Phasing Sequence and Signal Spacing Based Progression Bandwidth Optimization Technique

Yi Zhao1,2,a, Zong Tian2,b

1 School of Traffic and Transportation, Beijing Jiaotong University, MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing 100044, China
2 University of Nevada Reno, 89557, NV, USA

Keywords: Singal Control; Phase Sequence; Green Brand; NEMA Phase; Micro-simulation

Abstract. This study provided quantitative analyses about the influence of phasing sequences and the impact of intersection spacing. A large number of signal system scenarios were randomly generated to represent the real-world traffic systems. Based on simulation result, it was concluded that Leading and Lagging left turn phasing were more likely to be involved in progression bandwidth solution of signal systems with randomly distributed spacing. And the number of signals has significant impact on bandwidth attainability. Further conclusions were drawn from the fitting curve that it is impossible to obtain any two-way bandwidth solutions when more than 16 signals were involved in the system.

Introduction

Arterials have always been playing important parts and burdening with the majority of traffic load in urban traffic system. Therefore, it is critical of maintaining the arterials in an efficient manner to improve the mobility and safety of urban traffic system. Among the many control methods for arterials, coordination control is one of the most effective one which aims at making the vehicles driving smoothly and encounter less red light to shorten the driving time, decrease the number of stops and time delays. A well-configured coordination control system could make the vehicles meet less number of stops and lower the fuel consumptions, therefore leading to the improvement of air quality. The studies on arterial coordination control has begun in the 60s, IBM’s engineer Brooks has firstly initiated the two-phase coordination control optimization algorithm. Thereafter, many studies have been conducted on the related topic from different perspectives. Morgan and Little formulated an analytical model for the bandwidth optimization. Their model was established by mixed-integer programming, which insures equal maximum bandwidth can be obtained for both directions. Based on these previous studies, Messer improved the bandwidth optimization algorithm by introducing the left-turn phase. And this enhanced algorithm has found applications in many software packages for bandwidth optimization, including PASSER II and MAXBAND. Over the next decades, many researcher improved bandwidth optimization models continuously.

But in the reality, there are still several problems need to be solved in this field, including:

1. The influence of phasing sequences on bandwidth maximization. Although there were several completed research work on phasing sequence comparison, but most of them were concerned about traffic safety and capacity. Tian first tested effectiveness of phasing sequence using quantitative method. But due to the limitation of experiment restriction and sample size, a large scale experiment is still need to get more comprehensive result.

2. The influence of intersection spacing on the bandwidth optimization. Among the many ideas of coordination control for the arterial, someone thought that it might be much easier to obtain larger two-way bandwidth, under the condition of equal or similar intersection spacing in a group of intersections. Due to the limited geographical conditions and research resource, studies on this issue are still basically blank.
To answer the above questions, this study randomly generated a total of 90000 group scenarios based on intersection number from 2 to 10 with either random or uniform intersection spacing. Then, simulation was performed to optimize two-way bandwidth using the method introduced in this study.

**Bandwidth optimization model**

Several pioneering researches on bandwidth optimization devoted to the development of mathematical models and subsequently related computational algorithms. In this study, a computer program was developed for maximizing progression bandwidth to derive the overall optimal bandwidth solutions in different phasing sequence scenarios by iterative method. Actually, the authors reformulate Messer’s model in another expression, for the convenience of calculating and higher computation efficiency. The model is built as follows:

\[
B_{\text{max}} = G_{o,\text{min}} + G_{i,\text{min}} - \min\{\min[\max(I_{U,j,p}) + \max(I_{L,k,l})]_i\}\]

\[\forall \ j \in 1 \sim m, k \in 1 \sim m, l \in 1 \sim n\]

\[I_{U,j,n} = G_{i,x} - (r_{x,p} + t_{s,j} - r_{j,q} + G_{i,j} + t_{j,x}) + K_u * C\]  

\[I_{L,j,n} = r_{x,p} + t_{s,j} - r_{j,q} + t_{j,x} - G_{o,j} + G_{o,x} + K_L * C\]  

s.t. \[0 \leq I_{U,j,n} < C\]  

\[0 \leq I_{L,j,n} < C\]  

\[\forall \ k \ \exists I_{U,k} \geq I_{U,j}\]

\[B_{\text{max}}\] : Optimal system bandwidth  

\[G_{o,j}, G_{i,j}\] : Inbound and outbound green time, respectively, by phasing sequence \(p\) of intersection \(j\)  

\[I_{U,j,p}, I_{L,j,p}\] : Upper and lower interferences, respectively, caused by phasing sequence \(p\) of intersection \(j\)  

\(t_{s,j}\) : Driving time from intersection \(x\) to \(j\)  

\(r_{j,q}\) : Relative offset of \(G_{i,j}\) with respect to \(G_{o,j}\) for phasing sequence \(q\)  

\(x\) : Intersection that has the minimum outbound green;  

\(m\) : Number of signals in the system;  

\(n\) : Phasing sequences combination scheme, given 4 different situations at each intersection  

\(K_U, K_L\) : Adjusting coefficient to make sure \(0 \leq I_{U}, I_{L} < C\)

Each parameter is indicated in the following Fig.1.

![Fig.1 Illustration for bandwidth and interference calculation](image-url)
Analysis on Phasing Sequence Using Frequencies

Based on the above process, the authors developed a computer simulation program to derive optimal solutions for arterial coordination control. This program could randomly generate several groups of arterial systems, given the specified ranges of key system parameters including the number of intersections, cycle length, and driving time, etc. For each arterial system, the maximum bandwidth was derived, and the phasing sequence scheme for each intersection was also generated.

Here are the assumptions made for each randomly generated arterial system:

1) The program was designed to randomly generate 5000 traffic scenarios with the number of intersection ranges from 2 to 10 and intersection spacing is either “Random Distance” or “Uniform Distance”. Thus, a total of 5000×9×2=90000 traffic scenarios are generated for analysis;

2) Cycle length ranged from 30 seconds to 200 seconds;

3) The total major street phase split (effective green time) was configured at 50%~90% of the cycle length, the coordinated phase split was fixed at 50%~90% of the total major street phase split, therefore coordinated phase split take 25% and 81% of the cycle length.

4) Driving time between adjacent intersections ranged from 15 to 200 seconds.

5) As the phasing sequence of minor streets had no influence on the arterial coordination control, no side-street phasing sequence was specified in this simulation;

6) It has times when one system may have several maximum bandwidth solutions. In this case, the program recorded all the possible phasing sequence schemes that lead to the same maximum bandwidth. Besides, it was considered having no bandwidth solution when the maximum bandwidth equals $G_{\text{min}}$.

The simulation results are shown in Fig.2 (a) – (d), illustrating the frequencies in which a particular phasing was used at different number of intersections.

![Fig.2 Illustration of distribution on frequencies of phasing sequences](image)

As shown in Fig.2 (a) and (b), the mean frequencies of Leading phase in both cases of “Random Distance” and “Uniform Distance” are 21.8% and 21.4%, respectively. For Lagging phase, the mean frequencies are 21.9% and 21.3%. It can be concluded that these two phasing sequences were used at similar level of possibility to produce the maximum bandwidth.

It was also noted that the frequencies of leading phase under “Random Distance” that ranges from 21.1% to 22.7% had lower fluctuation than “Uniform Distance” which is between 20.4% and 22.7%. Similarly, for lagging phasing, the frequencies under “Random distance” ranged between 21.2% and 23.0% also fluctuated smaller than “Uniform Distance”.

---

*Sustainable Environment and Transportation*
Analysis on Bandwidth Optimization

The number of intersection involved in arterial road system is very important for bandwidth optimization. Although traffic engineers can tell that two-way bandwidth maximization cannot be achievable when the intersection number exceeds a certain limit, the relationship between them has never been quantified and studied in details. This study used the following three indicators, including attainability, average number of solutions and percentage of systems cannot be optimized, to measure the influence of intersection number on bandwidth maximization.

Attainability is the ratio of bandwidth to the sum of two-way through green time, which indicates the how effective the bandwidth is used. It is defined as \( A = \frac{B_{\text{max}}}{G_{o,\text{min}} + G_{i,\text{min}}} \).

Average number of solutions indicates the possible number of optimization solutions, which is defined as \( \frac{\sum \text{number of solutions}}{\text{number of arterial systems}} \).

The “Percentage of systems cannot be optimized” is formulated as \( \frac{\text{Number of systems cannot be optimized}}{\text{Number of arterial systems}} \). This indicator is designed to quantify the occasions when the maximum bandwidth equals the minimum of outbound through green time. Actually, these occasions mean that the bandwidth maximization solution cannot be achievable through adjusting phasing sequences. And this indicator could display the percentage of systems cannot be optimized to the total number of arterials systems, under different number of intersections.

Based on the analysis of attainability, it can be observed that the efficiency of progression bandwidth decreased by 5% with the number of intersections increase. Besides, as shown in Fig.3, when the intersection number is less than 7, the attainability under “Random Distance” is a slightly higher than “Uniform Distance”. When the intersection number exceeded 7, the attainability under “Uniform Distance” is higher.

![Fig.3 Attainability](image)

Further analysis on error curve indicates, compare to the “Random Distance” case, there are more pronounced fluctuations in attainability in “Uniform Distance”. This observation further proves that there are much more uncertainties in bandwidth maximizing progression for the “Uniform Distance” group.

The analysis for the “Average number of solutions” indicated that, the number of intersections involved in the arterials system has quadratic positive correlative relationship with the number of solution provided (as Fig.4 shown). And the regression result is as follows:
As the result suggested, there were more bandwidth maximization solution for UD intersections group when the intersection number is less than 7. And the RD intersections group has more feasible solutions when the intersection number is higher than 7. This implies that as more and more signals included in the arterials system, there are more chances of achieving feasible solutions when the signals are randomly distributed.

Lastly, the third indicator of “Percentage of systems cannot be optimized” is analyzed and shown in Fig. 5. It can be concluded from the regression result that the “Percentage of systems cannot be optimized” also has quadratic positive correlative relationship with the intersection number. The correlation coefficient R2 for RD and UD intersections groups are 0.997 and 0.9975, respectively, which depicted a perfect fitting curve for the sample data. Furthermore, the fitting curve of RD intersections group lies under the UD intersections group, representing lower “percentage of systems cannot be optimized” in RD intersections group, compared to UD system.

Generally speaking, the possibility of achieving maximum bandwidth decreases with the number of intersections increases. Due to the computing limitation, this paper only establishes simulated arterials system with 2~10 signals. Besides, the authors calculate several scenarios of more than 10 signals, by using the regression formula for RD intersections group. The calculation result indicates that it would be impossible to get a maximum bandwidth solution when the number of intersections reaches 16 in an arterials system. This conclusion reminds us to split a large intersections group into several smaller groups before bandwidth maximizing progression, when the number of intersections exceeds 16.
Conclusion
This paper conducted comprehensive research on the phasing sequence optimization problem for coordinated signals system. Firstly, the principles of bandwidth maximizing progression under the circumstance of NEMA phase are elaborated and the model is established accordingly. Then, the simulation experiment is performed in the randomly generated arterials systems with 2~10 signals. On the basis of the cases analyzed, the following major conclusions can be drawn:

1) To achieve the optimal two-way bandwidth maximization solution, Lead-Lag and Lag-Lead phasing should be paid more attention to in signal timing scheme.

2) Lead-Lag and Lag-Lead phasing showed more advantages in bandwidth optimization for intersections group with “Uniform Distance”; while the Leading and Lagging phasing are more suitable for intersections group with “Random Distance”.

3) When the system includes less than 7 signals, “Random Distance” group has distinct advantage of accessing maximizing progression bandwidth.

4) Furthermore, the “Random Distance” group could also get more chances of achieving optimized timing solutions.

5) It is basically impossible to obtain any two-way bandwidth when there are more than 16 signals in the arterials system.

Acknowledgements
This study is supported by the Fundamental Research Funds for the Central Universities (Grant No. 2012JBM061).

References