Multiheadway Gap-Out Logic for Actuated Control on Multilane Approaches

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The efficiency of actuated signals depends on quick detection when the queue has discharged and flow rate has dropped below the saturation rate. The traditional detection method is to measure headway between successive vehicles. In single-lane approaches, this measurement works well because the safety need for longitudinal spacing during saturation flow keeps headway variability small. However, on multilane approaches, headways are far more variable (headways near zero are common); for a low probability of premature gap-out, the critical gap has to be set extremely long so that traffic well below the saturation flow rate can hold the light green. This critical gap requirement makes multilane operations inefficient. This paper proposes a gap-out logic that is based on multiheadways, the time needed for several vehicles to pass a detector. For example, for three-lane approaches, the variability of three- or six-vehicle multiheadways is much lower than that of single headways, and this low variability enables the controller to distinguish saturation flow from lower flow more easily. Through microsimulation, intersection operations based on multiheadway logic were compared with traditional detection and lane-by-lane detection. Multiheadway logic performed best in reducing delay and cycle length; the greatest improvement occurred when traffic was heavy.

In actuated signal control, cycle length, phase sequence, and phase green times may vary from cycle to cycle on the basis of traffic demand. Actuated controllers serve phases if a vehicle call is registered (i.e., a call detector is occupied), and phases may be skipped if there is no registered call. Green phases are terminated when either the maximum green is exceeded (max-out) or the time since the last vehicle detection exceeds a threshold (gap-out). The controller continuously monitors the time that the detector has been unoccupied (gap time), and, subject to other constraints such as minimum green, ends the green when it exceeds a controller parameter variously called the critical gap, passage time, and extension increment. In traffic flow, gap time is related to headway, but they are not the same. "Headway" refers to the time between when the fronts of successive vehicles pass a point, whereas "gap time" refers to the time between when the rear of one vehicle clears the downstream edge of a detector and when the front of the next vehicle meets the upstream edge of the detector. Therefore, headway equals gap time plus detector occupancy time. The headway corresponding to the critical gap is called the "critical headway."

The efficiency of actuated traffic signal controllers depends on quick detection when the standing queue has discharged and flow rate has dropped below saturation flow rate. A termination logic that ends a green phase just after the saturation flow period ends reduces wasted green time and thus reduces average cycle length as well as probability of overflow queues, leading to smaller average delay (*1*). Furthermore, reduction in average cycle length as an outcome of efficient actuated operation increases safety at signalized intersections (*2*). The longer the cycle length is, the higher is the risk of a crash because of unsaturated green periods that encourage drivers to speed and encourage pedestrians and turning traffic to make risky crossings.

So, while a controller's objective is to detect a change in flow rate, what it actually measures is gaps and, implicitly, headways. The effectiveness of detection depends, therefore, on how closely related headways are to flow rate. On average, they are intimately related, as average headway is simply the inverse of flow rate. However, in actuated control, controllers make decisions on the basis of single headways, not average headway, and for traffic moving with a given flow rate, headways vary from vehicle to vehicle. The effectiveness of a controller in detecting a change in flow rate depends on the variability of headways within a given flow regime.

DISTINGUISHING SATURATION FLOW FROM LOWER FLOW ON SINGLE-LANE AND MULTILANE APPROACHES

Differences in Conditions for Single-Lane and Multilane Approaches

On a single-lane approach, common with left-turn lanes, headways during saturation flow have relatively low variability because each driver has to keep a safe following distance from the preceding vehicle, making very small headways physically impossible. This low variability in headway makes individual gap time a good indicator of flow rate, and so the traditional phase termination logic works efficiently, leaving only a small possibility of keeping the phase green long after flow rate has dropped below saturation.

However, on multilane approaches, vehicles using different lanes do not need safe following distance (i.e., longitudinal separation). With traditional vehicle detection logic, multiple lane detectors provide a single input to the controller. Headways are not monitored on a lane-by-lane basis; instead, the detectors on multiple lanes function as would a single, approach-wide detector. As a result, headways that are zero or close to zero become not only possible but common. And for a given average headway corresponding to the saturation flow rate, if there are very small headways, very large headways must also exist; the result is high headway variability during saturation flow. This situation makes it more

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difficult to distinguish when the flow rate has dropped. To be reasonably certain that early termination of the green phase does not occur, a generous critical gap value must be defined as the threshold. Then, when the queue is discharged and the flow rate drops, the controller may take a long time to detect the change because it is waiting for a relatively large gap, and this condition results in wasted green time, which, in turn, increases average red time, average cycle length, and average delay.

Figure 1 shows the difficulty of discriminating between saturation flow and below-saturation flow on the basis of individual headway measurements on a multilane approach. The same headways can be detected at high flow, with cars arriving in ranks, as at low flow, if the arrivals are staggered. With traditional detection, because all lanes must gap-out simultaneously, those two arrival patterns are perceived exactly the same by a signal controller. With well-staggered arrivals on a three-lane approach, the controller will extend the green even if the flow is only one-third of saturation flow rate, resulting in less efficient operation and higher delay.

A literature review reveals that only a few researchers have proposed different phase termination criteria for multilane roadways as a means to overcome this shortcoming of traditional gap-out logic. Smaglik et al. suggested lane-by-lane detection in which gap times are monitored on a lane-by-lane basis and an approach gaps out as soon as each of its lanes gap out (without requiring simultaneous gap-out) (*3*). Field tests showed a small improvement compared with traditional gap-out logic. The average gain in efficiency was a 5% reduction in needed green time, with higher benefits achieved during moderate traffic and lower benefits obtained during light and heavy traffic. Reflection on the nature of the problem shows that this focus on single-lane headways will clearly eliminate the problem of high variability with multilane flow; however, the requirement for each lane to gap out shows little relation to the problem of detecting when flow has dropped below saturation level; continuing flow in one lane would be enough to hold a signal green even though it is operating at one-third of its capacity.

Wang compared lane-by-lane and traditional detection schemes by using a simulation model (*4*). Both detection strategies were evaluated with various parameters, including traffic volumes, critical headway values, and number of through lanes. Simulation results revealed that max-out rates (i.e., the percentage of cycles during which actuated phases reached their maximum green time) were lower under lane-by-lane detection for moderate-volume scenarios than under traditional detection. Furthermore, lane-by-lane logic reduced average intersection delay by about 5 s at moderate volumes. However, under conditions of low and high traffic volume, average delay improvements approached zero. Finally, change in average delay with 3.0- and 2.5-s critical headway was not found significantly different.

Another study, conducted by Janos and Furth, used density to end the green phase on multilane approaches instead of simple gap detection (*5*). A running average of flow over the last 5 s was kept on the basis of a count of vehicles passing an upstream detector. Flow was then divided by vehicle speed (also measured by detectors) to obtain density. For green termination, an initial density threshold of 80 vehicles per kilometer was chosen, and the threshold was increased by one each second after the minimum green had expired, following the strategy known as volume–density control. Because the aim of that study was bus priority, the proposed termination logic was not explicitly compared with the simple gap detection. However, simulation results indicated that average cycle length along the arterial could be reduced from 90 s (existing arterial cycle length) to 53 s. The feasibility of such a low cycle length was attributable in part to the efficient gap-out logic.

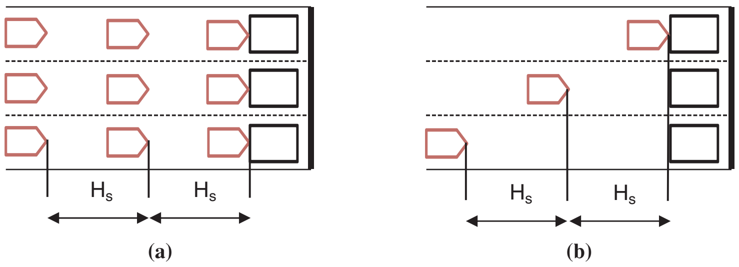
The current research proposes using multiheadways as a criterion for detecting when saturation flow has ended on a multilane approach. A multiheadway is the time required for several vehicles to pass a detector. The rationale is best explained by considering an approach with a given number of lanes, say three. During saturation flow, while the opportunities for passing afforded by multiple lanes create significant variability in the time until the next vehicle passes, longitudinal-spacing needs within a lane keep the headways within each lane more uniform and therefore should result in far less variability in the time until the next three vehicles pass.

The criterion for multiheadway gap-out is specified by the number of vehicles and the critical interval; for example, allow up to 3.3 s for three vehicles to pass. An upstream detector records each vehicle passage. If the number of vehicle arrivals detected in the last 3.3 s is fewer than three, the phase gaps out. It has a close relationship to flow rate, which is the number of vehicles in a given interval divided by interval length.

Because variability tends to decrease with sample size, one might imagine specifying multiheadways for a greater number of vehicles; for example, let the criterion for a three-lane approach be based on the time needed for six or nine vehicles to pass. However, the time it takes to measure many headways becomes a source of inefficiency and requires detectors to be placed far upstream. Therefore, the focus is on multiheadways of size kL, where L is the number of approach lanes and k is 1 or 2.

Lower Variability of Multiheadways

The traffic microsimulation model VISSIM was used to explore headway and multiheadway variability at saturation and lower flow rates. While the use of field data would have been preferable, find-



(a) (b)

FIGURE 1 Two extreme arrival patterns that are identically perceived by signal controller under traditional detection scheme: (*a*) high traffic flow and (*b*) low traffic flow (H_s = saturation headway within a single lane).

ing data with the necessary level of detail and with significant periods of saturation flow on multilane roads proved too difficult. With traditional presence detectors wired to a single channel, there was a nontrivial probability of two vehicles arriving during the same occupancy interval and that made that type of data unsuitable. A data set was examined from one city that has instrumented several intersections to record detector state changes in each lane, but the data were inconsistent and unreliable. The results of this analysis research must therefore be considered tentative; however, because microsimulation models generally capture the dynamics of longitudinal separation and passing on multilane roads, a simulation-based study can still serve well as a proof of the concept.

To model saturation flow for one-, two-, and three-lane approaches, an approach was given a high input volume [5,000 vehicles per hour per lane (vphpl)] and the signal was permanently held in green. Doing so guaranteed an effectively infinite standing queue. A point (pulse) detector just downstream of the traffic signal was used to obtain headway data. For multilane approaches, point detectors in each lane provided headways on a lane-by-lane basis. Lane-level headway data were later combined when the authors wanted to model single-channel detection. Data were collected for 3,600 s of simulation after a 300-s warm-up.

For model calibration, VISSIM's Wiedemann 74 parameters (*6*) were adjusted to get saturation flow rate of about 1,800 vphpl. Parameter values used were these: for the average standstill distance (ax), 8.2 ft; for the additive part of desired safety distance (bx_add), 2.3; and for the multiplicative part of desired safety distance (bx_mult), 3.4.

Headway distributions for a single-lane approach are shown in Figure 2 for saturation flow and 50% of saturation flow. The mean saturation headway was 1.98 s, which corresponds almost exactly with the calibration target of 1,800 vphpl. The coefficient of variation of the saturation headway was found to be .188. For single-headway gap-out, the critical headway was set to the 99.5th percentile value of the saturation headway distribution, which was 3.2 s. This implied a 0.5% chance (one out of 200 vehicles) of Type I error, also known as a false negative, for which the controller would conclude that saturation flow has ended when vehicles are still discharging at saturation flow.

The headway distribution when the input flow was 50% of saturation flow is also shown in Figure 2. It is used to assess the probability of Type 2 error (false positive, shown as a vertical dashed line), which concludes that saturation flow is continuing when the flow rate is lower. Figure 2 shows that, when flow is at 50% of the saturation flow rate, 40.5% of the headways exceed the critical headway of 3.2 s.

The discrimination power of the gap-out test (i.e., the power of discriminating low flow rates from the saturation flow rate) can be defined as the distance between cumulative headway distributions (saturation flow and 50% saturation flow) at the critical headway, which is shown as a black line in Figure 2. Discrimination power is given as 1 − *p* (of Type I error) − *p* (of Type II error). As Figure 2 shows, the discrimination power of a single-headway test on a single-lane approach is quite strong, about 40%.

However, on multilane approaches, the greater variability in single-vehicle headway results in much lower discrimination power for a single-headway test. Figure 3 shows results for a three-lane approach for three kinds of detection: single headway, three headway, and six headway. In each case, the critical headway, indicated by the vertical black line, is the 99.5% (multi)headway during saturation flow, which thus holds Type I error constant at 0.5% for each detection scheme. As Figure 3 shows, the power of single-headway detection is low, less than 20%, because the headway distribution during saturation flow is not much different from the distribution during half-saturated flow, except at the upper end of the distribution. Therefore, with single-headway gap-out, if flow falls to 50% of saturation flow, four of five arriving vehicles will extend the green phase and result in wasted green time. With multiheadway detection, discrimination power increases significantly. With three-headway detection, the power is increased to 55%, and with six-headway detection, the power is as high as 80%.

Figure 3 also reports the coefficient of variation for single-, three-, and six-vehicle headways during saturation flow. As expected, the

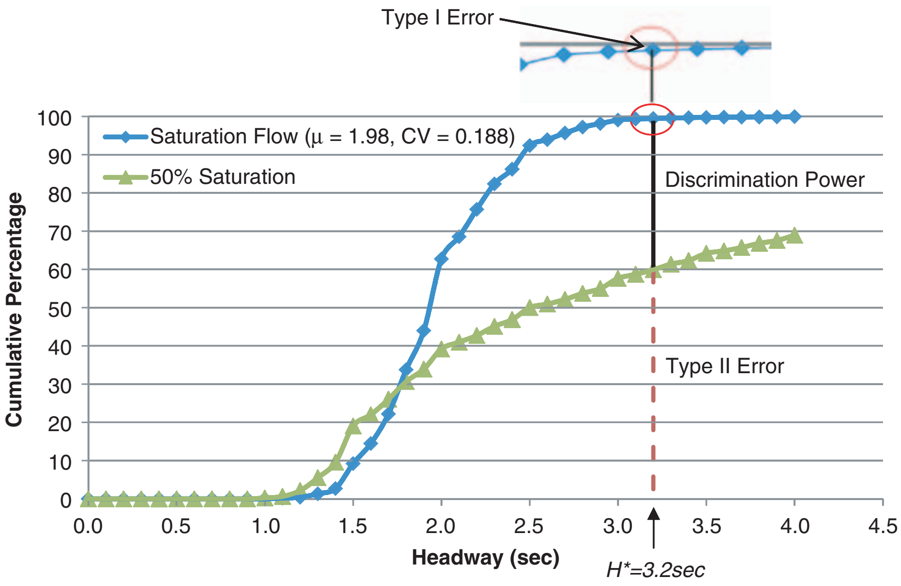


FIGURE 2 Cumulative headway distribution on a single-lane approach for saturation flow and 50% saturation flow (H* = critical headway with 0.5% Type I error; μ = mean saturation headway; CV = coefficient of variation of saturation headway).

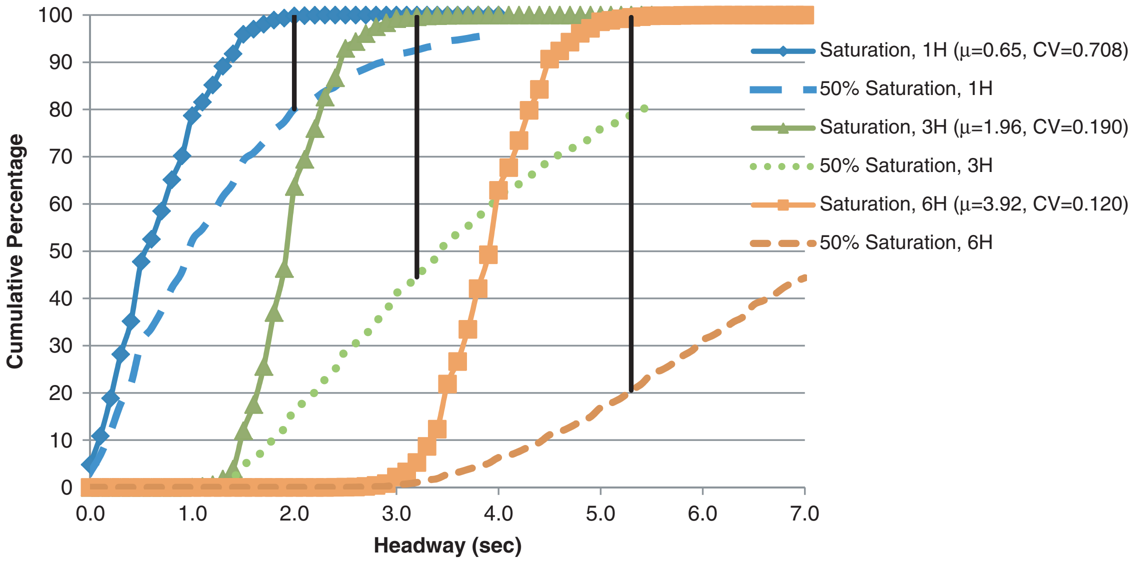


FIGURE 3 Cumulative headway distribution on a three-lane approach for saturation flow and 50% saturation flow with single-headway (1H), three-headway (3H), and six-headway (6H) detection scheme.

coefficient of variation falls dramatically from a single-vehicle headway to three headways (for a three-lane approach). The incremental gain from using six-vehicle headways is not so dramatic but still significant.

DETECTOR SETBACK AND VARIABLE MINIMUM GREEN TIME

Use of an upstream detector to extend a phase at an actuated signal reduces wasted green time because, with a stop-line detector, the green time during the wait to detect the critical gap is wasted (*1, 7*). Furth et al. showed that green extension using upstream detectors can reduce average cycle length by more than 20% under moderate-to-high traffic volumes compared with using stop-line detectors (*1*). Therefore, to analyze multiheadway gap-out, only upstream detectors were considered.

However, a primary concern with using upstream detection for extending the green is the risk of premature (early) gap-outs, in which a controller ends a green phase before the queue is fully served. Premature gap-out occurs when the queue does not reach an upstream detector and when the minimum green is not sufficiently long to clear the queue between stop-line and upstream detector.

To prevent premature termination of green, employment of variable minimum green time logic was proposed on the basis of the estimated number of vehicles queued at the stop line; this logic is also part of so-called volume–density control. The minimum green is set by the formula

$$\text{mingreen} = L_s + n * h_{\text{sat}} \tag{1}$$

where

L_s = start-up lost time (assumed to be 1.5 s),
n = queued vehicles per lane at the beginning of green, and
h_{sat} = saturation headway for a single lane (assumed to be 2 s for through phases and 2.15 s for left-turn phases).

Cars are expected to be in the queue if they pass the upstream detector later than X seconds before the start of yellow, where X = travel time from the upstream detector to the stop line minus the yellow time. The controller continually monitors the number of vehicles detected in the last X second, so that, when the signal turns yellow, the predicted queue length is initialized to this value and then incremented for every vehicle detected afterward.

In principle, queue estimation logic should also account for residual queues left from the previous cycle. This accounting could easily be done in simulation by placing a counting detector after the stop line and by using the difference between vehicles counted at the upstream detector and those counted when they exit the intersections. However, it is complicated in practice because detection errors result in drift, which makes such differences unreliable if they are not reset every cycle. In practice, residual queues tend to happen only for periods of long queues, during which the chance of premature gap-out is small. Therefore, the logic here includes no provision for increasing the minimum green on account of residual queues.

ACCOUNTING FOR TURNING VEHICLES LEAVING THROUGH LANES

It is a common assertion in traffic engineering that longer cycles lead to an increase in throughput, because a lower proportion of the cycle is consumed by lost time associated with change intervals. However, Denney et al. showed that headways increase (and therefore flow decreases) when green times become longer than the time required to discharge cars from an area as long as the left-turn bay (*8*). The reason this assertion is true is that a significant fraction of cars arriving after this point turn into the turn lane and therefore do not go through the intersection; this movement increases average throughput headway. Field studies indicate that increasing the cycle length does not increase throughput, and simulation results show that an increase in cycle length causes a reduction in throughput.

The issue of departing turning vehicles also affects the performance of gap-out logic if detectors are placed after the start of the turn bays (which is where they are usually placed so as not to confuse different movements). If the queue reaches beyond the start of a turn bay, through lanes adjacent to the turn lane may experience long headways even when the input flow is at the saturation flow rate because of cars turning into the turn bay. That movement can increase the probability of Type I error by making the controller think that the saturation flow period is over. One remedy is to use a modified headway distribution taken from a situation in which vehicles are turning out of the through lane. Doing so will result in a more generous critical headway threshold that will prevent a phase from gapping-out when a single turning vehicle departs from a through queue. Another solution is to reduce by one the number of headways that must be detected (e.g., instead of measuring the time for six headways, the time for five headways is measured), in effect allowing for a hole in the arriving vehicle stream. With either remedy, the controller should extend the green phase if the input flow is at the saturation rate and one vehicle turns off during a multiheadway period. However, if two consecutive vehicles turn off, the stream will probably fail to meet the multiheadway criterion.

In the simulation network explained later, both proposed solutions were tried on a three-lane approach. Results for both scenarios were almost identical, and the difference in average delay was insignificant.

SIMULATION MODEL

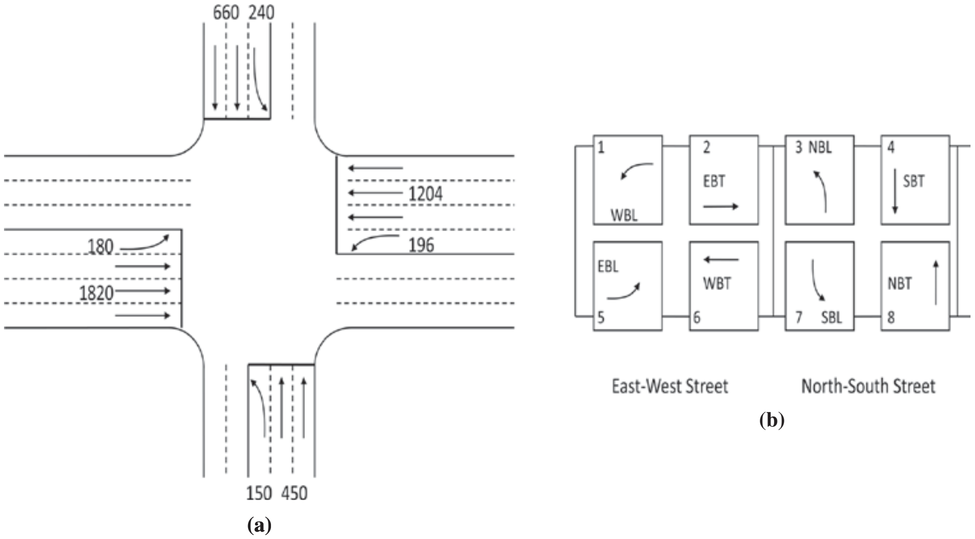
The effectiveness of multiheadway gap-out logic was evaluated with a simulation test bed developed in VISSIM. The test bed consisted of the junction of a six-lane road with a four-lane road, with left-turn bays with protected green only on all approaches and signal control following the standard dual-ring, eight-phase structure, as shown in Figure 4.

Base traffic volumes (v) (Figure 4) were chosen so that the intersection degree of saturation [$\sum(v/s)$ for the critical movements, where s = saturation flow rate] would equal 0.72. Right turns were treated, instead, as part of through volume. The split between left and right through volumes was done by using a biproportional model of origin–destination distribution, with a propensity ratio of 18:82, which has been shown to be consistent over a wide range of intersections when factored biproportionally to account for input and departure volumes (*9*). Base volumes were scaled up or down to create a heavy traffic scenario ($\sum v/s = 0.85$) and a lower traffic scenario ($\sum v/s = 0.60$).

Tested detection treatments included single-headway (traditional), lane-by-lane, and multiheadway. Multiheadway detection was tested only with upstream detectors; however, both stop-line and upstream detectors were tested for the single-headway and lane-by-lane detection schemes, because stop-line detection is the most common type of detection at actuated intersections.

In the dual-ring structure tested, left turns were leading and could be skipped for lack of demand; through phases had recall (i.e., could not be skipped). Phases that terminated at a barrier had nonsimultaneous gap-out; that is, whichever phase at the barrier gaps out first flags itself as gapped-out and waits until the other phase gaps out, and then both phases end their green (subject to minimum- and maximum-green constraints). As demonstrated by Furth et al., nonsimultaneous gap-out is more efficient than simultaneous gap-out (*1*); the latter would require that both phases have a gap greater than or equal to the critical gap at the same moment. For all phases, 6 s of minimum green was used unless it was superseded by a greater variable minimum green time (Equation 1). Maximum green time was set at 55 s for east–west through phases and 40 s for north–south through phases.

The control logic was programmed in C++ and interfaced to VISSIM through its application programming interface. In each simulation time step, the vehicle simulator advances vehicles on the basis of rules of vehicle behavior and then passes status to the controller. The controller will then change the signal state as appropriate on the basis of that detector information and then return control to the vehicle simulator.



(a)

(b)

FIGURE 4 Layout of VISSIM simulation model with (*a*) base traffic volumes and (*b*) eight-phase dual-ring control (WB = westbound; EB = eastbound; NB = northbound; SB = southbound; L = left turn; T = through traffic).

RESULTS AND ANALYSIS

Simulation experiments were based on five replications with different seeds. Each replication lasted 3,600 s after a 300-s warm-up. A comparison of average intersection delay and average cycle length for the different gap-out treatments is given in Figure 5. The results are provided in stacked columns, in which the height of the lower column shows average delay and the height of the top column (not its length but its final height) represents average cycle length.

With single-headway detection on three-lane approaches, the critical headway threshold was selected as 2.2 s (critical headway corresponds to 0.5% Type I error). With lane-by-lane detection, there is no easy way of applying the 0.5% Type I error criterion, because an error in one lane does not necessarily lead to gap-out. Therefore, a reasonable value of 2.8 s was assumed as critical headway. With multiheadway logic, the critical threshold for six headways when the 0.5% Type I error criterion was used was 5.3 s. However, to account for departing turning vehicles, the controller watched for five headways during this six-headway threshold value (i.e., 5.3 s), as described earlier. Also tested was the case of detecting six headways with 6.5 s as the critical headway, which yields 0.5% Type I error when cars in the left lane occasionally turn off. The results of the two scenarios were found to be almost identical, and so the results reported come from five-headway detection.

Upstream detection for both single-headway and lane-by-lane detection provides a strong benefit, with significant reductions in delay and cycle length compared with having the extension detector at the stop line, especially at higher volumes. Compared with traditional single-headway stop-line detection, upstream detection provides a greater benefit than the incremental benefit derived, once detectors are moved upstream, from using multiheadway detection. In the comparisons that follow, upstream detection will be assumed for all methods so as not to unduly distort the comparison.

Simulation results indicated that, when traffic flow is low (i.e., $\sum v/s = 0.60$), the average delay improvement because of multiheadway detection compared with single-headway and lane-by-lane logic was less than 1 s. Nevertheless, multiheadway detection resulted in a 7-s (12%) reduction in cycle length compared to single-headway detection, which significantly reduces delay for pedestrians.

In moderate-flow conditions ($\sum v/s = 0.72$), the benefits associated with multiheadway detection became noticeable, though still small. Compared with single-headway detection with an upstream detector, average delay fell by 1.6 s and cycle length fell by 12 s (15%). Benefits compared with those of lane-by-lane detection were slightly smaller.

The greatest reduction in delay and cycle length came under high traffic flow (i.e., $\sum v/s = 0.85$). Compared with single-headway upstream detection, multiheadway logic reduced average delay by 4 s (10%) and shortened the cycle by 16 s (15%). In this higher-demand scenario, lane-by-lane gap-out resulted in greater delay than single-headway gap-out, and both were clearly outperformed by multiheadway gap-out. The poor performance of lane-by-lane gap-out appeared to be attributable to the effect of turning vehicles leaving the leftmost through turn lane to enter the turn bay; this movement apparently caused that leftmost through lane to gap out early and to increase the frequency of premature gap-outs for the approach as a whole. This result can also be seen in the cycle length values. Cycle length under lane-by-lane logic was substantially smaller than single-headway detection; however, lane-by-lane logic resulted in higher delays because east–west phases often gapped out prematurely.

IMBALANCE IN LANE UTILIZATION

When a standing queue in a multilane approach dissipates, some lanes are bound to empty sooner than others. With snappier gap-out criteria, the chance increases that the phase will gap out because one or more

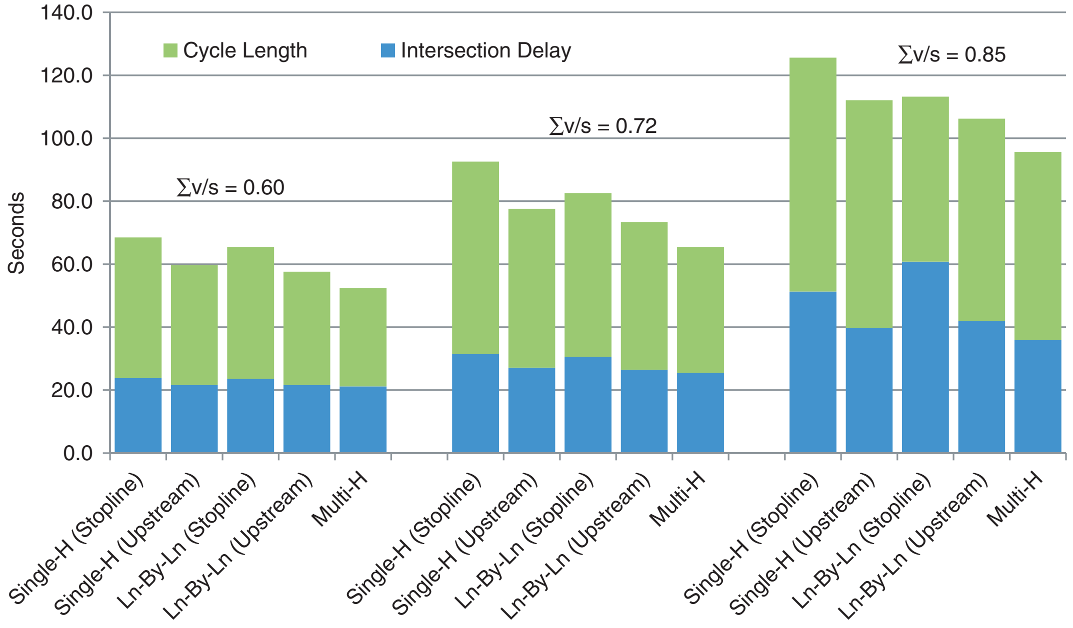


FIGURE 5 Average delay and average cycle length results under single-headway (single-H, traditional), lane-by-lane (ln-by-ln), and multiheadway (multi-H) detection logic with varying traffic flow rates and detector setback (cycle length = final height of top column).

lanes have no more flow while some queued cars remain in lanes that have not yet fully discharged their queue even though other lanes have no more traffic. Simulation models capture this kind of end-of-phase imbalance because of the extent to which it arises from randomness. However, in many realistic situations, motorists' clear preference for certain lanes can make the end-of-phase imbalance greater. On one hand, signal control strategies that reward drivers for making better utilization of lanes are desirable; on the other, some accommodation may be desirable, at least for the first few seconds of unsaturated flow.

CONCLUSION

Traditional gap-out logic on multilane approaches is inefficient because the high variability in headways makes it difficult, based on measurement of a single headway, to distinguish saturation flow from nonsaturation flow. The authors have proposed a new gap-out logic based on detecting multiheadways that exhibits far less variability. In simulation testing, the proposed approach outperforms both traditional single-headway and lane-by-lane detection. The advantage is most pronounced when intersections are close to saturation, when the difference between arrival flow and discharge flow is smallest. The experiments also suggest that the greater part of the benefit can be obtained simply by replacing stop-line detection with upstream detection.

The effect of traffic turning out of through lanes into turn bays can have a significant effect on vehicle flow and controller performance during heavier traffic periods. The remedy that was tested, reducing by one the number of vehicles required in a multiheadway, worked well in the experiments. Another complication that was not addressed is lane imbalance, especially when caused by motorists' preference for one lane over another.

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