MESCOP

A Mesoscopic Traffic Simulation Model to Evaluate and Optimize Signal Control Plans

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The design of traffic signal control has a profound impact on the performance of urban traffic systems. The current traffic signal plans involve complex control logic and have many parameters that need to be set. However, little attention has been given to the evaluation of these plans. Simulation-based signal optimization has been limited, mainly as a result of the heavy computational burden associated with it. This paper reports on the overall structure and the various components of a mesoscopic model for traffic simulation to evaluate and optimize complex actuated traffic signal plans. The model is named MESCOP (mesoscopic evaluation of signal control plans). MESCOP is detailed enough to represent the characteristics of actuated traffic signal plans, including the intersection layout and the detectors. The stochastic processes of the arrival at the intersection and the movement within it are also modeled in detail. The model represents passenger cars, transit vehicles, and pedestrians. The use of MESCOP is demonstrated through its application to a signalized intersection in Haifa, Israel. This intersection is controlled by an actuated traffic signal with transit priority and compensation and queue override mechanisms. Computationally, the results show that MESCOP is very efficient in comparison with microscopic models for traffic simulation, which are often used for similar evaluations. Evaluations of the intersection performance indicate a great potential for this model to improve the design of traffic signals.

Transportation systems face continuous increases in congestion. Congestion limits mobility and results in negative economic impacts. Traffic signal control is the main tool used by the operators and managers of transportation systems to allocate capacities and affect the state of the system and its performance. The efficient design of intersection traffic signal control has been recognized as one of the most cost-effective methods to improve accessibility and mobility in urban networks (*1*). However, the inadequate design of traffic signal timing plans may inhibit their potential to alleviate congestion (*2*).

Traffic signal timing has advanced dramatically since Webster developed the basic principles and theory of traffic signal optimization (*3*). Over the years, signal plans have evolved from pretimed plans to actuated plans that utilize detection technologies and are sensitive to variations in traffic demand. The complexity of traffic signal plans has increased further with the introduction of additional features, such as transit priority or pedestrian and bicycle phases and actuation. Thus, signal timing plans are increasingly complex, have more sophisticated logical conditions and constraints, and contain many parameters that need to be carefully set and fine-tuned. As a result, solutions for the setting of optimal parameter values are becoming analytically intractable; this intractability further contributes to the difficulty of the design and evaluation of traffic signal plans.

A variety of tools and methods have been developed to optimize traffic signal plans. Examples of these optimization tools include the *Highway Capacity Manual 2010,* SYNCHRO, TRANSYT-7F, PASSER II-90, PASSER V, and MAXBAND (*4–9*). These tools are suitable for pretimed plans and, in some cases, for actuated signal plans. These tools have embedded analytic or macroscopic traffic models that predict the value of intersection performance measure under a given demand scenario and a set of signal timing parameter values. The parameter optimization commonly considers four basic groups of parameter: cycle length, green splits, phase sequence, and offsets. However, actuated traffic signal plans may include many other parameters related to signal timing (e.g., the minimum and maximum green time for each phase), detectors (e.g., the minimum gaps), pedestrians (e.g., the maximum waiting time), and transit priority. As a consequence, analytical solutions for the optimization of parameter values become intractable. Thus, there is a need for reliable simulation-based tools to optimize or fine-tune complex traffic signal plans.

Despite the progress in the development of sophisticated signal plan designs, little attention has been given to the optimization of these plans. Signal plan optimization methods require a level of detail in the movement of vehicles that is supported by microscopic traffic simulation models. These models also provide the ability to account for system variability that stems from heterogeneity in driving behavior, the existence of different vehicle classes with different capabilities and characteristics, and fluctuations in demand. However, the use of simulation-based signal plan optimization has been very limited, mainly as a result of its heavy computational burden (*10*). Park and Schneeberger (*10*), Foy et al. (*11*), Hadi and Wallace (*12*), Rouphail et al. (*13*), Park et al. (*14*), and Stevanovic et al. (*15*) used microscopic traffic simulation models within stochastic optimization algorithms for the four basic parameters of traffic signal plans (cycle length, green splits, phase sequence, and offsets). A few other studies expanded these works to include additional traffic signal control settings, such as the minimum green time, the maximum green time, and the placement of detectors (*1, 16–19*). These studies demonstrated substantial potential for improvements to intersection operations. However, the study processes were computationally demanding. To curb the computational efforts, researchers limited the number of parameters that were optimized, used sequential rather than joint optimization of the parameters, or reduced the number of simulation replications that were used to evaluate the objective function. These measures may all yield suboptimal solutions. Therefore, there is a need for reliable and efficient optimization tools for complex traffic signal plans.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2488, Transportation Research Board, Washington, D.C., 2015, pp. 1–9.
DOI: 10.3141/2488-01

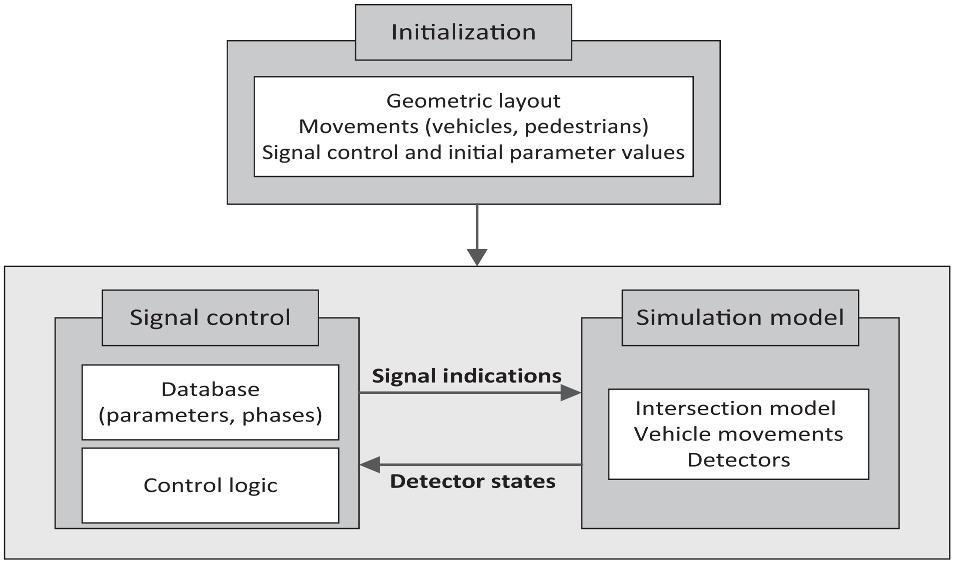


FIGURE 1 Overall framework and components of MESCOP.

This paper presents a mesoscopic traffic simulation model that supports the evaluation and optimization of complex actuated traffic signal plans. The model is called MESCOP (mesocopic evaluation of signal control plans). This model is computationally efficient compared with the microscopic models that have been used for this purpose in the past. The model maintains the level of detail required to model the characteristics of actuated traffic signal plans, including the features of transit priority and pedestrian actuation.

The next two sections of this paper describe the overall structure of MESCOP and detail the various components within it. Next, the computational characteristics of the model and its potential to generate time savings through signal plan optimization are demonstrated with an application to a signalized intersection in Haifa, Israel. Finally, a summary and discussion of the results are presented.

MODEL FRAMEWORK

MESCOP consists of two main components—vehicle movements and signal control—that interact with each other, as shown in Figure 1. The vehicle movement component explicitly represents the individual road users—including passenger cars, transit vehicles, and pedestrians—that pass through the intersection.

The vehicle movements are modeled by events that occur at detector locations and the stop line. The movement model is comprised of three stages: the initial approach to the intersection, the movement to the stop line, and the crossing of the intersection. Pedestrians arrive at the crossing line randomly, and an arrival rate is provided as an input. The simulation implementation is time based and has a step size of 1 s to fit with the resolution of the control logic.

The signal control component implements the control logic for the intersection and the parameters associated with this logic. This component is run every second to determine the light indications in the next second. In determining the light indications, the logic may use information on the current and previous indications and information on the states of the detectors in the system that is received from the vehicle movement simulator. In the next section, these components are described in further detail.

MODEL COMPONENTS

Mesoscopic Simulation

Vehicles

Vehicles are represented explicitly in the model as individual entities. Figure 2 summarizes the movement of vehicles from their approach to the intersection until their release from it.

Vehicles are generated in the model when they first arrive at the furthest detector in their approach to the intersection. On their

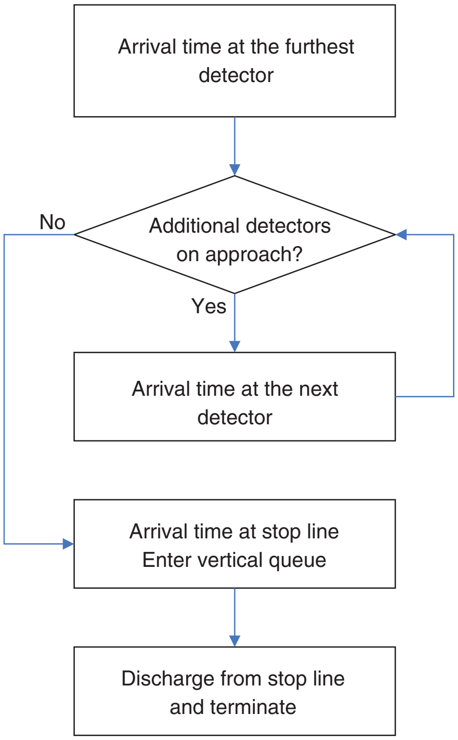


FIGURE 2 Vehicle movement model.

arrival, the vehicles activate the detector. The arrivals are modeled as a stochastic process. In the default implementation, the interarrival times are assumed to follow a negative exponential distribution. If an approach does not have any detectors, the arrival occurs at the stop line. For prevention of a situation in which two or more vehicles arrive in the same lane in the same time interval, the headway between vehicles is set to a minimum value of 1 s, and the arrival time of the second vehicle is adjusted accordingly. On arrival, vehicles are allocated to a specific lane according to their turning movement at the intersection. A lane-changing model, which is commonly implemented in microscopic traffic simulation models, is not implemented in this model. If more than one lane is appropriate for a certain movement, the proportions of the vehicles allocated to each of the lanes is calculated according to the method of critical lane flows, which aims to equalize flows on all lanes in a specific approach.

The next event that the vehicle will experience is the arrival at the next detector downstream of the current one (or the stop line, if no additional detectors exist). The arrival time at this detector is given by

$$t_n(i) = \max\left(t_n(i-1) + \frac{d(i,i-1)}{v_n} + \varepsilon_{ni},\, t_{n-1}(i) + h^{\min} \right) \tag{1}$$

where

$t_n(i)$ = arrival time of vehicle n at detector i (or stop line);
$d(i, i-1)$ = distance between detectors i and $i-1$;
v_n = approach speed of vehicle n, which depends on turning movement at intersection;
$h^{\min}$ = minimum headway between consecutive vehicles in same lane; and
ε_{ni} = random error term.

Vehicles that arrive at a detector activate it. The activation information is passed to the control logic. Vehicles advance from one detector to the next and to the stop line. At the stop line, the vehicles enter a vertical queue. The queue length in each lane and each time interval is monitored during the simulation. If, during any time interval, the number of vehicles in the vertical queue exceeds the number of vehicles that can be stored between the stop line and an upstream detector, the relevant detectors are activated for that interval. During the effective green time, vehicles are discharged from the queue at the saturation flow rate deterministically and according to the first-in, first-out rule. The saturation flow is an input to the model and may be different for each lane, depending on the turning movement.

Pedestrians

Figure 3 summarizes the movement of pedestrians through the intersection. The numbers of pedestrians arriving at crosswalks during a simulation time step follow the Poisson distribution, according to the assumed mean flow. During red light phases for a given crosswalk, the first arriving pedestrian activates the relevant push button, if one exists. Once the light turns green, the waiting pedestrians start to cross the intersection. Pedestrians that arrive during the green light phase cross the intersection without any delay. Crossing times are calculated under an assumption of constant pedestrian speeds:

$$t_p^c(i) = \max\left(t_p^a(i), t_p^g(i)\delta_p^{\text{ar}}\right) + \frac{l(i)}{v_p} \tag{2}$$

where

$t_p^c(i)$ = crossing completion time of pedestrian p at crosswalk i,
$t_p^a(i)$ = arrival time of pedestrian p at crosswalk i,
$t_p^g(i)$ = beginning of green phase after arrival of pedestrian p at crosswalk i,
δ_p^{ar} = indicator that takes value 1 if pedestrian p arrives at crosswalk during a red light phase and 0 otherwise,
$l(i)$ = length of crosswalk i, and
v_p = walking speed of pedestrian p.

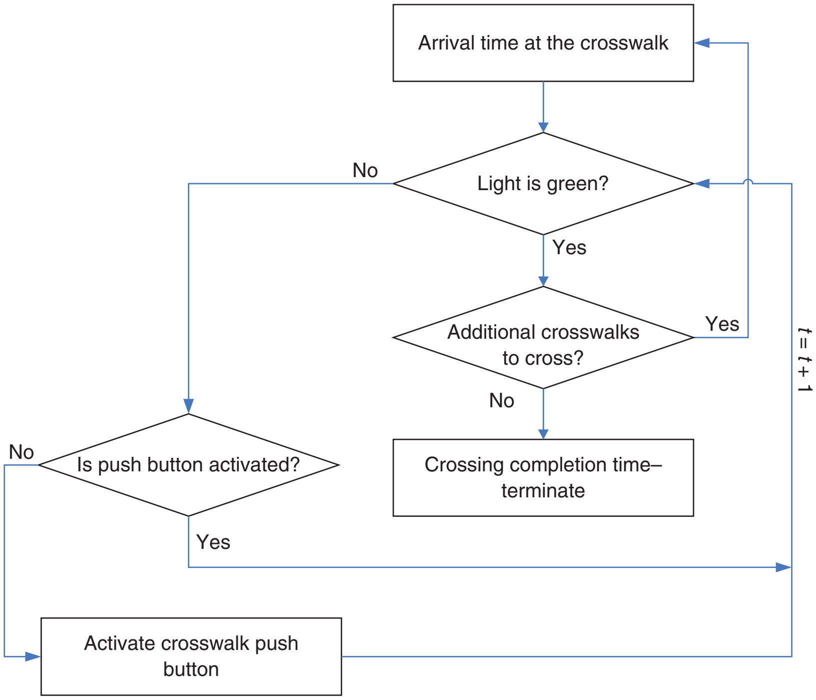


FIGURE 3 Pedestrian movement model (t = time).

In the current implementation, it is assumed that all pedestrians have the same walking speed. For multiple crosswalks at certain intersection legs, the time of the crossing completion of the first crosswalk is the arrival time at the next crosswalk.

Detector System

Actuated traffic signal plans use information about traffic flow to allocate green times. Various detection technologies, such as loop detectors and video, are implemented to support vehicle presence detection tasks. Presence detection is activated when a vehicle is within a detection zone. Presence information is used to identify vehicle demand as part of phase-skipping logic or to initiate calls for the extension of the green time of a phase. Detectors may be placed at any location on the approach to the intersection or downstream of the stop line. Their representation is currently not sensitive to the specifics of the detection technology being used. With transit priority plans, upstream detectors are used to identify an approaching transit vehicle and help predict its arrival time at the stop line. Downstream detectors are used to identify the release of the vehicle from the stop line and cancel the transit priority request. The detection of pedestrians is limited, in most cases, to push buttons.

Control Logic

The implementation of traffic control logic incorporates functions for detection and control tasks that support the representation of various traffic control plans. The detection functions include

- Presence detection, which queries the simulation model for the presence of a vehicle in the detection zone at a specific time;
- Demand detection, which determines whether the detector has been activated over a period of time;
- Queue detection, which determines the occupancy of a detector over a time interval; and
- Gap detection, which measures the time that has passed since the last presence detection.

The detection results are used by the various control functions to adjust the signal timings. The implemented control functions include both actuated and transit priority plans. The actuation functions follow:

- Phase skipping, which enables a specific phase to be skipped when a negative result is returned by the demand detection function on the relevant detectors.
- Phase extension, which extends the green light of an active phase if certain conditions are met. These conditions may be that the gap values are below a specified threshold or that queue lengths exceed their thresholds. A transit phase extension may be activated to provide transit priority when a transit vehicle is detected.
- Phase "gap out," which terminates an active phase if the gap between two consecutive vehicles that activate a detector exceeds a specified threshold.

Transit priority control logic functions include the following:

- Arrival expectation, which estimates the arrival time of the transit vehicle at the stop line. The time estimation is based on the time that the presence of the vehicle was detected and an assumed approach speed.
- Phase early termination, which can override the extension of active phases to provide priority to a transit vehicle that is approaching the intersection.
- Early transit phase start, which starts the transit phase a few seconds before the expected arrival time of the transit vehicle at the stop line to allow transit vehicles not to stop or slow down in the approach to the intersection, even if they arrive earlier than expected.
- Phase insertion, which activates a transit phase out of the normal phase sequence.
- Priority cancelation, which cancels the transit priority when the transit vehicle is discharged from the intersection and is detected on a checkout detector located downstream of the stop line. The priority may also be canceled if a transit vehicle is not detected at the stop line a certain time after it was expected.
- Compensation, which guarantees a minimum green time to certain movements or phases. The function measures the cumulative green time provided to a movement or phase within a certain period of time. If needed, the green time is extended to meet a minimum threshold.
- Queue length override, which aims to prevent long queues in the minor approaches. When the phase of that approach is active, transit priority functions are disabled if the relevant queue detection value exceeds a certain value over a period of time.

Further details about the control logic functions, including the transit priority strategies and their implementation, are provided in Balasha (*20*).

Performance Measures

A variety of measures of performance can be derived from the model output. Several studies have suggested person delay as a useful performance measure in the context of traffic signals at intersections (*18, 21, 22*). The average person delay is used in this model. The delay for each transit and nontransit vehicle is computed as the time that elapses from the time the vehicle enters the queue to the time the vehicle is discharged from the queue. Each vehicle is assumed to contain a certain number of passengers, depending on the vehicle type. Pedestrian delays are computed as the time that elapses from the arrival time at the first crosswalk the pedestrians need to cross to the crossing start time of the last crosswalk the pedestrians need to cross. Through a consideration of multiple simulation runs, the average person delay at the intersection is given by

$$d = \frac{1}{R}\sum_{r}\frac{\sum_{i}\sum_{n} d_{nr} N_i \delta_{ni}}{\sum_{i}\sum_{n} N_i \delta_{ni}} \tag{3}$$

where

d = average person delay,
d_{nr} = delay for transit or nontransit vehicle n or pedestrian n in simulation run r,
N_i = number of travelers in vehicle of type i (by definition, value of 1 for pedestrian),
δ_{ni} = indicator variable that takes a value of 1 if vehicle n is of type i (car, various bus types, pedestrian), and
R = number of replications.

MODEL APPLICATION

Intersection

MESCOP is demonstrated with an application to the planned control of the intersection of Haatzmaut Avenue and Hayat Street in Haifa. The intersection is shown schematically in Figure 4. The planned control of this intersection is fully actuated and incorporates transit priority for a bus rapid transit (BRT) line that crosses the intersection in dedicated lanes in both main directions (Movements 2 and 6). In addition to the BRT movements, there are four vehicle movements (1, 3, 5, and 7) and seven pedestrian signalized crosswalks (a through g). The movements in the intersection are organized into three signal phases (A, B, and C), as shown in Figure 5. Phase A is the main phase. It provides a green light to the BRT vehicles and to through vehicles from both main directions. Phases B and C provide green time to movements on the minor approach from the south and the north, respectively. The right-turn movement in Phase B must yield to pedestrians crossing crosswalk g. Presence detectors are located on the minor approaches. These detectors are used for demand (D1 and D5), extension (E1 and E5), and queue detection (Q1) tasks on the relevant phases. The demand detectors are located at the stop line. The extension detectors are located 10 m upstream of the intersection. There are two detectors on the eastbound BRT approach (DPT21 and DPT22) and one on the westbound BRT approach (DPT62). These detectors are used for the identification of an approaching BRT vehicle and for the arrival expectation task. An initial arrival expectation is estimated when the vehicle arrives at DPT21. This expectation is updated when the transit vehicle is detected at DPT22. The signal plan and timing are adjusted accordingly to provide priority to approaching BRT vehicles. DPT21 is located 200 m upstream of the intersection. DPT22 and DPT62 are located 100 m upstream of the intersection. There is only one detector on the westbound approach because of the presence of a

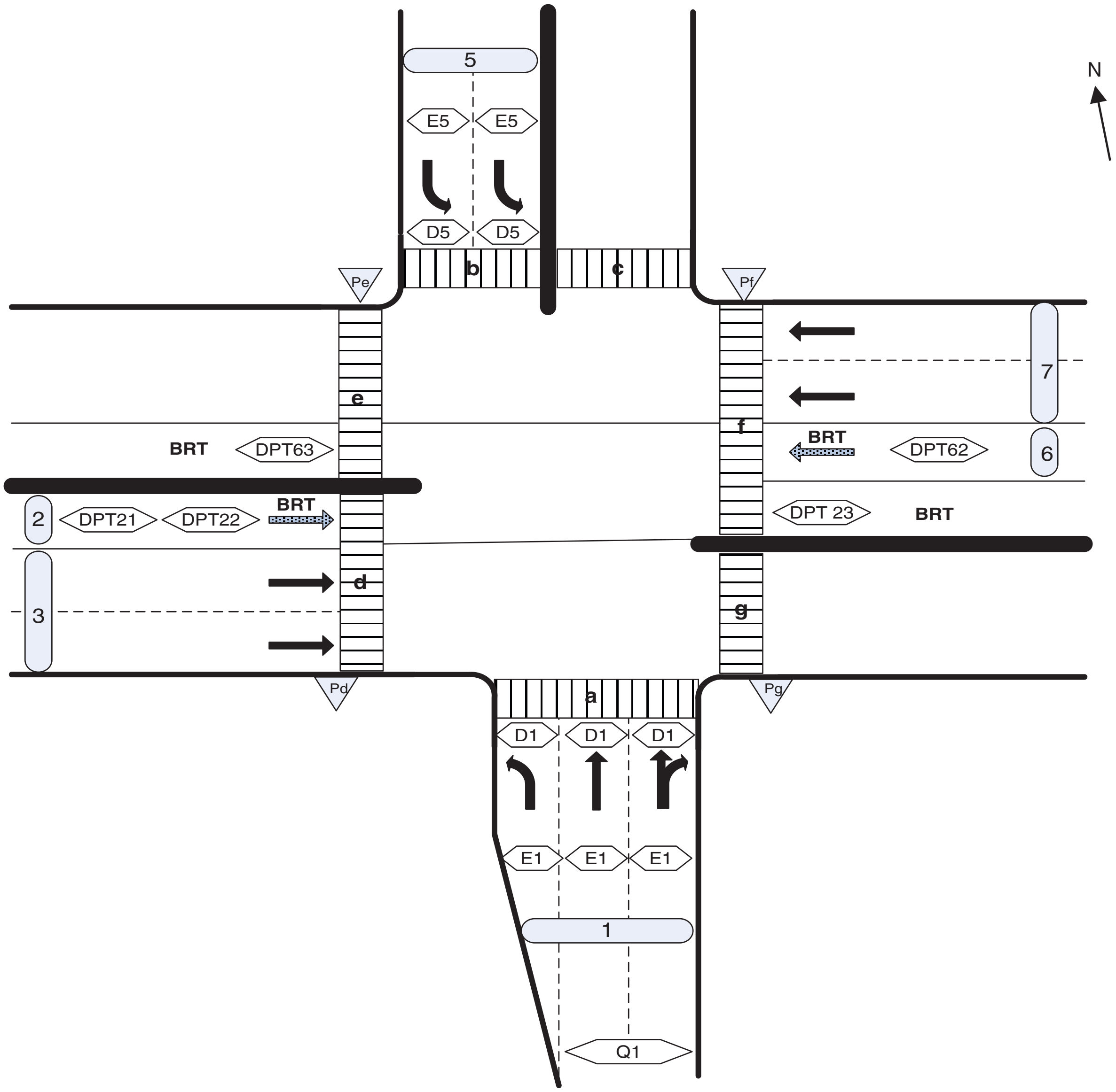
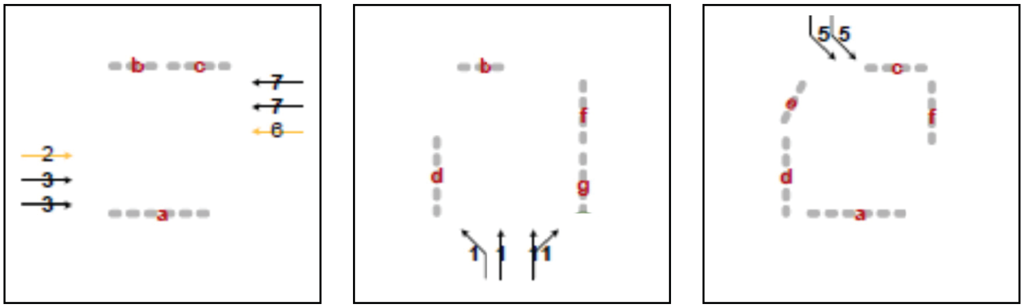


FIGURE 4 Case study intersection (P = push button).



(a) (b) (c)

FIGURE 5 Control phases at intersection: (*a*) Phase A, (*b*) Phase B, and (*c*) Phase C.

BRT station close to the intersection. Both approaches also include detectors downstream of the intersection (DPT23 and DPT63). The purpose of these detectors is to cancel the priority request after the BRT vehicle completes the crossing of the intersection. The four pedestrian crosswalks on the major approach are activated by push buttons (P_d, P_e, P_f, and P_g).

The design traffic flows in the intersection were estimated from traffic counts and updated with results from a traffic assignment model. Table 1 presents the design flows for the various movements within the intersection. The total flow was 3,194 vehicles per hour (vph). Occupancies of 50 and 1.2 passengers were assumed on transit and the nontransit vehicles, respectively.

The main objective of the control logic is to minimize the delay for BRT while limiting the delay to minor directions. Phase A serves as a default. If there is a vehicle demand or pedestrian actuation in Phases B or C, the control plan will activate these phases. Depending on which phase is active when a BRT vehicle is detected, the control logic examines the need for the early termination of Phases B and C or the extension of Phase A. The control plan does not limit the number of priority activations in a cycle. For example, the control plan may extend Phase A and terminate Phase B early in the same cycle to provide transit priority to two transit vehicles. BRT priority will be overridden if queues are detected in Q1, if a maximum pedestrian waiting time in Phases B or C is exceeded, or if Phases B or C require compensation (i.e., if they did not each get a minimum cumulative green time within a certain time period). The cycle length is fixed to 110 s, as this intersection is coordinated with other intersections. The reference point for offsets is defined at the beginning of Phase A. The remaining green time after the termination of all phases and until cycle completion is allocated to Phase A. Full details of the control logic and the parameters associated with it, including the design parameter values, are given in Balasha (*20*).

TABLE 1 Traffic Flows at Intersection

Movement	Traffic Flow (vph)
1L	115
1T	144
1R	45
2T	30
3T	1,058
5L	59
6T	30
7T	1,713

NOTE: vph = vehicles per hour; L = left turning; T = through; R = right turning.

Computational Performance

As noted above, the computational efficiency of the simulation model is essential to support the optimization of complex traffic signal plans with acceptable running times. The size of the intersection in terms of the number of traffic lights, movements, phases, lanes, detectors, and push buttons affects the running time. For a given intersection, the model running time is affected by the following:

1. The level of traffic flow, both vehicular and pedestrian, and
2. The complexity of the signal control logic.

The model running time is expected to increase with an increase in each of these factors. Figure 6 presents the running times of MESCOP as a function of the total traffic flow in the intersection. The simulation was run for a 1-h period. The total flow was changed by scaling the base flows up or down. These running times were compared with those obtained with TRANSMODELER, a widely used commercial microscopic simulation model (*23*). The reported running times were averages of 100 replications in each case. As expected, the MESCOP model produced running times that were lower by an order of magnitude compared with those of the microscopic simulation TRANSMODELER. For the base demand, the MESCOP running time was 0.31 s, which is a reduction of 95% compared with the 6.5-s running time for TRANSMODELER. Moreover, the running time for MESCOP was only slightly affected by the level of traffic flow. The running times increased by less than 0.1 s (20%) from the lowest (800 vph) to the highest (7,000 vph) levels of demand that were tested. For a comparable increase in flows, the running time of TRANSMODELER increased by 180%. These results were not surprising given the level of detail in the models. Nevertheless, the results highlighted the computational efficiency of MESCOP as a model to evaluate signal control plans, especially in the context of signal plan optimization, which may require many simulation runs.

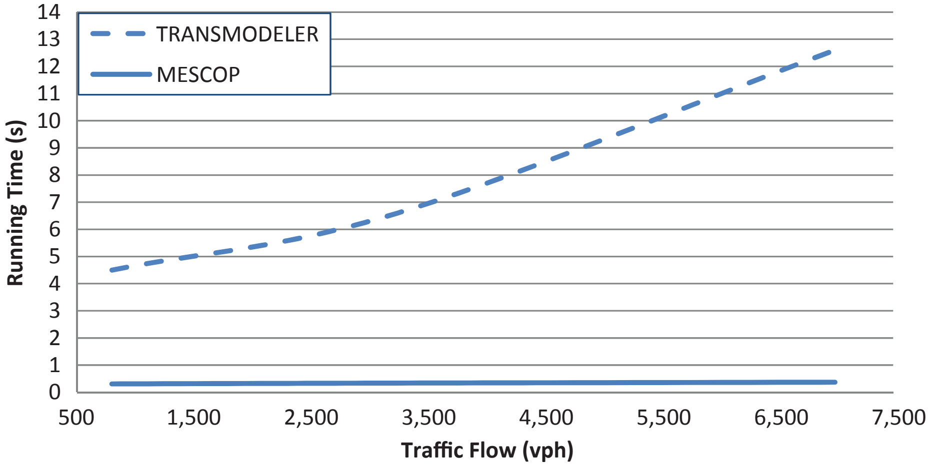


FIGURE 6 Running times for MESCOP and TRANSMODELER.

Figure 7 presents the effect of signal plan complexity on MESCOP running time. Four control plans with increasing levels of complexity were created: pretimed, actuated without transit priority, unconstrained transit priority (in which the compensation and queue constraints were eliminated), and constrained transit priority (the original design). The simpler control plans were created by eliminating functionalities and conditions from the original constrained transit priority plan. In the pretimed plan, the green times for all the phases were set to their respective maximum green times from the actuated plans. The remaining time within the cycle was allocated to Phase A.

The running time results were based on an average of one hundred 1-h simulations. The results were sensitive to the control logic complexity but remained low in absolute values, even under the most complex plan. The running time of the simulation with the constrained priority plan increased by 0.16 s (89%) compared with the pretimed plan. The sensitivity of the running time to the control logic can be explained by the internal breakdown among the model components, as shown below:

Model Component	*Running Time (%)*
Traffic dynamics	8.6
Control logic	81.1
Other (input and output)	10.3

The reported results are for the constrained transit priority plan. The control logic execution accounts for most of the running time; the traffic dynamics contribution is an order of magnitude smaller.

Evaluation of Intersection Performance

Figure 8 presents the average delay to road users at the intersection under the four control plans. The results are averages of 100 replications in each case. The average person delay (Equation 3), which accounts for the number of passengers in various vehicles and for pedestrians, slightly improved when transit priority functions were implemented. The transit priority functions significantly reduced

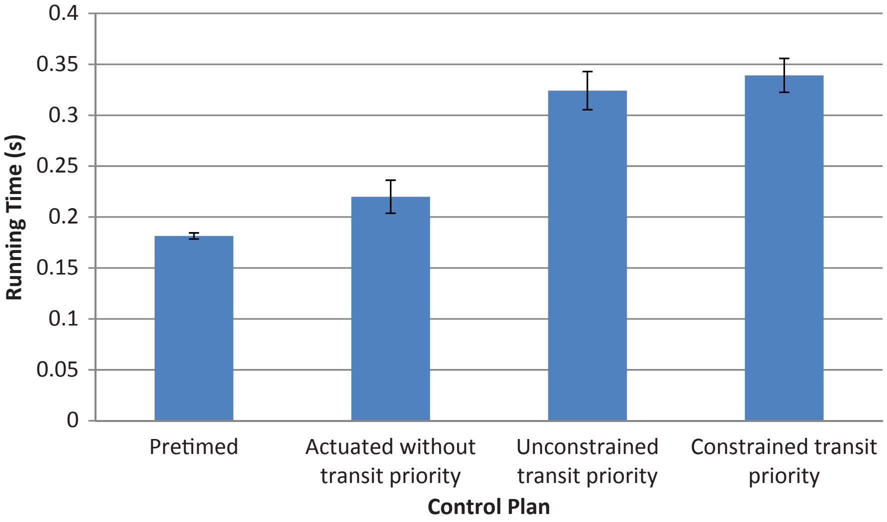


FIGURE 7 MESCOP running times and 95% confidence intervals by type of control plans.

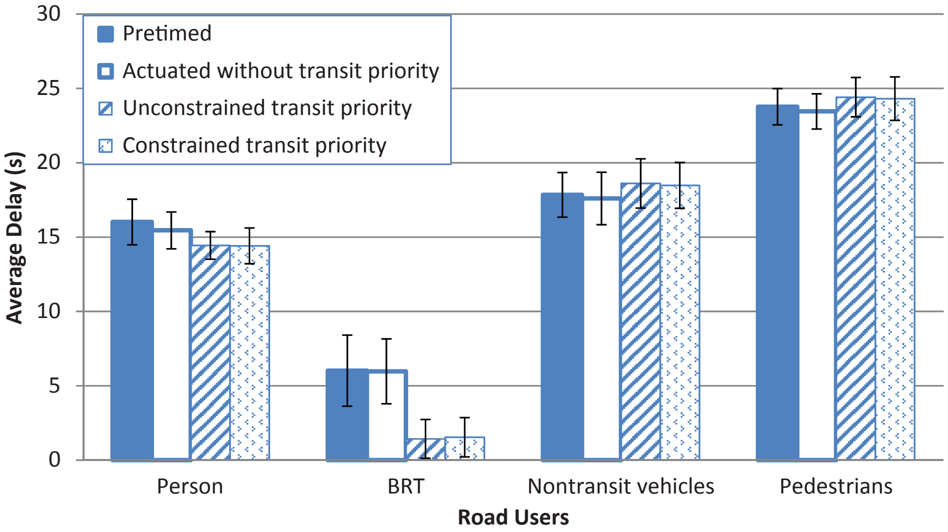


FIGURE 8 Average delay to road users, with 95% confidence intervals, under various control plans (person = passengers in vehicles).

BRT delays (by 76% from the pretimed plan to the unconstrained transit priority plan), at the expense of small increases in the delays of other vehicles and pedestrians (4% and 3%, respectively). The elimination of compensation and queue constraints greatly simplified the control logic but did not have any noticeable effect on the intersection performance. In addition, there was only a small difference (4%) in the delays measured with the pretimed and actuated (without priority) plans. In this intersection, vehicle actuation occurred only in the minor directions. Thus, the difference between the two plans was that with the actuated plan, less green time was allocated to the minor phases when their demand was low. However, since the time allocated to the major approach phase was very high in this intersection, the advantage of a further increase in green time was minimal to the vehicles that used that phase.

SUMMARY

This paper presents a mesoscopic simulation model that supports the evaluation and optimization of traffic signal plans. The model incorporates components of vehicle movement simulation and an implementation of detailed control logic. The application of the model to an intersection that implements an actuated signal plan with transit priority demonstrated the computational advantage that the model offers compared with microscopic traffic simulation models. The improved computational performance makes the simulation-based optimization of traffic control plans feasible.

The current implementation of the model has several limitations. The arrivals of both vehicles and pedestrians follow Poisson processes. Transit vehicles that receive priority are assumed to travel only on dedicated lanes. Lanes were assumed to be used equally. Finally, only the modeling of isolated intersections is supported. Extensions to the model to address these limitations can be easily implemented.

Ongoing research that uses this tool focuses on the optimization of traffic signals and the in-depth analysis of the optimization results, including a comparison between the original and the optimal parameter values. This analysis aims to identify the most influential parameters within a control plan to reduce the dimensionality of the optimization problem. This result may be achieved through various sensitivity analysis procedures.

Finally, an essential future activity is the calibration and validation of the model. The calibration and validation may be achieved through a comparison of the MESCOP results not only with field data but also with results of microscopic traffic simulations that can help establish the model validity under a wider range of demand levels from transit and nontransit vehicles.

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The Standing Committee on Traffic Signal Systems peer-reviewed this paper.