaller subsystems, a technique called system partition. SCATS can partition a big road network into several small subsystems, and calculate performance indices periodically to determine how to reorganize the existing subsystems. However, SCATS initial sub-network configuration has to be manually set up according to certain principles, methodology and algorithms. Hisai proposed a method for optimally dividing the signal-coordinated arterial street into subareas, and then utilized optimal, different cycle length and offset to get the maximum bandwidth. However, this study could not provide a method to optimize the phase sequence. In this study, optimizing the phase sequence is the most important process to get the optimal progression bandwidth. Tian has proposed the outline of system partition technique, and used software PASSER II to get the bandwidth, and then provided a case study to illustrate the proposed technique. In his study, a large system is first divided into subsystems. The attainability of maximum bandwidth is the main selection criteria to get the subsystems. Software Synchro is perhaps the only software that has a feature of system partition application. With the system partition feature, the software calculates an empirical coordinatability factor based on several variables such as distance, travel time, and traffic volume. This proposed approach is somewhat different from that used in the studies mentioned above. This study has indicated that bandwidth-based solutions generally outperform delay-based solutions based on several field studies.

This study has 3-fold purposes. First purpose is to improve Messer's method and provide a detail bandwidth optimization method. Second purpose is to provide a group partition method to get the optimal arterial progression bandwidth. Third purpose is to reduce the basic limitation of existing bandwidth maximization programs. Remaining part of this paper is organized as follows. Section 2 provides an improved and detail method of optimizing progression bandwidth based on Messer's method, with 8 conditions to calculate interference, and 6 conditions to obtain relative offset of every intersection, and then presents the methods of partitioning arterials with 4 steps to get optimal progression bandwidth. Section 3 shows a case study with the process of partitioning an arterial, using BOTSD to get optimal progression bandwidth for an arterial. Finally, Section 4 provides our summary and conclusions.

Notions and Terminology

$C[j]$	signal cycle length of subgroup j
$Offset[i, j]$	offset of intersection i in subgroup j, start green time of outbound through movement
$Offset[j, j+1]$	relative offset between subgroup j and subgroup $j+1$, as shown in Fig 1.

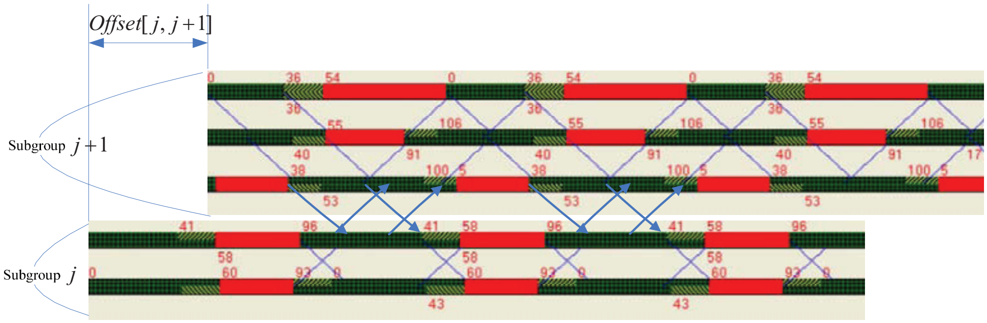

Fig. 1. Relative offset between two subgroups

$IBT[i]$	inbound through movement green time of intersection i
$IBL[i]$	inbound left turn movement green time of intersection i
$OBT[i]$	outbound through movement green time of intersection i
$OBL[i]$	outbound left turn movement green time of intersection i
$\min IBT$	minimum inbound through movement green time
$\min OBT$	minimum outbound through movement green time

m , n	phase sequence for master intersection x and intersection i , value are 1, 2, 3, and 4, in which 1--"Lead/Lead", 2--"Lead/Lag", 3--"Lag/Lead", 4--"Lag/Lag"; if there is no left turn phase, for example, if $OBL = 0$ and $IBL = 0$, in this case, m can be equal to 1, 2, 3, 4, the value does not impact the calculation of upper/lower interference
$RO[x,m]$	relative offset of $IBT[x]$ with respect to $OBT[x]$ for master intersection x , and $x = \{i, \quad IBT[i] = \min IBT\}$. Equation (1) shows the calculation of them.

$$RO[i,m] = \left\{ \begin{array}{ll} OBL - IBL & ,m = 1 \\ -IBL & ,m = 2 \\ OBL & ,m = 3 \\ 0 & ,m = 4 \end{array} \right\} \tag{1}$$

$RO[i,n]$	relative offset of $IBT[i]$ with respect to $OBT[i]$ for intersection i
$T[x,i]$	travel time from master intersection x to intersection i
$T[i,x]$	travel time from intersection i to master intersection x
$LI[i,m,n]$	lower interference for intersection i
$UI[i,m,n]$	upper interference for intersection i
$S[i]$	slack time between $OBT[i]$ and $OBT[x]$, $S[i] = OBT[i] - OBT[x]$;
$Is[i]$	slack time between $IBT[i]$ and $IBT[x]$, $Is[i] = IBT[x] - IBT[i]$

2. Bandwidth optimization

2.1. Messer's algorithm of optimizing progression bandwidth

The bandwidth optimization algorithm developed by Brook and Little established the primary principles of bandwidth optimization. The algorithm was originally developed for two-phase signals. Messer enhanced the original algorithm to handle multiphase signals with left turn phases, and software PASSER II was developed based on the algorithm, however it has some limits to get the optimal progression bandwidth for an arterial with many signalized intersections, and the progression bandwidth decreases with the increment of number of signals. The basic principles of the algorithm are presented below to show the reason of decrement of bandwidth.

Figure 2 illustrates basic concepts of Messer's bandwidth optimization algorithm using three signals with left turn phases. Maximum progression bandwidth is sum of outbound bandwidth and inbound bandwidth. Value of outbound bandwidth is a constant, equal to minimum outbound through green time $\min OBT$. And value of inbound bandwidth is determined by minimum total valid interference from other intersections. In Fig 2, second intersection is the master intersection, which has minimum inbound through green time $\min IBT$. Valid upper interference from first intersection is $UI_{\max}$, and valid lower interference from third intersection is $LI_{\max}$, then inbound bandwidth should be $\min IBT - \min(UI_{\max} + LI_{\max})$.

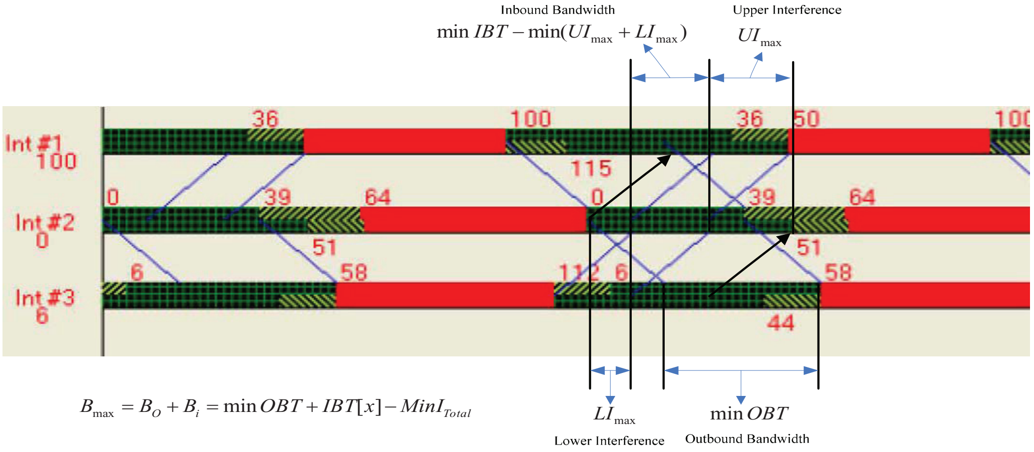

Fig. 2. Illustration of bandwidth optimization concepts of Messer's algorithm

2.2. Improved bandwidth optimization algorithm

Messer's paper provides a concept to calculate maximum progression bandwidth, however it does not provide specific description of all the possible cases for calculating upper and lower interference, but not offset at all.

This section provides detailed description on all possible cases to calculate interference and offset for every intersection.

(1) Upper and lower interference

To calculate the upper and lower interferences of intersection i, the location of i with respect to master intersection has an influence on interferences. By analyzing the principles and steps to calculate the interference, there are 4 common conditions and 4 special conditions to get the correct upper and lower interference for every intersection.

Condition 1: $OBT[x] \le OBT[i]$ and $i > x$

First part of this condition means that the outbound through movement green time of the master intersection is the minimum value on the arterial. And second part of it means that the location of intersection i is behind master intersection in the outbound direction. The function of % is the same to MOD.

$$UI[i,m,n] = IBT[x] - (-RO[x,m] + T[x,i] + RO[i,n] + IBT[i] + T[i,x])\%C[j] \tag{2}$$

$$LI[i,m,n] = (-RO[x,m] + T[x,i] - S[i] + RO[i,n] + T[i,x])\%C[j] \tag{3}$$

Condition 2: $OBT[x] > OBT[i]$ and $i > x$

First part of this condition means that the outbound through movement green time of the master intersection is not the minimum value in the arterial.

$$\begin{aligned} UI[i,m,n] = IBT[x] - (&-RO[x,m] + OBT[x] - \min OBT + T[x,i] + RO[i,n] \\ &+ IBT[i] + T[i,x])\%C[j] \end{aligned} \tag{4}$$

$$LI[i,m,n] = (-RO[x,m] + T[x,i] - S[i] + RO[i,n] + T[i,x])\%C[j] \tag{5}$$

Condition 3: $OBT[x] \le OBT[i]$ and $i < x$

Second part of this condition means that the location of intersection i is in the front of master intersection in the outbound direction.

$$UI[i,m,n] = (IBT[x] - (-RO[x,m] - T[i,x] + RO[i,n] + IBT[i] - T[i,x])\%C[j])\%C[j] \tag{6}$$

$$LI[i,m,n] = (-RO[x,m] - T[i,x] - S[i] + RO[i,n] - T[x,i])\%C[j] \tag{7}$$

Condition 4: $OBT[x] > OBT[i]$ and $i < x$, the calculation of upper interference in this condition is shown in Fig. 3.

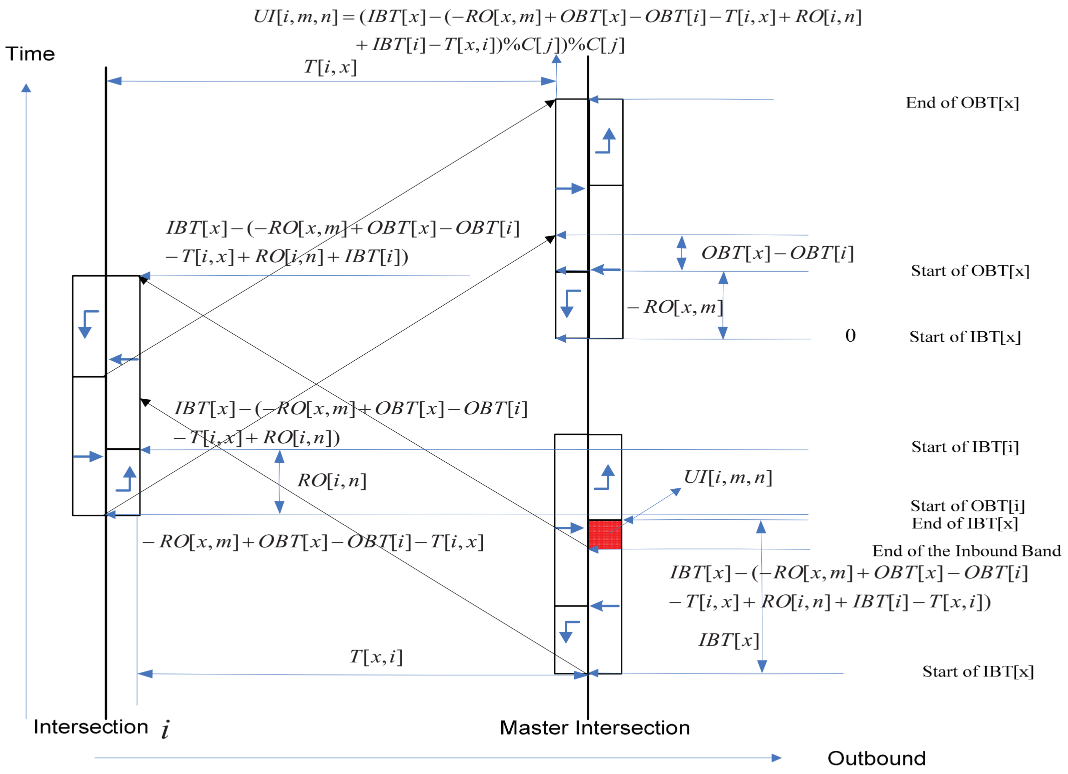

Fig. 3. The calculation of upper interference (condition 4)

$$UI[i,m,n] = (IBT[x] - (-RO[x,m] + OBT[x] - MinOBT - T[i,x] + RO[i,n] + IBT[i] - T[x,i])\%C[j])\%C[j] \tag{8}$$

$$LI[i,m,n] = (-RO[x,m] - T[i,x] - S[i,n] + RO[i,n] - T[x,i])\%C[j] \tag{9}$$

After calculating the lower interference, there are 4 special conditions to get the valid interference. If upper or lower interference satisfies these conditions, then valid interferences should be calculated using following formulas.

Special Condition 1: $C[j] + Is[i] \le LI[i,m,n] \le C[j]$

$$LI[i,m,n] = LI[i,m,n] - C[j] \tag{10}$$

Special Condition 2: $C[j] + LI[i,m,n] \le IBT[x]$

$$LI[i,m,n] = LI[i,m,n] + C[j] \tag{11}$$

Special Condition 3: $C[j] + Is[i] \le UI[i,m,n] \le C[j]$

$$UI[i,m,n] = UI[i,m,n] - C[j] \tag{12}$$

Special Condition 4: $C[j] + UI[i,m,n] \le IBT[x]$

$$UI[i,m,n] = UI[i,m,n] + C[j] \tag{13}$$

(2) Valid upper / lower interference and maximum bandwidth

Valid upper and lower interferences should be smaller than the minimum inbound through movement green time, and greater than slack time between $IBT[i]$ and $IBT[x]$.

$$Is[i] \le LI[i,m,n] \le IBT[x]\,,\; Is[i] \le UI[i,m,n] \le IBT[x] \tag{14}$$

Additionally, for intersection i, only upper or lower interference can be valid, they can not be valid at the same time.

Step 1: Select negative (or equal to 0) and valid interference for every intersection, meaning that there is no interference.

Step 2: Select all passive and valid interference for every intersection, then compare all the combinations of them to get $MinI_{Total}$.

$$Min\ I_{Total} = Min[Max\ UI[i,m,n] + Max\ LI[i,m,n]] \tag{15}$$

Then, maximum progression bandwidth is:

$$B_{\max} = B_O + B_i = \min OBT + \min IBT - MinI_{Total} \tag{16}$$

(3) Calculation of Offset

The reference phase is start of green time of outbound through movement $OBT[x]$. There are 6 conditions to calculate offset of every intersection.

Condition 1: $OBT[x] \le OBT[i]$ and $i > x$, and $UI[i,m,n]$ is valid.

$$Offset[i,j] = T[x,i]\%C[j] \tag{17}$$

Condition 2: $OBT[x] > OBT[i]$ and $i > x$, and $UI[i,m,n]$ is valid , or $LI[i,m,n]$ is valid.

$$Offset[i,j] = (T[x,i] + OBT[x] - OBT[i])\%C[j] \tag{18}$$

Condition 3: $OBT[x] \le OBT[i]$ and $i > x$, and $LI[i,m,n]$ is valid.

$$Offset[i,j] = (T[x,i] + OBT[x] - OBT[i] + K * C[j])\%C[j]\text{, and } K \text{ is an integer} \tag{19}$$

Condition 4: $OBT[x] \le OBT[i]$ and $i < x$, and $UI[i,m,n]$ is valid.

$$Offset[i,j] = K * C[j] - T[i,x] \tag{20}$$

Condition 5: $OBT[x] > OBT[i]$ and $i < x$, and $UI[i,m,n]$ is valid, or $LI[i,m,n]$ is valid.

$$Offset[i,j] = K * C[j] - T[i,x] + OBT[x] - OBT[i] \tag{21}$$

Condition 6: $OBT[x] \le OBT[i]$ and $i < x$, and $LI[i,m,n]$ is valid.

$$Offset[i,j] = K * C[j] - T[i,x] + OBT[x] - OBT[i] \tag{22}$$

2.3. Method of partitioning arterials to get optimal progression bandwidth

We have developed a window program BOTSD to draw the time-space diagram for all the intersections on arterials, based on the data results from the maximum progression bandwidth program. Time-space diagram drawn by BOTSD can show the numbers of start and end points of green time, that are not included in the other traffic control software tools, such as Synchro 6.0, PASSER II.

Using BOTSD, we have analyzed many case studies, including Kietzke Ln ,Reno (E 2nd St -- Peckham Ln, totally 8 intersections), S Virginia St , Reno (S McCarran Blvd – US395 SB, totally 9 intersections), Virginia St , Reno (Plumb Ln -- Peckham Ln, totally 8 intersections) and S Texas Ave, College Station, Texas (University Dr W -- Deacon Dr, totally 10 intersections).

In the case studies, we have calculated the progression bandwidth for all possible subgroups on the arterials. If number of intersections on an arterial is N , it is clearly known that the number of possible subgroups is equal to $\sum_1^{N-1} i$.

On the other hand, not all the possible subgroups has valid progression band using the BOTSD tool. For example, if an arterial has 8 intersections, then the number of possible subgroup should be 28. Based on the analyzed results from BOTSD, all the valid subgroups with valid and optimal progression bandwidth can be obtained, as shown in Fig. 4.

$$\begin{cases}1,2 & (1,1)\\ 1,2,3 & (1,2)\\ 1,2,3,4 & (1,3)\\ 1,2,3,4,5 & (1,4)\end{cases} \quad \begin{cases}3,4 & (3,1)\\ 3,4,5 & (3,2)\\ 3,4,5,6 & (3,3)\end{cases} \quad \begin{cases}4,5 & (4,1)\\ 4,5,6 & (4,2)\\ 4,5,6,7 & (4,3)\end{cases} \quad \begin{cases}5,6 & (5,1)\\ 5,6,7 & (5,2)\\ 5,6,7,8 & (5,3)\end{cases} \quad \begin{cases}6,7 & (6,1)\\ 6,7,8 & (6,2)\end{cases} \quad \{7,8 \quad (7,1)$$

Fig. 4. Valid subgroups with valid progression bandwidth

There are 8 valid combinations for the arterial with valid subgroups. (1,1)+(3,1)+(5,1)+(7,1)=2+2+2+2 =8,and (1,3)+(5,3)=4+4=8 are two examples of valid combinations. Group offset of the first subgroup is set to 0, and then group offsets for other subgroups are adjusted one by one to get arterial bandwidth. Subsequently, arterial progression bandwidth for every combination of all the valid subgroups is obtained. At the same time, traffic volumes, signal timing plans and geometric parameters are inputted into Synchro 6.0 to get the control delay for every intersection, which is used as another comparison parameter except progression bandwidth.

The detailed results for these 35 intersections on 4 arterials have showed that the volumes of turning movement and through movement play an important role in partitioning the arterial into several subgroups to get optimal bandwidth. The method of partitioning arterials with 4 steps can be used to get optimal bandwidth and minimum intersection delay, based on the analyzed results.

Step 1: Analyze traffic volumes

Traffic volumes for every movement are very important parameters for obtaining the optimal length of green time for every phase. Additionally, they have an important influence on optimizing the phase sequence to get the optimal arterial progression bandwidth. Traffic volumes of through movement can determine the direction of an arterial as well as the selection of partitioning points. And the volumes of turning movement play an important part in partitioning the arterials.

The intersections with minimum total traffic volumes of turning movement and maximum total traffic volumes of through movement are selected as the points to partition an arterial. There can be more than one partitioning point, in which turning volumes are much less than others, and through volumes are much more than others.

Step 2: Partition an arterial into several possible subgroups

With the points selected in the first step, the arterial can be partitioned into several possible subgroups. There are two possible conditions to partition the arterial, i.e. before the points and after the points. It must be noted that some of these possible subgroups may not have a valid and optimal progression bandwidth, in this case, the number of intersections in the subgroup can be reduced to get the maximum bandwidth.

Step 3: Get optimal bandwidth for possible subgroup

There are two cases to get the optimal bandwidth, if the direction of arterial is south / north, outbound can be either the southbound or northbound. After partitioning the arterial, the valid and optimal bandwidth of every possible subgroup can be obtained, using improved bandwidth optimization method.

Step 4: Get phase sequence and offset for every intersections with optimal progression bandwidth

Based on phase sequence and offset for every subgroup with maximum bandwidth, the optimal solution can be obtained with maximum arterial progression band. Using the BOTSD, the time-space diagram can be drawn with link band, including the number of start green time of every phase.

3. Case study

The direction of outbound should be selected to get the maximum progression bandwidth using bandwidth optimization method. The selection of the outbound direction is significant to get optimal progression bandwidth. The direction of outbound decides the selection of the master intersection, which has minimum inbound through movement green time, which is the most important part to calculate upper and lower interference for other intersections.

There are eight intersections (E 2nd St -- Peckham Ln) on the Kietzke Ln, Reno, Nevada, USA. The coordinated cycle length of this arterial is 130 seconds (16:00 pm-18:00 pm) and speed limit is 40 mph.

3.1. Traffic volumes

Table 1 shows the traffic volumes of the turning and through movements in these 8 intersections, which came from the data collection in the field.

Table 1. Traffic volumes (pcu/h) of 8 intersections

	Turning movements					Through movements		
INTID	NBL	NBR	SBL	SBR	Total	NBT	SBT	Total
1	226	169	56	54	505	820	430	1250
2	220	259	120	121	720	897	492	1389
3	96	120	109	146	471	962	689	1651
4	253	313	299	143	1008	770	483	1253
5	89	72	6	148	315	1198	855	2053
6	119	51	30	79	**279**	1153	889	**2042**
7	166	168	296	140	770	892	678	1570
8	71	249	305	168	793	911	633	1544

By analyzing the volumes of northbound and southbound turning movements for these 8 intersections in Table 1, the total volume of turning movements in intersection "6" is much smaller than the other intersections. On the other hand, the total through movement volumes of intersection "5" and "6" are much more than other intersections. In summary, intersection "6" is selected as the partitioning point of the arterial to get the maximum progression bandwidth.

3.2. Possible combinations of possible subgroups

The progression bandwidths for all possible subgroups are calculated to confirm that the selected points are correct using the partition method. Table 2 shows the results of optimal bandwidth for possible subgroups. These possible subgroups have valid and optimal bandwidth using the improved bandwidth optimization method.

Using results of possible subgroups, we can get possible combinations of them with optimized arterial bandwidth. Table 3 shows the optimized results of bandwidth and control delay for possible combinations of possible subgroups. There are many other possible combinations, which either have not optimal subgroup bandwidth or have the same results to some of them. Every column has a special meaning. For example, in the column of “Combination”, “6+2” means that the first subgroup has 6 intersections, and the second subgroup has 2 intersections, and the total number of intersections is 8. In the column of “Subgroup Bandwidth”, “66+75” means that the maximum total bandwidth of the first subgroup is 66 seconds, and the total bandwidth of the second subgroup is 87 seconds. In the column of “Arterial Bandwidth”, “NB=21, SB=37” means the northbound arterial bandwidth is 21 seconds, and southbound arterials bandwidth is 37 seconds. In the column of “Average Int Delay (s)”, “30.86” means that the average value of intersection delay for all the eight intersections is 30.86 seconds.

Table 2. Bandwidth for possible subgroups

Outbound	Subgroup	INTID	Subgroup Bandwidth	Subgroup	INTID	Subgroup Bandwidth
Southbound	1	1+2	SB=37, NB=31	8	4+5	SB=50, NB=48
	2	1+2+3	SB=37, NB=29	9	4+5+6	SB=50, NB=48
	3	1+2+3+4	SB=37, NB=29	10	5+6	SB=77, NB=57
	4	1+2+3+4+5	SB=37, NB=29	11	5+6+7+8	SB=49, NB=13
	5	1+2+3+4+5+6	SB=37, NB=29	12	6+7+8	SB=49, NB=13
	6	3+4	SB=50, NB=48	13	7+8	SB=49, NB=26
	7	3+4+5	SB=50, NB=48	--	--	--
Northbound	1	1+2	NB=46, SB=26	7	4+5+6	NB=48, SB=39
	2	1+2+3	NB=46, SB=6	8	5+6	NB=79, SB=55
	3	3+4	NB=48, SB=50	9	5+6+7+8	NB=41 SB=16
	4	3+4+5	NB=48, SB=50	10	6+7+8	NB=41 SB=16
	5	3+4+5+6	NB=48, SB=35	11	7+8	NB=41 SB=28
	6	4+5	NB=48, SB=50	--	--	--

Table 3. Bandwidth and delay for possible combinations

Outbound	Num	Combination	Subgroup Bandwidth	Arterial Bandwidth	Average Int Delay(s)
Southbound	1	2+2+2+2	69+98+134+75	NB=0, SB=37	33.55
	2	2+3+3	69+98+62	NB=0, SB=37	34.30
	3	3+3+2	66+98+87	NB=18, SB=37	32.16
	4	3+2+3	66+98+62	NB=0, SB=37	32.99
	5	4+4	66+62	NB=0, SB=37	33.31
	6	5+3	66+62	NB=0, SB=37	32.35
	7	6+2	66+87	NB=21, SB=37	30.86
Northbound	8	2+2+2+2	72+98+134+68	NB=41, SB=0	33.53
	9	2+2+4	72+98+57	NB=41, SB=0	33.83
	10	2+3+3	72+98+57	NB=41, SB=0	33.69
	11	2+4+2	72+83+69	NB=41, SB=0	33.56
	12	3+2+3	52+98+57	NB=41, SB=0	32.7
	13	3+3+2	52+87+69	NB=41, SB=0	32.84

According to the results in Table 3, it is known that combination “6+2” has the maximum arterials progression bandwidth, and has the smallest average intersection delay, which is 30.86 seconds. It can then be concluded that the combination “6+2” is the optimal solution. This result matches that using the group partition method mentioned.

3.3. Time-space diagram with optimal progression bandwidth

Reference phase is the start point of outbound green time, and southbound is outbound. The group offset of the first subgroup with 6 intersections is set to be 0 second, and the group offset of the second subgroup is equal to 88 seconds. Then the time-space diagram with optimal arterials bandwidth and link bandwidth can be drawn, as shown in Fig. 5, in which arterial bandwidth of southbound is 37 seconds, and that of northbound is 21 seconds.

3.4. Comparison to optimized results from Synchro 6.0 and Messer’s algorithm

Synchro 6.0 can optimize cycle length and offset to get the optimal solution with minimum delay. After all the parameters are inputted into Synchro 6.0, we can get the time-space diagram using the “Optimize-Network Offset” option. The arterial progression bandwidth for southbound is 32 seconds, and 0 second for northbound. By the way, average intersection control delay is 32.27 seconds, which is bigger than 30.86 seconds.

Using Messer’s algorithm, the arterial progression bandwidth of southbound is 36 seconds, and 14 seconds of northbound, that are less than the results from the proposed method. As a result, the signal timing plan from BOTSD with group partition method is much better than the solution from Synchro 6.0 and Messer’s algorithm.

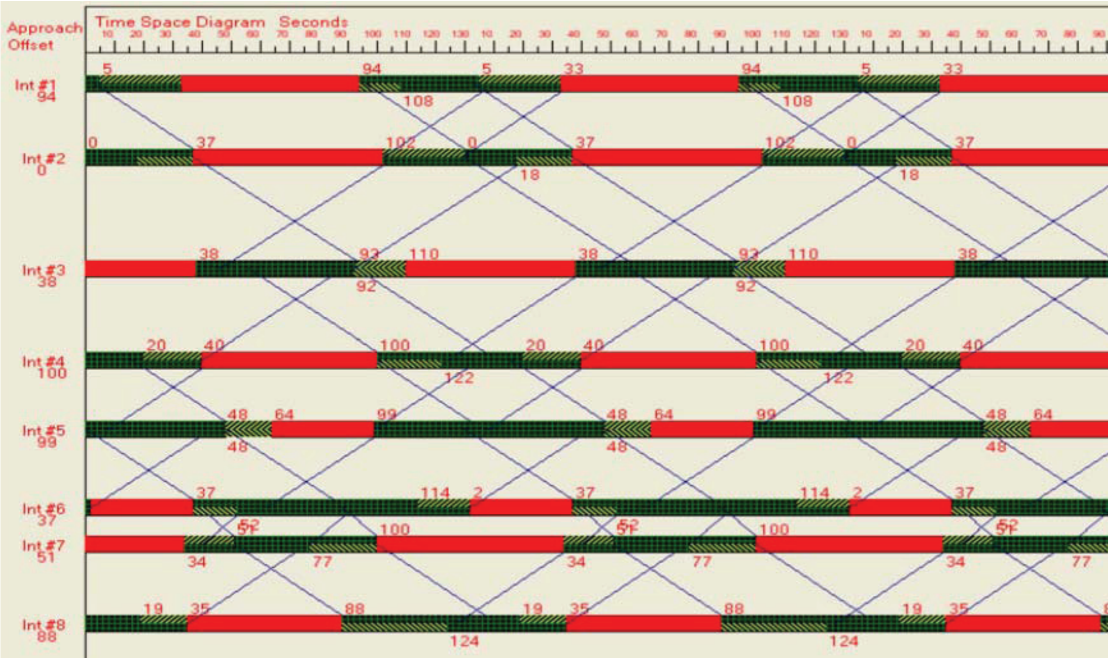

Fig. 5. Time-space diagram on the Kietzke Ln with proposed algorithm

4. Conclusions

Unlike the traditional bandwidth-based signal-timing methodologies, a heuristic signal timing approach based on group partition technique for arterials was proposed in this study. The following part is a summary of the major findings and conclusions.

(1) This paper provides improved and detailed description of bandwidth optimization on all possible cases to calculate upper/lower interference and offset for every intersection, based on Messer's method. The optimization method includes both steps to calculate the upper/ lower interferences for intersections under 4 common conditions and 4 special conditions, and the way to obtain relative offset for intersections under 6 conditions.

(2) Based on the optimization method and the analyzed results from case studies, this paper has provided the method of partitioning an arterial to get optimal bandwidth and minimum intersection delay with 4 steps, in which traffic volumes play an important role to get the partitioning points.

(3) Using the improved bandwidth optimization and group partition method, the results of case study show that BOTSD is a very useful tool to get the optimal bandwidth for subgroups and arterials. The solution from BOTSD with group partition method is much better than the solution from Synchro 6.0 and Messer's method.

(4) Using Synchro 6.0, we have achieved control delay for every intersection, which shows that bandwidth-based solutions generally outperform delay-based solutions. In the case study, according to the results in Table 3, the combination "6+2" has maximum arterial progression bandwidth (58 seconds), meanwhile it has minimum average intersection delay (30.86 seconds).

In the future, continuous studies will be done to obtain the relationship between traffic volumes, distance, travel speed and the group partition technique to get optimal link and arterial progression bandwidth for a bigger system with a large number of intersections.

References

Baass, K. G. (1983). Another Look at Bandwidth Maximization. *In Transportation Research Record* 905, TRB, National Research Council, Washington, D.C., pp. 38-47.

Chang, E. C.P., C. J. Messer, and S. L. Cohen (1986). "Directional Weighting for Maximal Bandwidth Arterial Signal Optimization Programs." *In Transportation Research Record* 1057, TRB, National Research Council, Washington, D.C., pp. 10-19.

Cohen, S. L., and J. R.. Mekemson (1985). Optimization of Left-Turn Phase Sequence on Signalized Arterials. In *Transportation Research Record 1021,* TRB, National Research Council, Washington, D.C., pp. 53-58.

Hisai, M., and Usami, T. (2006). "Optimal Division of Signal-coordinated Arterial Street into Subareas." *Memoirs of the Faculty of Engineering,* Vol. 56, No. 2, pp. 69-81.

Husch, D., and Albeck, J. (2003). Synchro 6: *Traffic Signal Software, User Guide*. Albany, Calif.

Liberman, E. B., and J. L. Woo (1976). SIGOP II: A New Computer Program for Calculating Optimal Signal Patterns. In *Transportation Research Record* 596, TRB, National Research Council, Washington D.C., pp. 16-21.

Little, J. D. C., and M. D. Kelson (1980). *Optimal Signal Timing for Arterial Signal Systems, MAXBAND*. Summary Report 1. Operations Research Center, Massachusetts Institute Technology, Cambridge.

Lowrie, P. R. (1982). The Sydney Coordinated Adaptive Traffic System-Principles, Methodology, Algorithms. *International Conference on Road Traffic Signaling,* Institution of Electrical Engineers, London, UK, pp. 67-70.

Messer, C. J., H. E. Haenel, and E. A. Koeppe (1974). A Report on the User's Manual for Progression Analysis and Signal System Evaluation Routine - PASSER II. *Research Report 165-14,* Texas Transportation Institute, College Station, Texas.

Messer, C. J., Whitson, R. H., Dudek, C. L., and Romano, E. J. (1973). A Variable -sequence Multiphase Progression Optimization Program. *Highway Research Record.* 445, Transportation Research Board, Washington, D.C., pp. 24-33.

Robertson, D. I. (1969). TRANSYT: A Traffic Networks Study Tool. *Road Research Laboratory Report 253*, *Crowthorne, Berkshire, Great Britain.*

Sripathi, H. K. (2007). "Want to Improve Operations? Get Back to Basics." *ITE Journal,* Vol. 77, No. 4, pp. 24-27.

Tian, Z., Mangal. V, and Liu, H. (2008). Effectiveness of Lead–Lag Phasing on Progression Bandwidth. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2080, Transportation Research Board of the National Academies, Washington, D.C. 22-27.

Tian, Z., and T. Urbanik (2007). System Partition Technique to Improve Signal Coordination and Progression. J*ournal of Transportation Engineering,* Vol. 133, No. 2, pp. 119-128.

Yang, X. K. (2001). Comparison Among Computer Packages in Providing Ttiming Plans for Iowa Arterial in Lawrence, Kansas. *Journal of Transportation. Engineering,* Vol. 127, No 4, pp. 314-318.