AN INTEGRATED OPTIMIZATION MODEL FOR SIGNAL TIMING PLAN AND LANE ALLOCATION DESIGN

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ABSTRACT

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 design of signal timing plan and lane allocation pattern should be complementary to each other; however, existing research works have been concentrated on signal optimization, and few of them considered the impact of lane allocation pattern. This paper proposed an optimization model for the integration design of signal timing plan and lane allocation pattern at signalized intersections. A Genetic Algorithms (GA) model is developed and validated with the Cube transportation software suites. A fully optimized intersection design, including cycle length, phase durations, phase sequence, permitted movements, lane allocations, and shared movements, can be generated according to the assigned traffic flows and geometric properties at the intersection. A set of constrains are set up to guarantee feasibility of the optimal signal timing plan and lane allocation pattern design.

Keywords: Signal Optimization, Lane Pattern Optimization, Genetic Algorithm

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.

Signal optimization is considered as one of the most cost-effective methods to solve existing problems within signalized intersection networks and improve traffic signal operations (Park & Yun, 2006). There have been considerable amount of relevant research studies reported. A good number of research papers have been published that provide procedures for both online and offline methods for offset tuning (Kell & Fullerton, 1991; Yin et al., 2006; Gettman et al., 2007). Meanwhile, some interesting work has been conducted for utilizing travel time or delay information to optimize the signal settings (Massart et al. 1995; Liu et al. 2002). Recently, some research has begun to focus on developing analytical models for signal optimization. For example, Wey and Jayakrishnan (Wey & Jayakrishnan, 1999; Wey, 2000; Wey & Jayakrishnan, 2004) formulated the network signal optimization problem as a mixed–integer linear problem, and the cell transmission model (CTM) is also utilized by Lo (Lo 1999; Lo et al., 2001). There is also extensive research on combining signal optimization problems with traffic assignment problems, which tend to usually be limited to static models with user equilibrium (UE) assignment (Allsop, 1974; Smith, 1981a; Smith, 1981b; Meneguzzer, 1997). A variety of heuristic algorithms that utilized Genetic Algorithm (GA) are also proposed (Foy et al., 1992; Hadi & Wallace, 1993; Park et al., 2001; Park & Schneeberger, 2003).

With improvements in computation technology, a variety of computer based signal timing optimization software became widely used, including MAXBAND (Little et al., 1981) SYNCHRO (Husch & Albeck, 2004), TRANSYT-7F (Hale, 2005), and PASSERTM V-03 (Texas Transportation Institute, 2002). These tools provide off-line optimization capabilities for estimation of timing parameters, such as cycle, offsets, splits and bandwidth, based on specified performance objectives, such as intersection delays and numbers of stops. Additionally online adaptive signal optimization systems have also been developed and implemented over the past years, which provide the highest level of sophistication and constitute the major thrust in

research on signalized intersection control. Most notable of these systems include SCOOT (Hunt et al. 1982) and SCATS (Lowrie, 1982), TRAC (Lees, 1989), UTOPIA (Mauro & DiTarano, 1990), PRODYN (Henry & Farges, 1989), OPAC (Gartner, 1990), and RHODES (Mirchandani & Head, 2001). In 2002, the FHWA initiated the ACS-Lite program to provide a low cost adaptive traffic signal optimization solution framework for real time traffic conditions (Federal Highway Administration, 2002).

Comparing with the plenty of studies on signal optimization, previous research works on lane allocation are quite limited. All the models discussed above assume that the lane markings at signalized intersection are fixed and thus overlook the importance of lane allocation. The traditional approach to design lane allocation pattern is still on a trial and error basis (Wong and Wong, 2003). A set of the initial lane markings is first assumed based on engineer's judgment, and then the signal timing plan is determined using offline signal optimization tools, such as SYNCHRO. The lane markings are then fine-tuned according to the engineer's experience. The procedure is repeated several times until the performance of the operation is acceptable. The efficiency of the final lane allocation pattern highly depends on the experiences of the traffic engineer, which cannot guarantee to produce an optimal set of lane markings. Moreover, experienced traffic engineers are scare in many regions, especially in developing countries. However, the need for designing new signalized intersections and experienced engineers is high in the undeveloped regions and countries.

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. For example, consider the lane markings of an approach to a signalized intersection as shown in Figure 1. The three-lane approach has one exclusive lane for through traffic, one exclusive lane for left-turning traffic, and one shared lane for both movements. With such lane pattern, the through traffic and left-turning traffic must be assigned to move during the same signal phases; otherwise, the middle-lane through traffic would be blocked by the left-turning traffic on the same lane, and vice verse. Due to the same reason, a permitted left-turn phasing is also not suitable for the approach. Therefore, the only possible signal timing plan for the approach is directional separation phasing, i.e., the traffic of the approach moves with all opposing traffic stopped. Moreover, it also determines the signal timing plan for the opposing approach should be the directional separation phasing as well, no matter the lane allocation pattern of the opposing approach. Traffic engineers have to give up the chances of implementing other timing plans, such as lagging / leading left-turn phasing, to improve the service level.
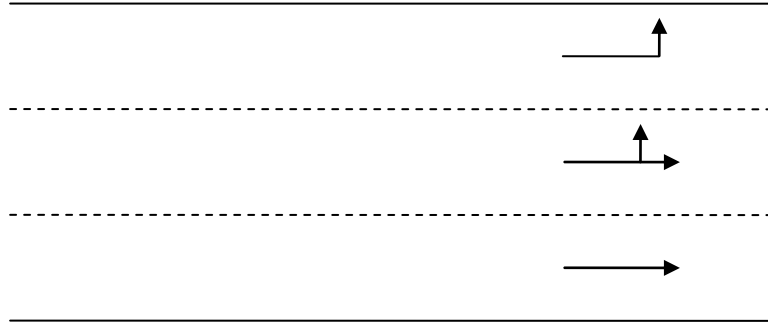
Figure 1. An Example Three-lane Approach to a Signalized Intersection.

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 very 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. Use the lane configuration in Figure 1 as the example, the middle lane is considered as a de facto left-turn lane when excessive delays and queues discourage through vehicle drivers from using the lane. It is usually difficult to identify such de facto left-turn lane until the proportion of left turns in the shared lane can be computed (Transportation Research Board, 2000). 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.

Although studies on an integrated design of signal timing and lane pattern are rare in practice, there have been a few research works addressed. As one of the earliest relevant attempts, Lam et al. (1997) found that the integrated design of lane allocation pattern and signal timing plan can increase the capacity and significantly minimize the overall delay, stop and fuel consumption at a signalized intersections. The authors proposed a mixed-integer linear programming model to minimize the sum of flow ratio of all phases. All possible sets of movement patterns at an approach were enumerated based on intersection geometry. The model is solved by a heuristic solution procedure consisting of three optimization steps on the basis of vehicular flows, pedestrian flows and phase sequences. One of the drawbacks of the model is that the minimization of flow ratio may not lead to an optimal solution for other objectives, such as delay or number of stops. The separate consideration of traffic movements and phase sequence may also produce sub-optimal results. In 2003, Wong and Wong developed a lane-based signal optimization model which aimed to maximize intersection capacity and minimize cycle length. The model is formulated as Binary-Mix-Integer-Linear-Programs and solved by standard branch-and-bound routine. Similar as Lam's model, the bi-objective model is limited to its fixed objectives and thus lack of flexibility. Moreover, it may also not lead to global optima.

In this paper, an optimization model for an 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 GA model is presented following in next section.

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 2 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. The signal timing design should give green, yellow and all-red durations for each phase, the phase sequence, and permit properties of the left-turning movements. 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 is thus considered in this research to solve the problem. (Goldberg 1989, Michalewicz 1996).

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.
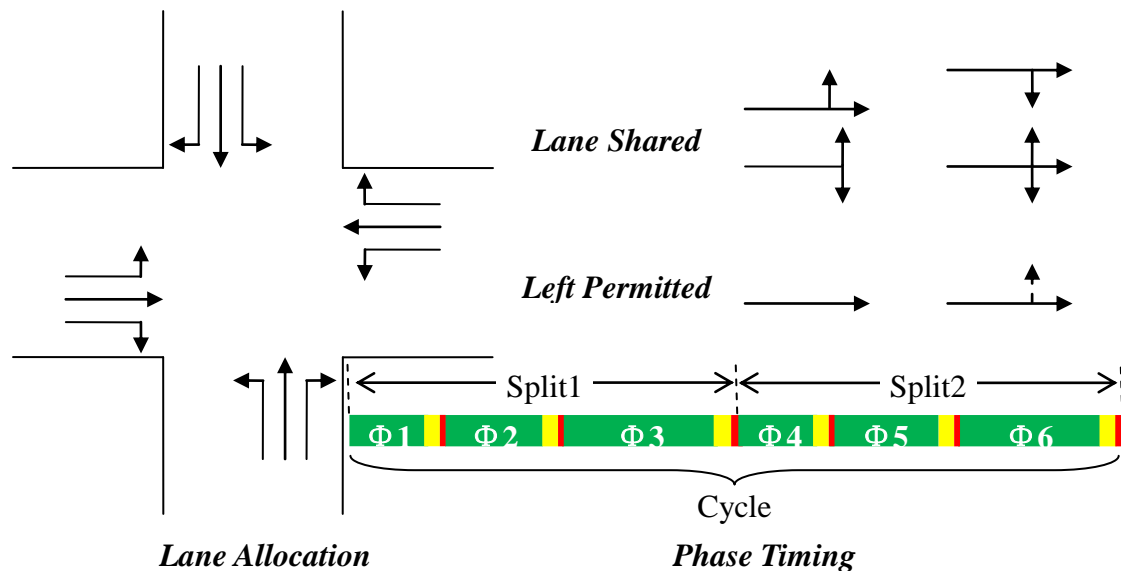

Figure 2. Decision Variables at Isolated Intersection.

As shown in Figure 3, 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. Some other factors, such as minimum green, durations of yellow and all-red should also be considered in the calculation. 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. For a right-hand-drive intersection, Figure 3 lists the 8 cases of the combination of the through and left-turning movements at each pair of opposing approaches (i.e., each split). It can be enumerated and presented by a set of 3 binary digits.
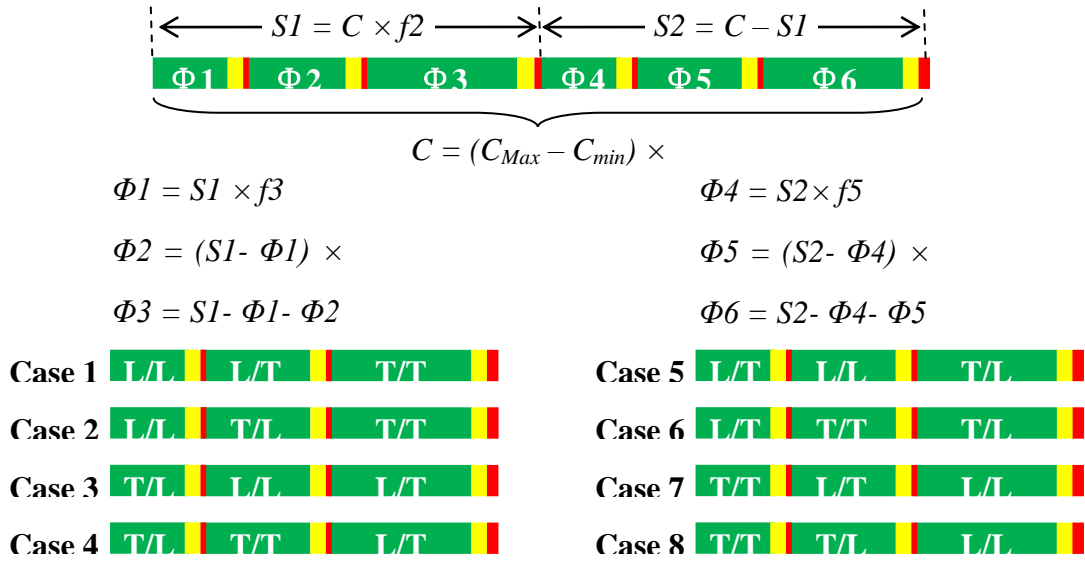
$$S1 = C \times f2 \qquad S2 = C - S1$$

$$\Phi1 \quad \Phi2 \quad \Phi3 \quad \Phi4 \quad \Phi5 \quad \Phi6$$

$$C = (C_{Max} - C_{min}) \times$$

$$\Phi1 = S1 \times f3 \qquad\qquad \Phi4 = S2 \times f5$$

$$\Phi2 = (S1 - \Phi1) \times \qquad\qquad \Phi5 = (S2 - \Phi4) \times$$

$$\Phi3 = S1 - \Phi1 - \Phi2 \qquad\qquad \Phi6 = S2 - \Phi4 - \Phi5$$

Case 1 L/L L/T T/T   Case 5 L/T L/L T/L

Case 2 L/L T/L T/T   Case 6 L/T T/T T/L

Case 3 T/L L/L L/T   Case 7 T/T L/T L/L

Case 4 T/L T/T L/T   Case 8 T/T T/L L/L

Figure 3. 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 4, 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.
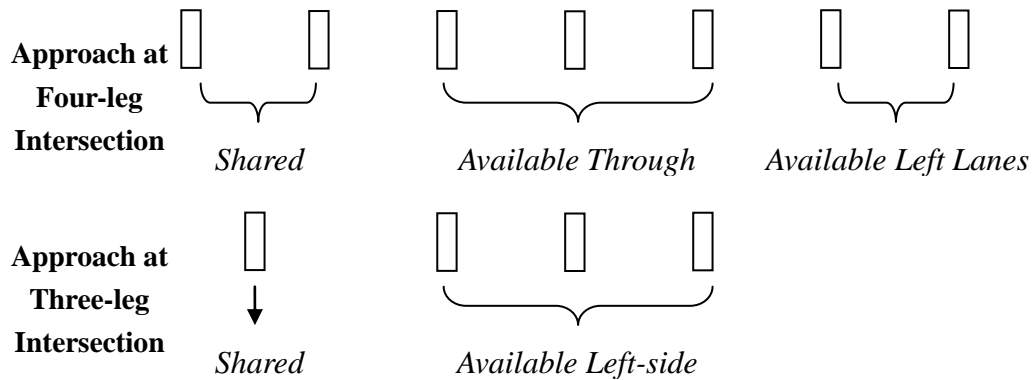

Figure 4. Binary Encoding Schema at an Approach

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 4, 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 5 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.
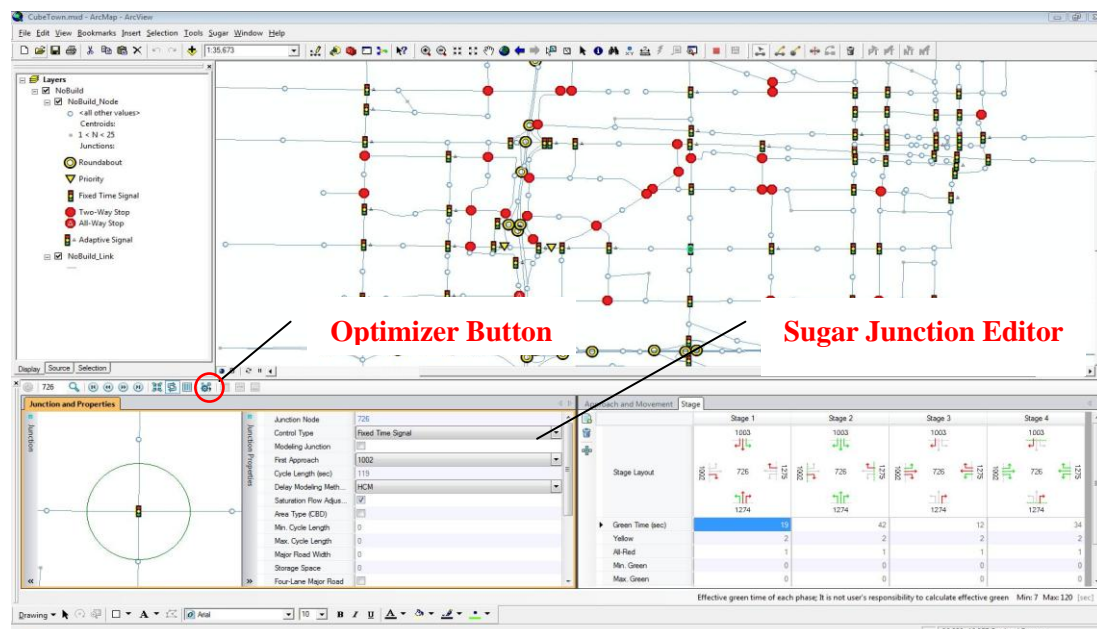

Figure 5. Screenshot of the Sugar AcrGIS Modeling Extensions

Figure 6 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 5. 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.

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.
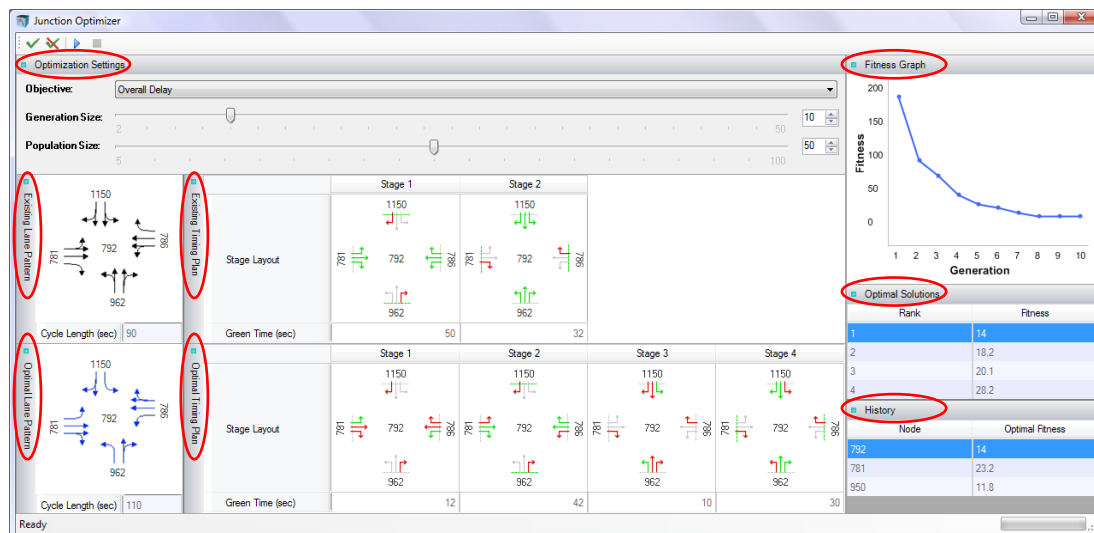

Figure 6. Screenshot of a Sample Sugar Optimizer Results Window

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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