Automatic design of optimal actuated traffic signal plan

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INTRODUCTION

Efficient design of traffic signal systems can help improve accessibility and mobility [1]. Traffic signal plans consists of two components. The first is the control logic which contain set of rules to determine the light states. The second is the set of parameters associated with this topic such as, minimum and maximum green times, cycle length and offsets. Most previous works (e.g., [1]- [10]), aimed to improve the traffic signal performance by optimizing the plan parameters, without changing the control logic, which is often generated manually according to general guidelines.

Only limited works has been dedicated to the automation of the generation of traffic signal plans (e.g., [11]- [13]). These works focused on simple pre-timed traffic signal plans, that do not contain complex procedures such as, transit priority or compensation functions. Furthermore, these methods try to mimic the experts design and not to generate optimal signal plans.

Some recent studies (e.g., [14]- [18]) developed automatic programs for designing adaptive traffic signal plans. Several AI technologies have been utilized, such as, self-organized systems, auction, neural network, and Genetic Programing (GP). However, these programs are only able to handle adaptive traffic signal plans for simple intersections and determine the green time allocation among the phases in real time. In best case scenarios, they were able to determine the phase sequence in addition to the green time allocation. Additional traffic signal plan settings such as phase structure or detectors placement were not considered.

In this paper, we present a method to automatically design a control plan, including both its logical structure and parameters. This method demonstrated with an application of a real-world intersection controlled by actuated traffic signal. A mesoscopic traffic simulation is used to evaluate the performance of the signal plan. The proposed system aims to set the optimal phase structure, detector location, control logic, and the timing parameters simultaneously. The rest of the paper is organized as follows: The next section introduces the automatic control plan design framework and its components. The following section presents the case study. The results of the case study and their discussion are presented next. Finally, conclusions are provided.

METHODOLOGY

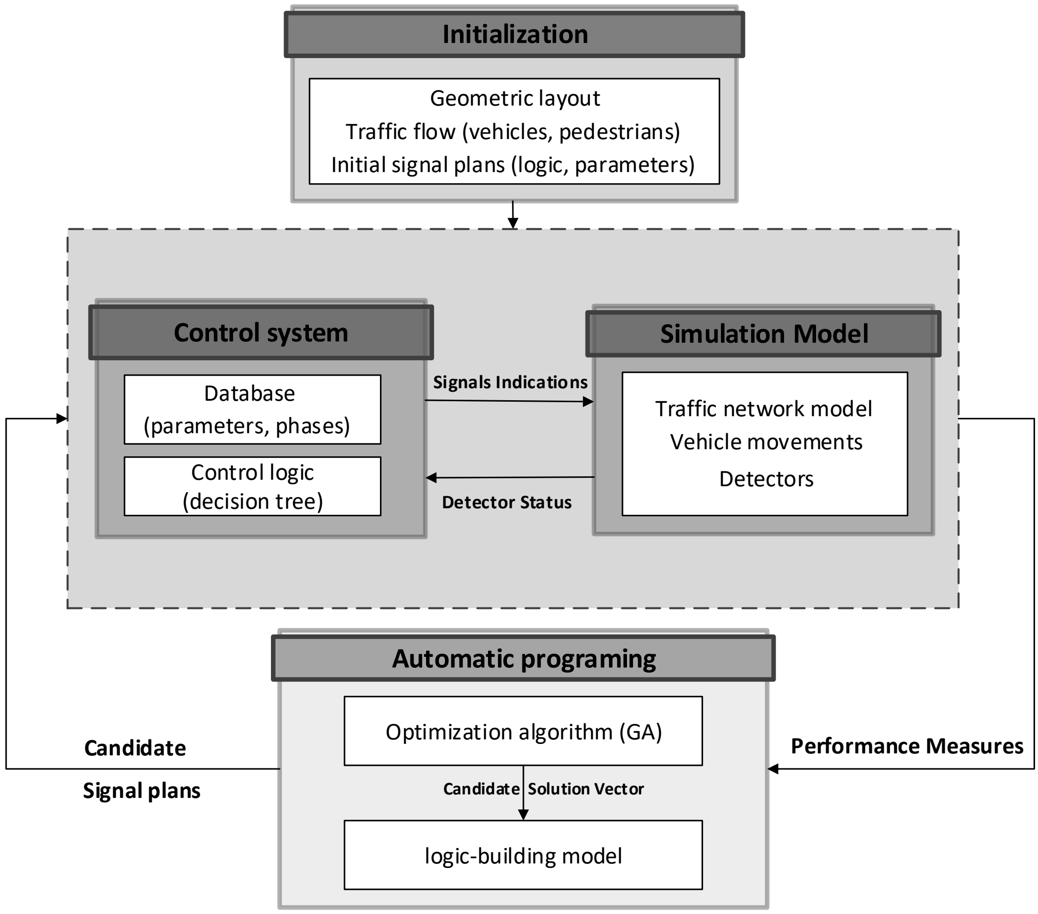

Figure 1: The overall structure of the automatic design system.

The automatic design system, which is described in Figure 1, consists of three components: (1) a traffic simulation model, (2) an intersection control system, and (3) an automatic programming module. The traffic simulation model is used to evaluate the specific control plan.

The simulation model uses the intersection layout geometry as an input and updates the detectors' states according to the traffic flow in the intersection. In each time step, the simulation model gets information from the control system about the traffic light states. When the light is green, the vehicles are released from the queues according to the First-In-First-Out (FIFO) rule and at a rate based on the approach saturation flow. The simulation model outputs performance measures such as queue length, average person delay, number of stops, etc. The control system executes and determines the traffic signal indications every time step according to the detectors states.

After the completion of the simulation runs, the automatic programming module gets as an input the performance measures of the traffic signal plan that calculated by the simulation model. It generates a new set of traffic signal. These plans are sent to control system for the next simulation runs. This process continues until the system converges to the optimal signal plan.

Automatic programing model

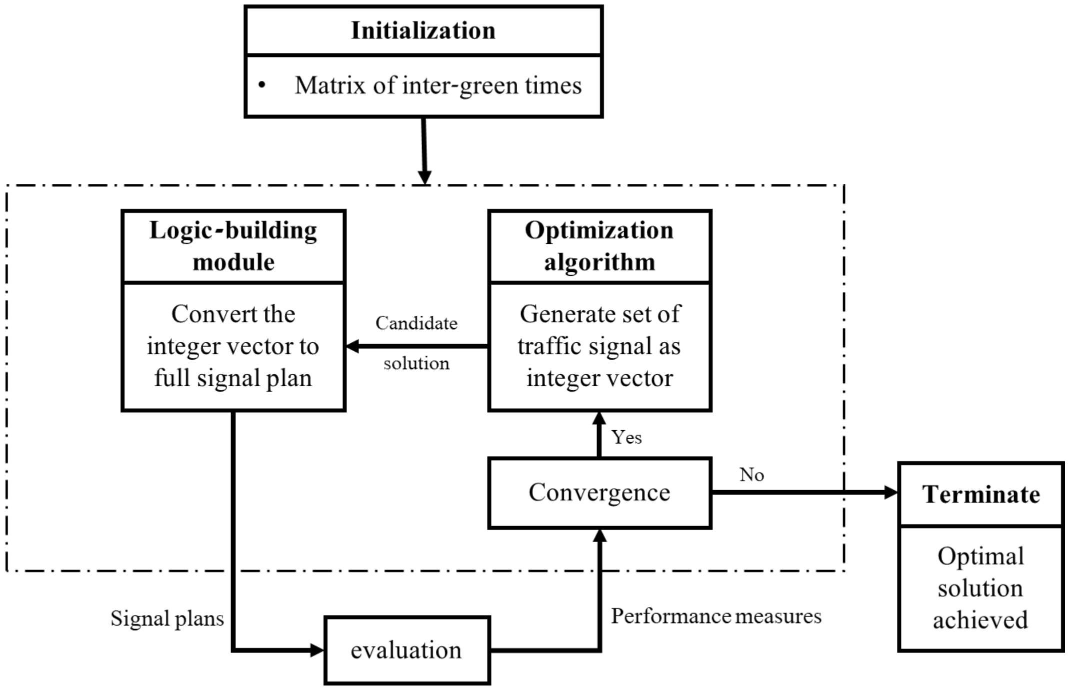

Figure 2: The automatic programing module optimization flow chart

The automatic programming module as shown in Figure 2 includes two parts: (1) an optimization algorithm that searches for an optimal vector of the signal plan (Figure 3). (2) A logic-building module, which converts the integer vector obtained from the optimization algorithm to a full traffic signal plan.

A Genetic Algorithm (GA) [19] was implemented for the optimization reported in this work. This algorithm has been shown effective in the context of signal plan optimization (e.g., [1] and [8]). All phase structure, control logic and plan parameters were optimized jointly.

Initially the input date is pre-processed by the automatic programming module, in which all possible phases are produced using the matrix of inter-green times (minimal time required between two consecutive movements) and save them as a list in the logic-building module. The possible phases consist of all possible combination of the vehicle movements, and pedestrian crosswalks that can use the intersection safely at the same time. After that the automatic programming module initializes the GA parameters such as population size, initial population and generation size, depending on the number of the signalized movements and crosswalks in the intersection.

Later, during the optimization process, in each iteration the optimization algorithm generates a set of traffic signal plans as an integer vector (candidate solutions) and feed these vectors to the logic-building module in order to convert them to a full traffic signal plans (phases, control logic, and plan parameters), that can be saved in the intersection control system and evaluated after that by the simulation model.

$$\underbrace{x_1 \ldots\ldots x_P}_{1} \,|\, \underbrace{x_{P+1} \ldots\ldots x_{2P}}_{2} \,|\, \underbrace{x_{2P+1} \ldots\ldots x_{3P}}_{3} \,|\, \underbrace{x_{3P+1} \ldots\ldots x_{3P+M}}_{4} \,|\, \underbrace{x_{3P+M+1} \ldots\ldots x_{3P+2M}}_{5} \,|\, \underbrace{x_{3P+2M+1} \ldots\ldots x_{3P+3M}}_{6} \,|\, \underbrace{x_{3P+3M+1} \ldots\ldots x_{3P+3M+2N}}_{7} \,|$$

Figure 3: The candidate solution, generated by GA.

Every candidate solution (integer vector) consists of seven groups, as shown in Figure 3. Where P is the number of all possible phases. M is the number of the signalized vehicle movement in the intersection. N is the number of signalized crosswalks in the intersection.

The first group of variable are integers that indicates possible phase sequences. In order to select the phases that will take part in the new design, the logic-building module uses two rules: (1) the selected phases of the new design must include all intersection movements, while (2) each vehicle movement can be found in a maximum number of phases (in this work, the maximum number was set to 2). The second and the third groups are integer variables that indicate the minimum and maximum green time of each possible phase, where the fourth and the fifth group of variables are binary, that indicate if there is a demand or extension detectors in the approach of each intersection movement. The sixth group are float variables that determine the distance of each extension detector from the related stop line, and finally the last group indicates if there is a pedestrian push button in every pedestrian crosswalk edge.

CASE STUDY

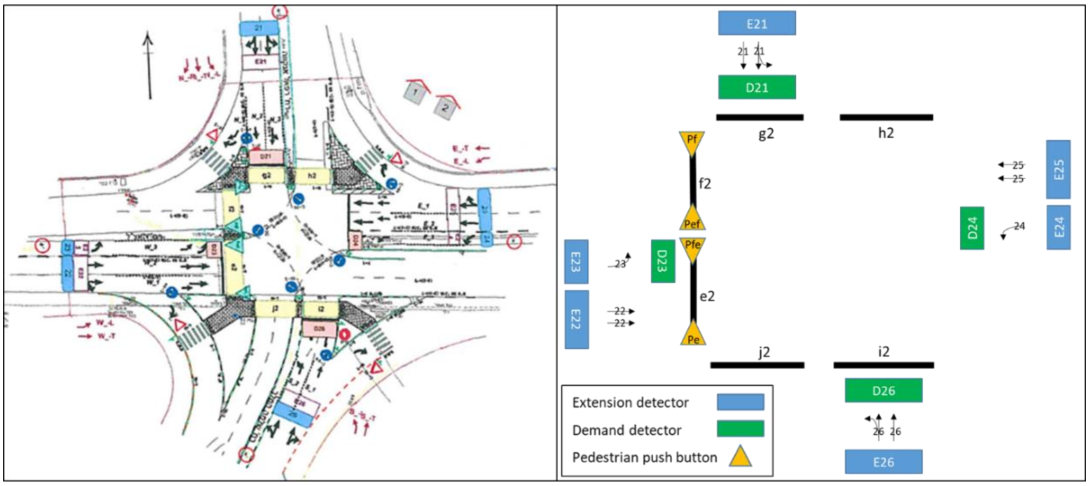

Figure 4. Schematic structure of the tested intersection

The proposed automatic design system was tested with a real-world intersection. The intersection is the crossroads of Etsel, Anakua, and Hameleck Shlomo streets, in Haifa, Israel. Figure 4 shows the schematic structure of the intersection. The intersection consists of ten vehicle movements: six signalize movements (movements 21 to 26) and four free right turn movements. In addition, the intersection contains six crosswalks (e2 to j2). In the existing traffic signal design, this intersection is part of coordinated intersections system, and it operates in fixed cycles by full actuated traffic signal plan. The two crosswalks that cross the main movements (f2, e2) are operated by four pedestrian push buttons. At the intersection there are four demand detectors (D21, D23, D24, D26) located behind the stop line of the secondary movements (21, 23, 24 and 26), in addition to six extension detectors (E21 - E26) located on all approaches.

Table 1. The demand matrix at morning peak hour (7:00-8:00) (veh/h).

Movement	**26**	**25**	**24**	**23**	**22**	**21**
Demand	412	940	120	230	585	412

The peak hour traffic flows in the system are presented in Table 1. These values were estimated from traffic count measurements. The largest demands are on the main arterial (movements 22 and 25).

The traffic simulation model had been calibrated and validated for this intersection in keblawi and Toledo (2018). This validation showed a root mean square error equal to 35 for the simulated hourly green times from the field observations for this intersection for the six movements.

RESULTS

The design performed using the proposed system was in two ways: (1) using a fixed cycle length; and (2) using a variable cycle length.

The optimization aims to minimize the delay in the simulation evaluation. four simulation repetitions were used, so that the variance resulting from the stochastic processes in the simulation model, such as the vehicle arrival rate to the intersection stop lines would be reduced. The optimization process included a total of 60 parameters related to phase selection, phase sequence, detectors placement, maximum and minimum green times,

To test the quality of the traffic signal plans obtained by the automatic design system, a comparison was made with the base plan before and after determining the optimal plan parameters. All base plan parameters were optimized jointly by a mesoscopic simulation model that have been used in keblawi and Toledo (2018), coupled with GA; the optimization process included a total of 28 parameters related to signal timings (minimum and maximum green time), meaning that the optimization process provided the optimal signal timing, without any change in the base control logic, phases structure, phase sequence, and detector location.

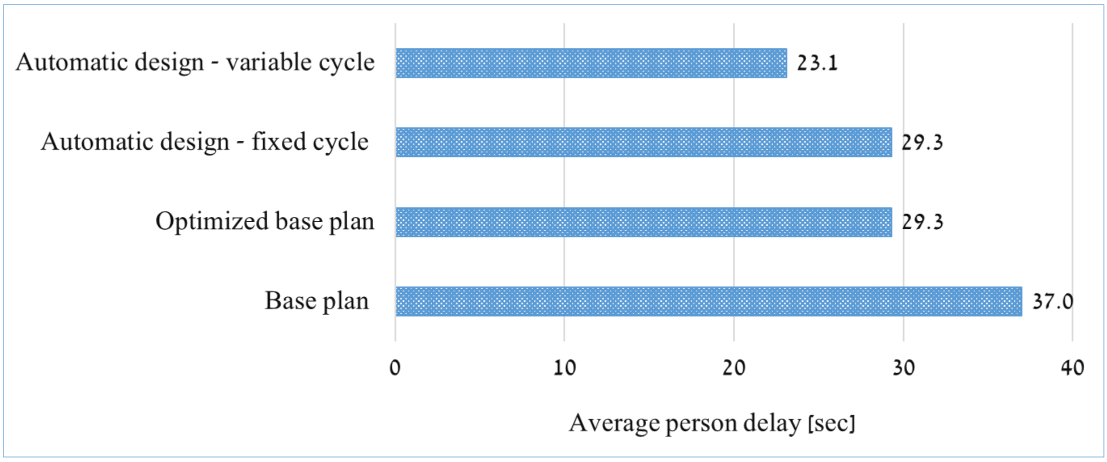

Figure 5. Average person delays in various signal plan strategies.

Figure 5 presents the average person delay in the intersection with the four plan strategies. These values show that after setting the optimal plan parameters, the average person delay in the intersection decreased by 20% compared to the base design. The traffic plan obtained by the automatic design system with fixed cycles was compatible with its performance to the base signal plans with optimal plan parameters. The signal plan obtained by the proposed method with variable cycles outperformed the other optimized fixed cycle plans by 21%

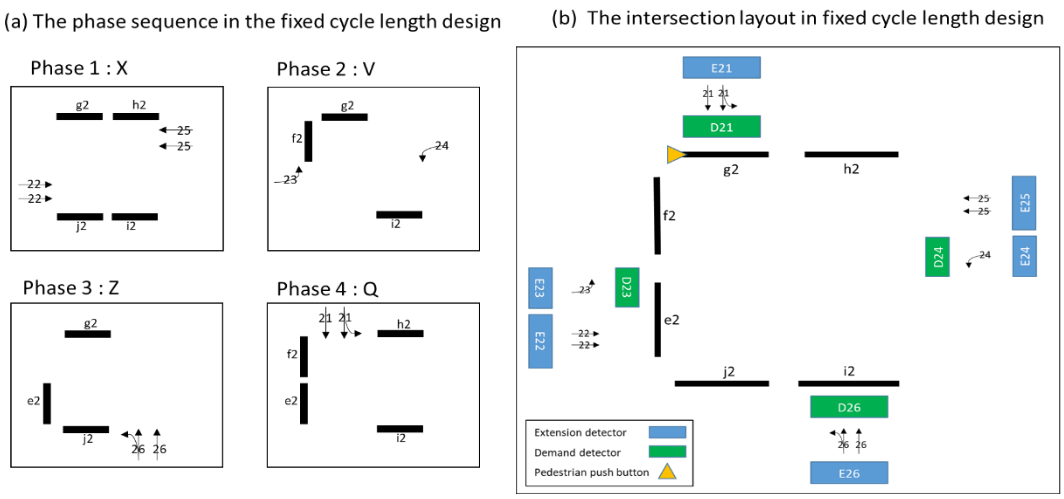

Figure 6. Phase sequence and schematic structure in the new signal design with fixed cycle length.

The generated signal plan with a fixed cycle length included four phases, as shown in Figure 6-a. The main phase (phase X) included the movements with the largest demands (movements 22 and 25 shown in Figure 6). This is to utilize effectively the green time that is left at the end of the cycle. The second phase (phase V) included the left turn movements in the major arterial (23 and 24). The last two phases included the secondary movements 21 and 26, respectively. In addition to the vehicle movements, each phase included the crosswalks that can simultaneously be used with the vehicle movements. Figure 6-b shows the new schematic structure of the intersection. The figure shows that four demand detectors were located in movements 21,23,24 and 26. Extension detectors were located in all vehicle movements (21-26). A pedestrian push button is located at crosswalk g2.

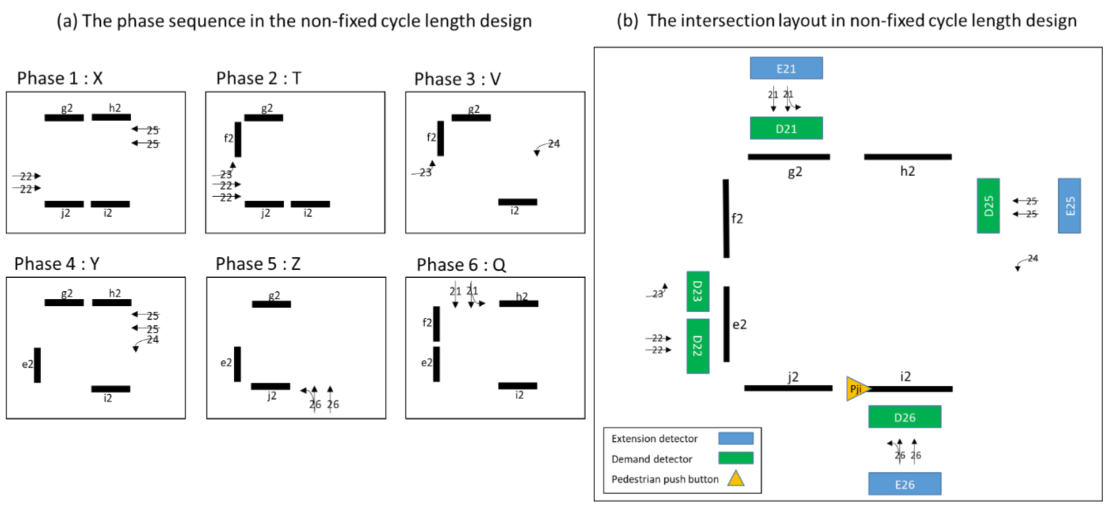

Figure 7. Phase sequence and schematic structure in the new signal design with variable cycle length.

The generated variable cycles signal plan includes six phases as shown in Figure 7-a. This traffic plan does not have a main phase because after the last phase it immediately passes to the next cycle. The six phases found in this traffic plan are a combination of the phases in the base plan and the new fixed cycle plan. As shown in Figure 7-b, in this design, five demand detectors were located in movements 21,22,23,25 and 26. Three extension detectors were located in the approach to the movements 21,25 and 26. A pedestrian push button is located at crosswalk i2. The detector configuration differs from that of the base design, as a result of the different phases and their sequence.

The most significant difference in the control parameters is that cycle time decreased from 120 seconds in the base design to 100 and 99 seconds in the base design with optimal plan parameters and new design with fixed cycles, respectively.

CONCLUSION

This paper introduces an automatic design system of actuated traffic signal plans. The proposed system uses Genetic Algorithms (GA) combined with mesoscopic traffic simulation model to design and evaluate optimal traffic signal plans. It takes into consideration not only the plan parameters but also the phases structure, detectors location and the control logic as well.

Based on the results presented in the previous section, it can be concluded, that the proposed approach has potential in designing the optimal traffic signal plan without human intervention. However, the automated design system developed so far can only handle simple intersections (for example, intersections that do not include lanes dedicated to public transportation vehicles), and the signal plans produced by this system does not include complex functions, such as transit priority functions, and green time compensation mechanism for part of the movements.

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