Automatic Design of Optimal Actuated Traffic Signal Control with Transit Signal Priority

Mahmud Keblawi[1], **Tomer Toledo**[1]
[1] Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, Haifa, Israel

Abstract

In traffic networks, appropriately determining the traffic signal plan of each intersection is a necessary condition for a reasonable level of service. This paper presents the development of a new system for automatically designing optimal actuated traffic signal plans with transit signal priority. It uses an optimization algorithm combined with a mesoscopic traffic simulation model to design and evaluate optimal traffic signal plans for each intersection in the traffic network, therefore reducing the need for human intervention in the design process. The proposed method can simultaneously determine the optimal logical structure, priority strategies, timing parameters, phase composition and sequence, and detector placements.

The integrated system was tested by a real-world isolated intersection in Haifa city. The results demonstrated that this approach has the potential to efficiently design signal plans without human intervention, which can minimize time, cost, and design effort. It can also help uncover problems in the design that may otherwise not be detected.

Keywords: traffic control, transit signal priority, optimization, automatic design, traffic simulations

1 Introduction

Traffic signal control is considered among the most cost-efficient tool used to improve the accessibility, mobility, and performance of the system by effectively allocating the capacities and managing the different movements [Par06]. Due to this, the proper design of traffic signal timing plans is crucial to relieve congestion [Par00]. Furthermore, improving mobility in urban areas can also be done by treating the high-occupancy vehicles, such as buses, differently from low-occupancy vehicles [Chr11]. In particular at bottlenecks, such as signalized intersections, since they are the primary sources of delays [Hel11]. Ideally, this can be achieved by granting priority to transit vehicles at signalized intersections. Most of the previous studies [Par03; Ste07; Yan08; Hu12] that aimed to improve the actuated signal control performance are focused on optimizing the four basic parameters of the signal control (cycle length, phase sequence, green splits, and offsets). A limited number of studies [Par06; Li10; Lee09] have investigated the benefits of incorporating additional parameters into the optimization process, such as minimum gap time, vehicle extensions, and detector placements. However, these studies considered simple control systems that did not include complex functions such as Transit Signal Priority (TSP). Studies that handled actuated signal control with TSP [Ste08; Ste11; Bal15; Tol20] developed optimization systems to optimize the four basic parameters alongside the TSP parameters, such as green extension and early green times of transit movements. While the other components of the signal control, such as phases, detector placements, logical structure, and transit priority strategies, are generated manually by experienced traffic engineers according to general design guidelines, making the design process inefficient, complicated, and time-consuming. Therefore, to address these issues, this study introduces an automatic design system that can automatically set all design settings for actuated traffic signal control with TSP functions.

2 Methodology

The overall structure of the automatic design system of traffic signal control plans is shown in Figure 1. The general inputs of the automatic design system are the intersection geometric layout, information on traffic demands for all road users (passenger cars, transit vehicles, and pedestrians), and optional design constraints defined by the user such as maximum cycle length, default phases minimum green time, maximum allowed queue lengths or waiting times. The system output is the optimal traffic signal plan produced based on the optimization algorithm results. The integrated system comprises two main components: a simulation model, which is used to evaluate candidate traffic signal plans, and an optimization algorithm, which generates new plans as the process of finding the best one proceeds.

The simulation model incorporates both simulations of the individual road user movements, including non-transit vehicles, transit vehicles, and pedestrians, through and between the intersections, and simulations of the traffic control system. The simulation model uses the intersection's geometric layout and information on traffic demands as inputs. In each time step within the dynamic simulation stage, the traffic flow model receives information from the control system about the traffic light states and releases vehicles from the relevant queues. The model updates detector states accordingly, which are transferred and used by the simulated control system. The traffic flow model also calculates performance measures such as queue length, average person delay, and number of stops. The control system receives detector states from the traffic flow model, executes the control logic and determines the traffic signal indications for the next time step. These indications are transferred back and applied in the traffic flow model.

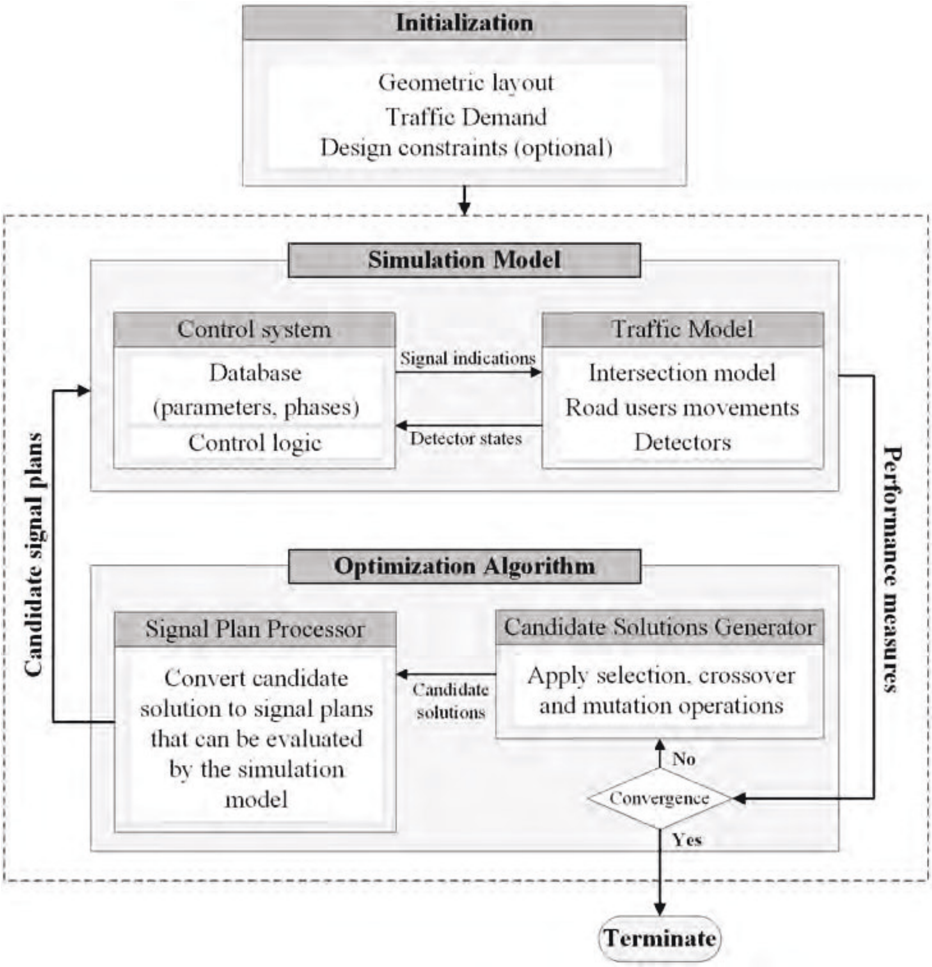

Figure 1: The overall structure of the automatic design system.

The optimization algorithm runs replications of the simulation, and with different traffic signal plans. It calculates the objective function value from the simulation results, generates new candidate solutions, post-processes this solution in order to generate applicable traffic signal plans, and sets these plans as inputs to the simulation model for the next simulation run. Optimization of the integrated system was carried out with the Grammatical Evolution (GE) algorithm [ONe03]. It is considered one of the most widely applied grammar-based approaches [McK10]. GE has successfully been applied to search for various complex structures (e.g. control systems, electrical circuits, and artificial neural networks) during the past years, producing human-competitive results. To the best of our knowledge, GE was never used in the field of traffic signal control.

The decision variables in this optimization problem include the parameters of the control plan (phase composition and sequence, green times, transit priority rules) and system layout parameters (detector placements including extension detectors, demand detectors, and pedestrians pushbuttons). Note that in this application, optimization did not consider the implementation and maintenance costs of the detection devices.

The number of decision variables may vary depending on the intersection layout and control plan. Therefore, the candidate solutions suggested by the optimization algorithm at each iteration are length-varying. The integrated system may consider all decision variables or a subset of them, determined by the user (e.g. optimizing the phase sequence or green splits for an existing design).

3 Case Study Intersection

Figure 2: Case study intersection.

The proposed design system has been demonstrated with a single intersection in Haifa, shown schematically in Figure 2. At this intersection, there are four free right-turn vehicle movements and eight signalized vehicle movements: Two bus rapid transit (BRT) movements (7, 8) pass through dedicated lanes and six non-transit vehicle movements (1 through 6). In addition, there are eight signalized pedestrian crosswalks (a through h). In the current design, the intersection operates by actuated traffic signal plan, with presence detectors on all non-transit movements employed for demand (D2, D5) and extension (E1, E2, E3, E4, E5, E6) tasks. The demand detectors are located at the stop line, while the extension detectors are 6 to 24 meters upstream of the intersection. In addition, three presence detectors are placed in each BRT lane. Two are located upstream between 150 and 600 meters to detect approaching BRT vehicles and predict their arrival times. The third is located downstream of the intersection and used for priority cancellation after the BRT vehicle passes the intersection stop line.

The design traffic flows, presented in Table 1, were estimated from traffic counts for the morning peak hour (7 am to 8 am). In addition, 24 BRT vehicles per hour arrive in each direction, and occupancies of 50 and 1.2 passengers were assumed on BRT vehicles and

Table 1: Traffic flows at the case study intersection.

Movement	Traffic flow [vph]
1	494
2	231
3	286
4	1244
5	215
6	695

private cars, respectively. The pedestrian flow was estimated using CCTV (Closed-circuit television) camera data. They were set at 25 pedestrians per hour, crossing from each side of the intersection to every other side.

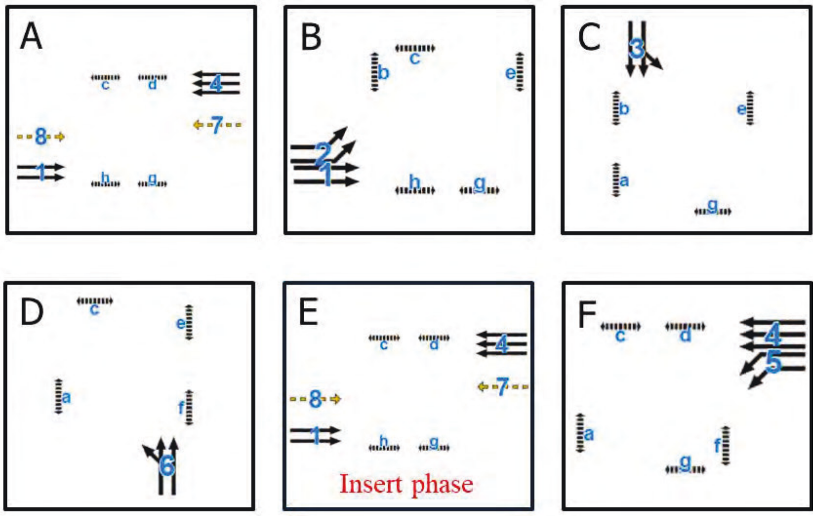

Figure 3: Control phases at case study intersection.

The movements in the intersection are organized in six signal phases (phases A through F), as shown in Figure 3. Phases A, B, C, D, and F are basic phases that compose the normal phase sequence, while phase E is an insert phase devoted exclusively to the BRT signal priority tasks. Furthermore, priority can be granted by extending phase A or starting it earlier depending on the time within the cycle that the transit vehicle is expected to arrive at the intersection stop line and the currently active phase. Implementing the three priority strategies, phase insertion, phase extension, and an early start, may result in early termination of the other intersection phases to prevent exceeding the maximum cycle length. Therefore, the current control design includes a compensation mechanism that dictates that non-transit movements receive a certain minimum cumulative green time over several cycles to avoid over prioritizing the BRT vehicles and reduce the negative impacts on the other intersection movements.

4 Results and Discussion

The automatic design system was employed to generate a new signal control plan for the case study intersection. In this paper, the expected value of the average person delay was served as an objective function, following several studies that proposed it in this context [Ste11; Tol20]. In the design process, the objective function value at each point has been estimated based on ten parallel simulation replications. Next, a comparison was conducted between the automatically designed plan, base design (current design), and optimized base design (the base design after optimizing its timing parameters, i.e. cycle length and minimum and maximum green time of each phase). Phases, detectors, and control logic in the optimized base design remain unchanged from those in the base design. The purpose of this comparison is to evaluate the proposed system's ability to provide optimal control designs automatically. Moreover, examine the benefits of optimizing all signal control components against optimizing only the timing parameters. The three control plans (Automatic design, base design, and optimized base design) were evaluated with twenty simulation replications by the microscopic simulation model Aimsun.

Table 2 presents the average delay of various road users with the three control designs. Compared to the base design, the optimized base and the automatic designs reduced the average person delay by 22 % and 25 %, respectively. Reduced delays are due to a reduction in non-transit vehicles and pedestrian delays. Note that this reduction occurred with a slight increase in BRT delays with automatic design. Nevertheless, the delays of the BRT vehicles increased dramatically by over 50 % with the optimized base design. These results demonstrate the benefits of simultaneously optimizing all signal control components beyond the timing parameters like cycle length and green splits. The average person delay has been reduced by an additional 4 %, compared to the optimized base to the automatic design.

Table 2: Comparison between delays with three different designs.

	Average road users delay [s]				Change [%]			
Designs	**All**	**BRT**	**Other vehicles**	**Pedestrians**	**All**	**BRT**	**Other vehicles**	**Pedestrians**
Base design	39.77	19.75	45.24	26.96	-	-	-	-
Optimized base	31.12	30.2	31.71	22.04	-22	+53	-30	-18
Automatic design	29.8	20.72	32.61	15.43	-25	+5	-28	-43

Table 3 presents the average delay of each vehicle movement at the intersection with the three designs. In the optimized base and the automatic designs, delay times for movements 2, 3, 5, and 6 significantly decreased at the expense of transit movements 7 and 8 alongside movements 1 and 4 that served in the same phases. The improvement is primarily due to an increase in minimum green times allocated to the non-transit movements (2, 3, 5, and 6), reducing the adverse effects of priority actions. Knowing that priority actions might shorten the maximum green times of non-transit movements but they cannot change their minimum green times. In the optimized base design, the maximum cycle length dropped from 130 to

110 seconds, compared to the base design, while it remained approximately the same in the automatic design (129 seconds). Consequently, in the optimized base design, priority actions for transit vehicles have been limited, particularly when multiple requests are received in one cycle, to avoid exceeding the maximum cycle time. Accordingly, only 39 % of BRT vehicles have been prioritized by the optimized base design, compared with 62 % and 61 % by the base and automatic design, respectively.

Table 3: Comparison between vehicle movements delays with three different designs.

	Average person delay [s]			**Change [%]**	
Movement	**Base design**	**Optimized base**	**Automatic design**	**Optimized base**	**Automatic design**
1	26.42	29.18	30.99	+10	+17
2	79.07	51.78	53.33	-35	-33
3	122.14	68.3	56.47	-44	-54
4	28.44	31.34	38.39	+10	+35
5	69.67	56.33	57.37	-19	-18
6	84.92	47.5	42.67	-44	-50
7	20.37	30.01	21.21	+47	+4
8	19.13	30.39	20.22	+59	+6

5 Conclusions

This paper presented the structure and application of an automatic design system for actuated traffic signal control with TSP. The system incorporates a mesoscopic simulation model and an optimization algorithm based on GE. it can automatically generate signal control designs by simultaneously setting the optimal control components, including phases, timing parameters, detector placements, and logical structure. It has been tested with a case study of an isolated intersection. The results showed potential for substantial improvement in the average delay. In addition, the control designs generated by the proposed system have the potential to successfully replace experienced traffic engineers' designs with less time, effort, and cost. Moreover, the results demonstrate that optimizing all design components can be more beneficial than focusing only on timing parameters.

Acknowledgments

This research was partially funded by a grant from the Israeli Smart Transportation Research Center.

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Corresponding author: Mahmud Keblawi, Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, Haifa, Israel, e-mail: mahmudkeblawi@gmail.com