An Integrated Optimization Design of Signal Timing Plan and Lane Allocation Pattern

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Keywords: Signal Optimization, Lane Allocation Pattern, Genetic Algorithm, Cube Sugar, ArcGIS

INTRODUCTION

With increasing traffic on major roads controlled by traffic signals, many problems have become common, specifically during periods of peak demand. In most urbanized settings worldwide, drivers have become accustomed to undesirable congestion and excessive delay. The traffic congestion makes them trifle time away on roads and lose the opportunity to do other things. Usually, it is difficult to widen existing roads or build new roads in urban areas to improve the service of traffic networks. Better utilizing the existing traffic facilities is the only reasonable answer to most traffic congestion problems. For traffic engineers and transportation researchers, signal timing and lane allocation are most important settings at signalized intersections to control the operation. Efficiently operated traffic signals and reasonably designed lane markings can reduce congestion and bring about significant payoffs in time and energy benefits. The need for efficient traffic signal operation and lane allocation has never been more important.

The design of signal timing plan and lane allocation pattern should be complementary to each other. A lane allocation pattern requires an effective signal timing plan to improve the operation service; on the other hand, a signal timing plan cannot function properly without a reasonable lane allocation pattern. Usually, the lane allocation pattern, to some extent, limits the choice of signal timing plans. On the other hand, inappropriate lane allocation pattern would cause difficulty on measuring intersection operation performance. The de facto left-turn (right-turn) lane is a good example. When an approach with a lane shared by both through and left-turning (or right-turning) vehicles, it is necessary to determine if the lane essentially acts as an exclusive through / left-turning (or right-turning) lane. If the de facto lane is caused by irregular traffic flow, traffic engineers do not have much to do on fine-tuning lane markings; however, if the traffic flow is consistent and it is not the reason lead to de facto lane, traffic engineers need to examine the design of lane allocation patterns.

In this research, an optimization model for the integrated design of signal timing plan and lane allocation pattern at signalized intersections is presented. The decision signal variables including cycle length, phase durations, phase sequence and permitted movements; the decision lane allocation variables including number of exclusive lanes and shared properties for each movement. A fully optimized intersection design can be generated according to the assigned traffic flows and geometric properties at the intersection. The problem is formulated and solved by a Genetic Algorithm-based model. The detailed description of the model is presented following in next section.

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METHODOLOGY

The purpose of an integrated design for a signalized intersection is to determine the best combination of signal timing plan and lane allocation pattern at the intersection, based on traffic flow and geometry information, so as to achieve the user-specified objective. The objective function could be any intersection performance measure, such as overall traffic delay, overall throughput, overall fuel consumption, level of service (LOS) of a specified approach, or a perform index that pre-defined by users. The only requirement is that the fitness of the function should be obtained based on the available input data. Usually, there are two sets of input data need to be specified. One is the traffic data, i.e., the flow of all the turning movements (left, through and right) to the intersection. The other is the geometry data, specifically, the number of lanes at each approach. The lane pattern must be allocated based on the lanes available.

Correspondingly, the decision variables can also be categorized into two groups, i.e. the signal timing design and the lane pattern design. Figure 1 demonstrates the decision variables at a typical four-leg intersection. As indicated in the figure, each approach has three movements: left-turning, through and right-turning. The lane pattern design should specify the number of available lanes for each movement and the shared properties between the movements For an eight-phase dual-ring timing plan operated intersection, the signal timing design should give the green, yellow and all-red durations for each phase, the phase sequence, and if left-turning movements are permitted at the through phases. It can be seen that the problem is complex due to the large number of decision variables. It is difficult to be formulated and solved by conventional analytical models. The genetic algorithm (GA) is thus considered in this research to solve the problem (Goldberg 1989, Michalewicz 1996).

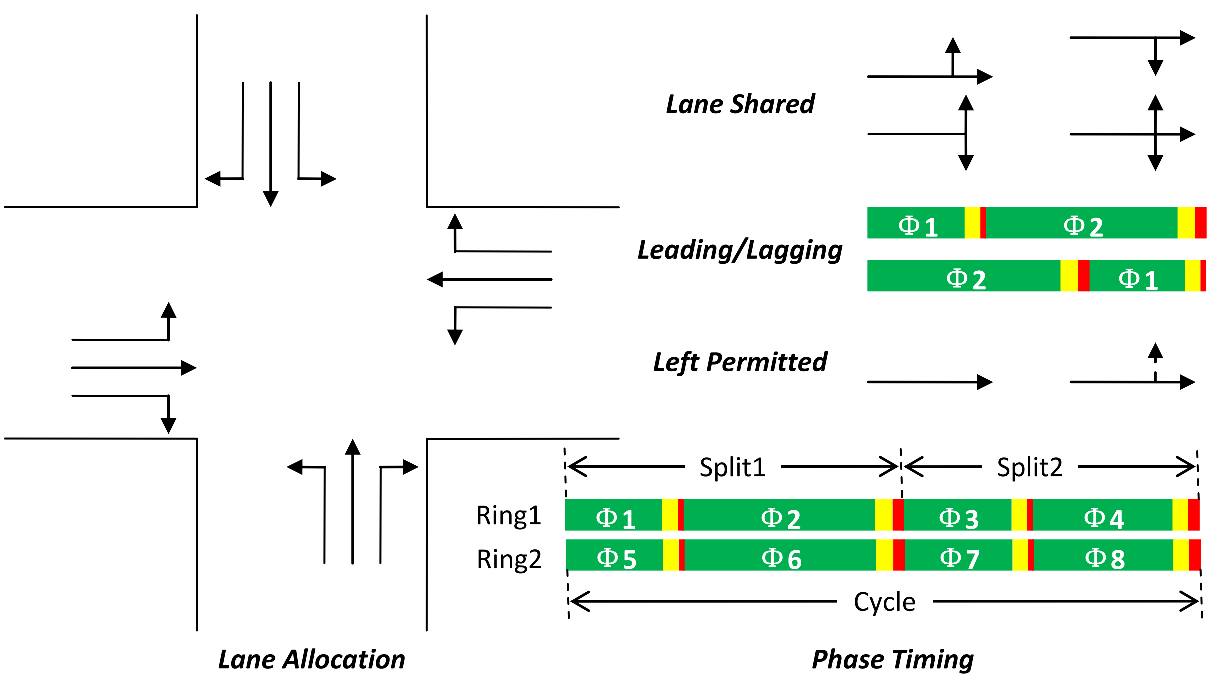

Figure 1. Decision Variables at Isolated Intersection

Encoding is the most important step in GA's model. It is the method to represent the potential solutions of the problem to the format that GA can process to chromosomes. Good encoding schema improves the efficiency of the GA model. At an isolated intersection, a potential integrated design solution is a set of values represents a signal timing plan and a lane allocation pattern. The set of values here is a chromosome in GA's model. It can be treated as the combination of a signal timing chromosome and a lane pattern chromosome. The signal timing chromosome is a set of values for the basic signal timing parameters. Amongst, phase green, yellow, and all-red are integer values, and phase combination and permitted left-turning data are binary values. This study implements a similar fraction-based encoding schema that originally proposed by Park et al. (1999). The major difference is that the model proposed in this paper further considered the permitted property of left-turning movement. The integer values, i.e. cycle time, barrier splits and phases durations, are produced by prorating available green times.

As roughly shown in Figure 2, a set of binary digits (usually 4 ~ 8 digits depending on the required precision) is decoded as decimal value (i.e., *f1, f2, …, f6*) within [0.0, 1.0), which represents the fraction of the available green. The fraction-based schema formulates all the signal timing parameters into a series of binary digits, and thus formulates the signal timing chromosome. To keep this paper concise, the fraction-based signal timing encoding schema is not elaborated here. Readers may refer to Park's paper for more details.

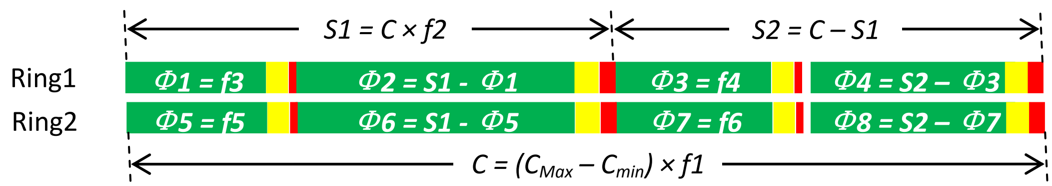

Figure 2. Fraction-based Signal Timing Encoding Schema (Park et al., 1999)

A similar fraction-based encoding schema for signal timing is implemented for lane pattern schema encoding as well. As shown in Figure 3, a length of seven binary digits set is used to encode a typical approach at a four-leg intersection. The first two digits represent the shared property of the approach; digits at position 3 to 5 are decoded as a decimal representing the fraction of number of available through-lanes among all the lanes available (if the total available lanes less than 4, then only two digits are needed here); and the last two digits represent the fraction of number of available left-turning lanes among the remaining lanes, and the right-turning lanes can be calculated based the decoded results.

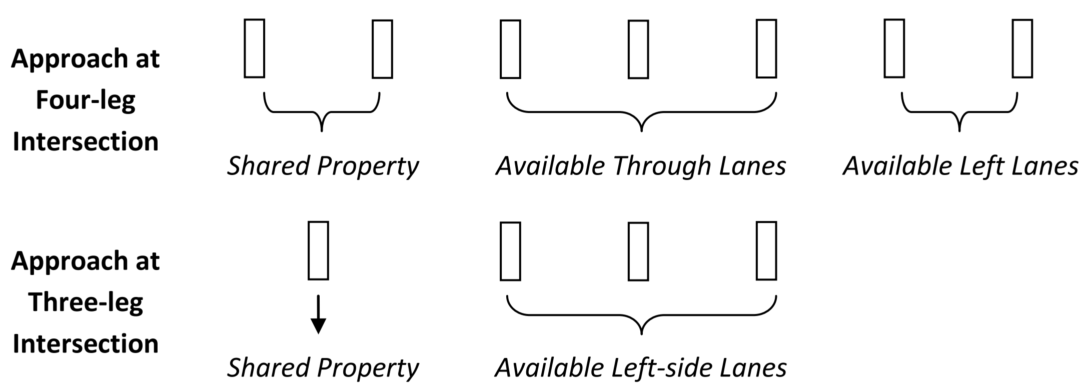

Figure 3. Binary Encoding Schema at an Approach

For an approach at a typical three-leg intersection, or an approach at a four-leg intersection with one movement banned (no encoding needed if two of the three movements are banned), only four digits (or three digits if the total lanes available are less than 4) are enough to encode the lane allocation pattern. As depicted in Figure 3, the first digit represents if the two movements are shared; the remaining digits represent the fraction of the number of available lanes to the left-side movement (i.e., left-turning movement if through or right-turning is banned, and through movement if left-turning is banned) among the total lanes available; and the available lanes to the other movement can be calculated accordingly.

IMPLEMENTATION

The proposed GA-based integrated signal timing plan and lane allocation pattern optimization model has been implemented into Sugar AcrGIS modeling extensions that developed by Citilabs, Inc. Sugar software tools are extensions for built specifically for ESRI users. Each extension is designed to support specific user needs or organizational operations. The Sugar Network Editor is an extension that efficiently codes and maintains the appropriate topology of roadways, public transit services, and intersection related data (traffic signals). Sugar junction editor is part of the Sugar Network Editor. Figure 4 shows the screenshot of the Sugar Extensions. As can be seen, the junction data could be edited through the Sugar junction editor, and the signalized intersection can be optimized through the optimizer button.

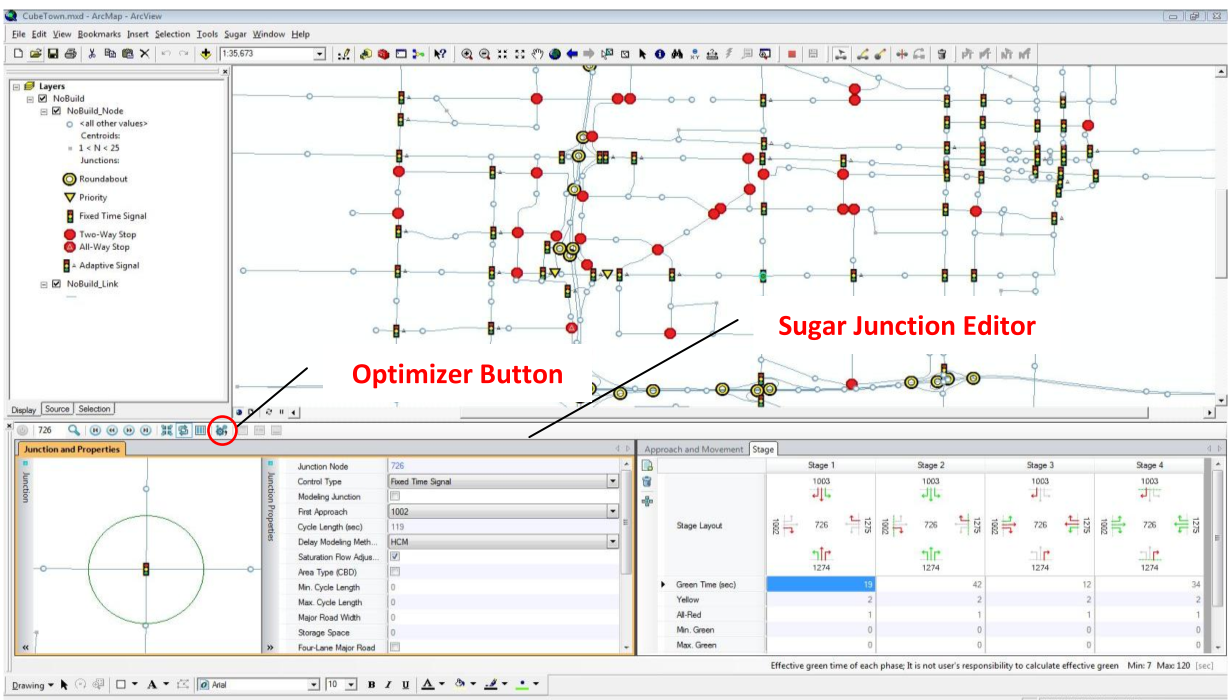

Figure 4. Screenshot of the Sugar AcrGIS Modeling Extensions

Figure 5 shows a screenshot of a sample Sugar optimizer results window. Once the user click the optimizer button, the window would pop-up to do junction optimization. A list of the objectives, including minimize overall delay, maximum overall throughput, or any other user predefined objective function, can be chosen from the drop-down menu on the window. The GA generation size and population size can be specified through the slider. To be note, the number of available lanes and traffic flow data are specified in the Sugar junction editor as shown in Figure 4. The data and the existing signal timing plan (if available) would be automatically loaded and shown in the results window. GA model would process at the background once users clicking the start button. The best fitness of each generation would be shown dynamically in the "Fitness Graph". Once the optimization procedure finishes, the optimal lane pattern and signal timing plan would be presented. It is easy for user to comparing the optima with the existing design. At the right bottom, a set of the best optimization plans are also provided for users to compare and select. Users can also load the optimization history from other nodes in the network.

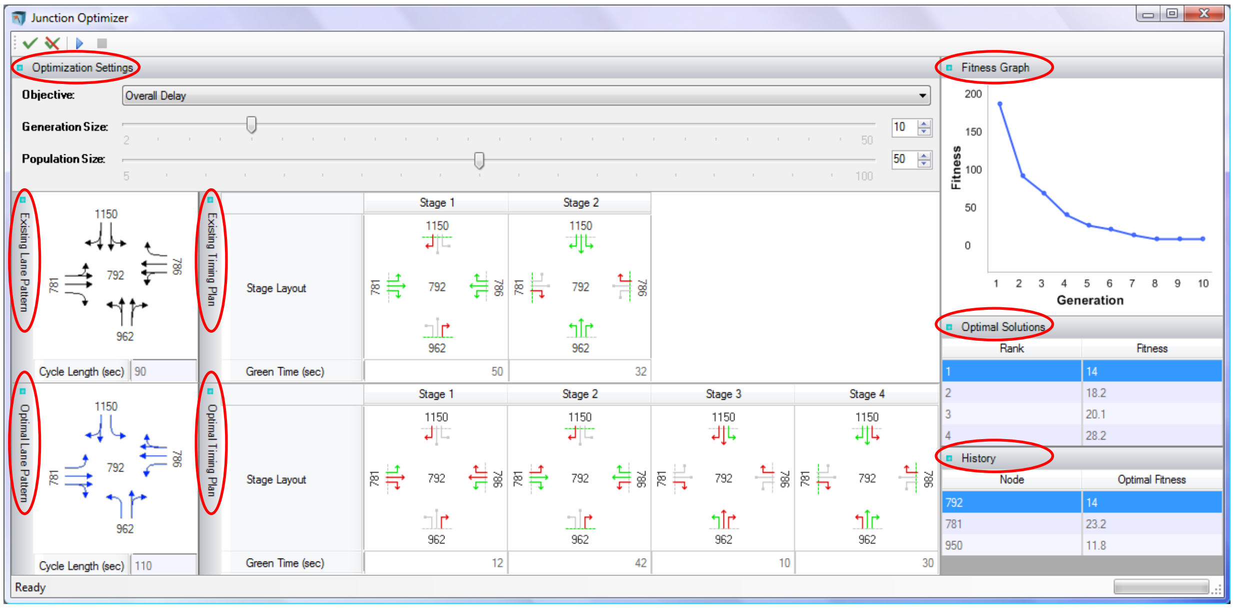

Figure 5. Screenshot of a Sample Sugar Optimizer Results Window

Sugar junction optimizer is the only software tool available for integration designs of signal timing plan and lane allocation pattern at signalized junctions. One of the most important advantages of the Sugar optimizer is its flexibility. The chromosome size is changeable according to different users' requirements. As discussed above, it implements an integrated optimization model for both lane allocation and signal timing. However, for those users only want to optimize signal timing plans at a fixed-lane-markings intersection, the lane pattern chromosome could be simply cutoff. The process of the GA model is still the same. Similarly, if users want to fix the cycle time, the corresponding part of the genes can be cutoff as well. If users want to optimize additional variables, such as offset, it only needs to add a set of binary digits that represents the corresponding additional decision variables, and the GA model is still processed in the same way.

CONCLUSION

This paper proposed an integrated signal timing plan and lane allocation pattern optimization model. The GA-based model has been implemented in the Sugar ArcGIS extensions that released by Citilabs, named as Sugar junction optimizer. Sugar junction optimizer can generate a fully optimized junction design based on traffic flows and junction geometric properties. The design provides optimized signal variables including cycle length, phase durations, phase sequence, and permitted movements, as well as optimized lane allocation variables including lanes for each movement and shared properties between the movements. The optimizer provides high flexibility to accommodate different user needs. For example, users could choose to only optimize signal timings and ignore the lane markings. The objective could be delay, LOS, stops, throughput or any other user-defined measures.

Future research includes comparing the results from Sugar junction optimizer and other commercial transportation software, such as Synachro and Transyt-7F. More validation works need to be done with more networks in reality. Moreover, the developers also have plans to enhance the functionalities of the Sugar junction optimizer, including the optimization of junction control type and the optimization of signal coordination parameters along the network.

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