Daniel B. Fambro Student Paper Award: Evaluation of Lane-by-Lane Detection at Signalized Intersections Using Simulation

The ITE 2008 Daniel B. Fambro Student Paper provides analysis of an emerging lane-by-lane detection scheme at signalized intersections. Unlike the current single-channel detection, where all the detectors across all the lanes on a particular approach are connected to the same signal phase, lane-by-lane detection monitors the headways/gaps on a lane-by-lane basis. Lane-by-lane detection is expected to provide more efficient detection by gapping-out the phase when the vehicle queues have discharged, improving the efficiency of traffic signal operations. To evaluate the effectiveness of lane-by-lane detection schemes, a traffic simulation model was developed in VISSIM. Several scenarios were analyzed that included factors such as traffic volume, maximum allowable headway and number of lanes. The measures of effectiveness used in the evaluation included vehicle delays and the percentage of cycles when the actuated phases reached maximum. Results from extensive simulation runs indicated that lane-by-lane detection was more efficient than single-channel detection under moderate traffic volumes. Lane-by-lane detection was also more efficient when more lanes existed on an intersection approach.

BY XUAN WANG

INTRODUCTION

For actuated signal control at intersections with multilane approaches, detectors are normally placed in each lane. Two types of traffic detection schemes can be utilized for vehicle detection associated with multiple detectors: single-channel detection and lane-by-lane detection.[1]

The current single-channel detection method connects detectors in all lanes on an approach into a single detection circuit. Therefore, when any detector on the approach senses a vehicle, the controller's gap-out timer for that phase will reset. The phase only terminates once the entire approach gaps out. Such a detection scheme may cause unnecessary green extensions for a multilane approach based on the desired headway.

Lane-by-lane detection, however, is an emerging detection scheme in which each lane is monitored with a separate detector and gap-out timer. Under this method, the vehicle phase for the approach terminates when all lanes have individually reached the desired gap-out condition.

Vehicle actuated programming (VAP) is an add-on module of the VISSIM traffic simulation software created to develop user-defined controller logic within the simulation. To simulate the lane-by-lane detection and evaluate its effectiveness, traffic-actuated signal control logic for the detection scheme is coded in VAP, and the VISSIM simulation simulates traffic performance. For a multilane approach, FLAG variables were used to record the status of each lane, and the conditional statement was used to check these FLAG variables at each simulation second. When all of the lanes are flagged to reach the desired gap-out condition, the phase for the approach gaps out. With this signal control logic, the lane-by-lane detection scheme can be represented by the simulation model.

The primary objective of this article is to use VAP within the VISSIM traffic simulation software to simulate the two detection schemes and compare their performance. VISSIM model comparisons were performed to evaluate how the two detection schemes would affect the performance of an actuated signalized intersection. Several scenarios using different variables such as volume, maximum allowable headway (MAH) and number of lanes were examined to determine which variables affect the performance of lane-by-lane detection.

PREVIOUS RESEARCH

Several research efforts have been conducted regarding signal timing and modeling of actuated signal controls.[2–5] Appendix B in Chapter 16 of the *Highway Capacity Manual,* 2000 Edition, documents a methodology developed by Akcelik for estimating green extensions for actuated traffic signals.[6,7] Based on that methodology and Cowan's M3 model, which is commonly used to describe headway distributions, Tian developed a microscopic simulation model of the lane-by-lane detection scheme utilizing the Visual Basic programming language in Microsoft Excel.[8,9] Using the simulation model, comparisons were made between the green extensions of the two detection schemes over a wide range of traffic flow scenarios. The study found that the difference in average green extension was generally minimal between the two detection schemes, although large differences did exist among certain cycles.

In a study conducted by Wu and Tian based on probability theory, a mathematical model was derived for the lane-by-lane detection scheme.[10] The mathematical model was validated based on an earlier simulation model by Tian.[11] The study suggests that lane-by-lane detection generally delivers shorter green extensions than the single-channel detection for multilane approaches.

Effectively distributing green times among different phases is critical to the efficiency of traffic signal operations. As for the efficiency impact of lane-by-lane detection, Smaglik et al. found that the largest improvements associated with lane-by-lane detection occurred during periods with moderate volume-to-capacity ratios, while smaller benefits were observed during periods of heavy or light traffic.[12]

SIMULATION MODEL AND ANALYSES

Because lane-by-lane detection is a recently proposed detection scheme, adequate field data are not available to compare the two detection schemes. A simulation model was deemed a suitable method to address the issue. Among the available traffic simulation packages, the VISSIM software was selected due to its VAP module, which features user-defined controller logic capabilities required for the purposes of this study. To carry out the study, some assumptions were made regarding lane configuration, traffic volumes and signal timing, which are described below.

A symmetric lane configuration was assumed on the four intersection approaches. Each approach had one exclusive left-turn lane with protected left-turn phasing and multiple through lanes, including one shared right-turn and a through lane allowing right turn on red. The detection scheme was applied to the multiple through lanes. Therefore, the number of lanes in the detection analysis referred only the number of through lanes. The number of through lanes varied based on the scenario. Detectors were placed on each lane for fully-actuated signal control. Fifteen-foot-long detectors were used for both presence and extension purposes.

Different traffic volumes were assumed for the scenarios to be analyzed. Because the study focused on detection schemes in multiple through lanes, 90 percent of the approach volume was defined to be through traffic. Left-turn and right-turn traffic each was 5 percent, which was a relatively minor component of the approach volume and would not influence the traffic performance significantly.

An eight-phase, fully-actuated signalized intersection was built in VISSIM, and the signal control for the intersection was defined by VAP coding, which could perform both the single-channel detection scheme and the lane-by-lane detection scheme. For this study, a maximum green time of 50 seconds was used for signal timing.

The VAP variable "DetectionMode" was used to define whether the controller ran under the single-channel or lane-by-lane detection scheme when performing the simulations. The gap-out logic of the two detection schemes was analyzed accordingly.

Single-Channel Detection

Current practice for vehicle detection uses the single-channel detection scheme. In this method, all the detectors in individual lanes on an approach are linked to a single input for the same signal phase. The controller sees the combined gaps across all the lanes and determines when a gap-out condition is reached. A phase does not necessarily terminate even if all the individual lanes may have exceeded their MAH. The single-channel detection may result in unnecessary green extension, which may not be efficient from an operations point of view.

For example, under certain conditions, traffic in individual lanes may already exceed the MAH, but the controller may still see the combined headways less than the MAH and, thus, will not gap out.

During a VISSIM simulation run, the VAP program logic is usually called at the end of each simulation second after the vehicles have moved. VAP programming is able to report the detected headway for each of the detectors. To simulate the single-lane detection control logic in the program, a green phase was designed to terminate at the simulation second when it had reached the minimum green time and the headways for all the lanes were detected to be greater than MAH.

Lane-by-Lane Detection

In the case of lane-by-lane detection, the detectors monitor the headways in each lane independently. The phase gaps out when all the lanes reach the gap-out condition. The program developed simulated this logic using a FLAG variable. For a multilane approach, each detector was assigned a FLAG variable, which was used to indicate if the lane in which the detector was placed had reached the gap-out condition. The program logic checked every simulation second and terminated the phase when the green time was greater than desired minimum green time and all the FLAG variables for that approach had reached the gap-out condition.

MAX-OUT RATE AND DELAY ANALYSIS WITH TWO DETECTION SCHEMES

Properly extending the green time after clearing the queue is important for efficient signal operation. For single-channel/single-lane detection, Akcelik presented the following model for estimation of green extension:[13]

$$\o_e \text{ (single lane)} = \frac{\int_0^h tf(t)\,dt}{1-p} \qquad (1)$$

where:
$\o_e$ (single lane) = expected phase extension for single-channel detection
h = value of MAH
$f(t)$ = headway distribution function
p = probability of having headway less than h

For lane-by-lane detection, the probability of phase gap-out is the total probability that one lane gaps out while the other lanes have gapped out earlier. Based on the green extension estimation in Eq. 1 and probability theories, Wu developed the following model to estimate green extension $\o_e$ for lane-by-lane detection with m lanes:[14]

$$\o_e = \o_e \text{ (single lane)} K_m \qquad (2)$$

where:
K_m is a factor of p and m
$K_2 < K_3 < \ldots < K_m$ and $K_i < i$ holds

From the above equations, it can be seen that the major factors that would affect the signal timing for lane-by-lane detection are the distribution of headways, which are largely related to the traffic volume, MAH and number of lanes. Therefore, the scenarios developed in this study were mostly based on these three variables. The different scenarios used different variable values and were analyzed based on two major performance measures: the phase max-out rate and the average intersection delay.

Volume Scenarios

Effectively allocating the green times among conflicting movements is critical to the efficiency of traffic signal operations. Under actuated signal control, the green extension portion of a phase relies primarily on vehicle detection. In an extreme case, if the detection scheme is not able to properly gap-out the phase after clearing the queue, the green time would keep extending until it reaches the designed maximum green time, or max out point. A higher max-out rate not only indicates inefficient signal operations but also imposes potential safety concerns where normal detector functions for dilemma zone protection are disabled.

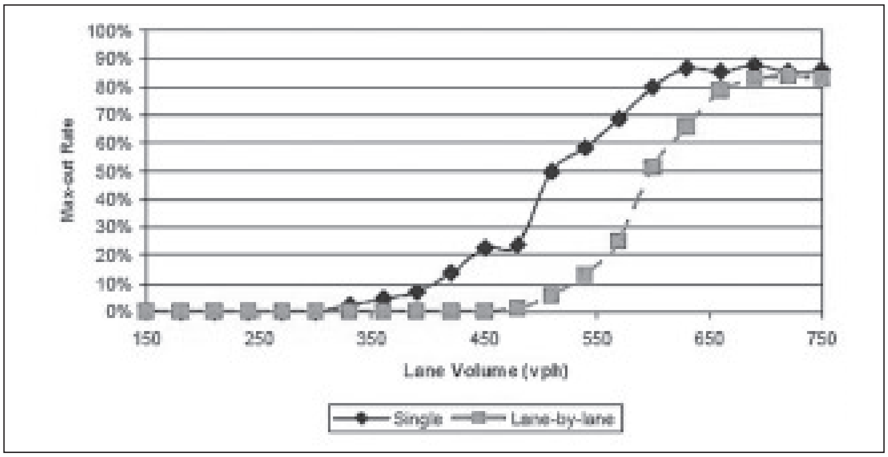

Figure 1. Max-out rates under the two detection schemes with 3.0-second MAH.

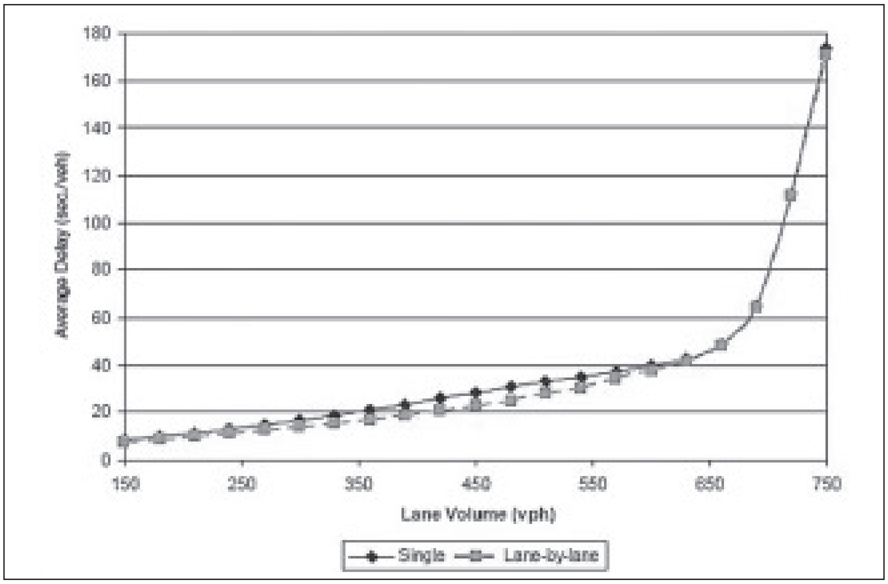

Figure 2. Average delay under the two detection schemes with 3.0-second MAH.

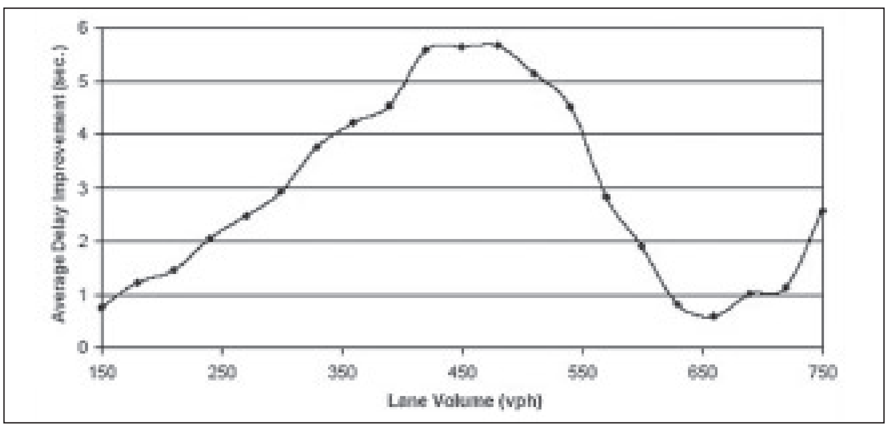

Figure 3. Average delay improvement using lane-by-lane detection.

Using the VAP, the percentage of cycles in which the phase maxed out was reported for the north-south and east-west movements during each simulation run. Because the intersection had symmetric geometry, the max-out rates for the two streets were usually very close during the simulation runs. The intersection max-out rate represented the average max-out rate for both north-south and east-west approaches.

In the base model with three through lanes, the MAH of the model was set at 3.0 seconds. To illustrate the effects of two detection schemes on green allocation regarding the max-out rate, the simulation module under each detection scheme was run with 21 approach traffic volume scenarios ranging from 500 vehicles per hour (vph) to 2,500 vph. As stated above, 90 percent of the link volume was assumed to be through traffic. Given three lanes on each approach, the calculated lane volumes ranged from 150 vph per lane to 750 vph per lane. All scenarios were simulated 10 times with each run lasting for a 1-hour period. The average value from the 10 simulation runs was used to produce the results. The intersection max-out rates under each detection scheme are presented in Figure 1.

As shown, the max-out rates for both detection schemes increased from 0 percent at relatively low volumes to around 90 percent for higher volumes. Max-out rates did not reach 100 percent due to simulated volumes not being extremely high and randomness in vehicle arrivals causing gap-out conditions even when through volumes were high. However, the overall results are considered justified in the scope of the study.

Under the single-channel detection scheme, the max-out rate began to increase at volumes around 300 vph, compared to an increase near 450 vph in the lane-by-lane condition. In addition, the max-out rate was larger with the single-channel detection for most of the moderate volume scenarios, which was an indication that the lane-by-lane detection was able to allocate the green time more efficiently than the single-channel detection.

Unnecessary extra green time for a phase for which the headway has already been greater than the desired MAH would be better used to serve other conflicting phases. Also, the improper green extension may increase the cycle length, impacting the intersection capacity. The delay analysis shown in Figures 2 and 3 further verifies this.

Figure 2 illustrates the average delay of the intersection under each scenario for the base model. The average delay for both cases increased gradually until the volume reached near- or over-capacity conditions, where the green time could not clear the queue in one cycle. From there, the average delay from these volume scenarios grew dramatically. An analysis using the Synchro model showed that the capacity for such an intersection was around 700 vph for the through traffic, which is consistent with the results obtained in this study. It is easily observed from the figure that the average delay under lane-by-lane detection was lower than that under the single-channel detection for most of the moderate traffic volume scenarios. The difference in average delay is more apparent in Figure 3.

As shown, the difference in average delay resembles a bell shape. The largest difference appeared at moderate volumes with the average delay improvement approaching zero for increasing or decreasing traffic volumes. There were significant variations around the near- or over-capacity volumes. This variation, as described in a study by Tian, could be a phenomenon in which high variations in microscopic simulation models normally occur when the traffic demand approaches capacity.[15]

From this analysis, the lane-by-lane detection scheme was able to provide better traffic operation than the single-channel detection for moderate traffic volume scenarios. The biggest improvement of 5.7 seconds (22.6 percent) appeared when the lane volume for through traffic was around 450 vph. The effect of lane-by-lane detection was minor for light and near- or over-capacity volume scenarios.

MAH Scenarios

MAH is another important factor that influences the operation of lane-by-lane detection. In this section, a MAH of 2.5 seconds was used to generate results for both detection schemes. The same volume scenarios from the previous analysis were used to demonstrate the trend of the max-out rate and average delay. The results were compared with those using a 3.0-second MAH to see the similarity and difference. Max-out rates from the 2.5-second MAH scenario are shown in Figure 4, compared with the results from the 3.0-second base model.

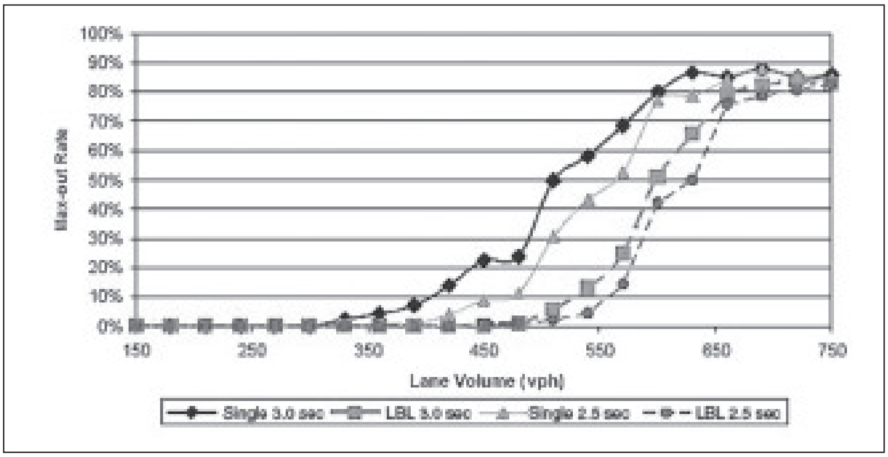

Figure 4. Max-out rates under the two detection schemes with 2.5- and 3.0-second MAH.

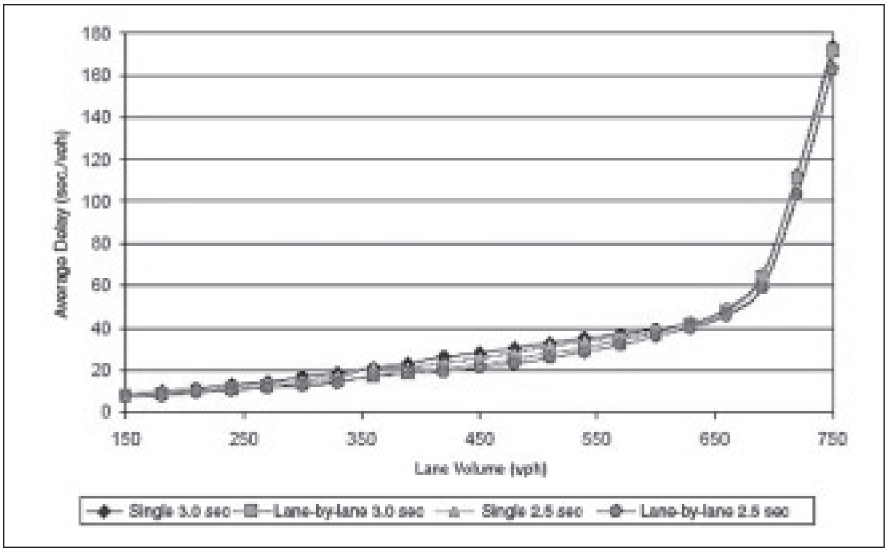

Figure 5. Average delay under the two detection schemes with 2.5- and 3.0-second MAH.

Figure 4 shows that the relationship between the max-out rates under the two detection schemes with a 2.5-second MAH was similar to the 3.0-second MAH case. However, the max-out rates for both detection schemes increased from zero at higher volumes in the 2.5-second MAH scenario. In addition, max-out rates were always lower in the 2.5-second MAH case for most moderate traffic volume scenarios.

Similar trends regarding average delay are reported in Figure 5. Although the average delays were lower for the 2.5-second MAH compared to the 3.0-second scenario, the difference between the two detection schemes using a 2.5-second MAH followed the previous pattern.

The results regarding the delay improvement are illustrated in Figure 6. The average delay improvement with the 2.5-second MAH showed a trend similar to the 3.0-second case, except that there was an offset between the traffic volumes for which the delay improvement reached the maximum of approximately 5.5 seconds. Noticeable variations were again found in the near- or over-capacity volume scenarios.

The overall analysis suggested a 2.5-second MAH was generally able to produce better intersection performance in terms of average delay. The lane-by-lane detection scheme with 2.5-second MAH provided the best efficiency among the four scenarios under most volume conditions, especially those with moderate traffic. The largest delay improvement of 5.5 seconds (21.3 percent) was obtained when the lane volume for through traffic was around 510 vph. The effects of lane-by-lane detection for both MAH scenarios were minor for light and near- or over-capacity volume scenarios.

Number of Lanes Scenarios

The effect of the number of lanes on the through approach was examined. Max-out rates and average delay improvements for all lane volume scenarios from the previous analyses were generated again, this time with a different number of lanes on the through approach. Models utilizing both detection schemes were simulated with two and four lanes, using a MAH of 3.0 seconds. These cases were then compared with results from the three-lane base model. The results from these simulation runs over the same lane volume range are depicted in Figures 7 and 8.

As can be concluded from the figures, the difference in max-out rate between the two detection schemes generally became larger with the increase in the number of lanes. The obvious improvements still exist for the moderate traffic volume scenarios. Again, for light and near-capacity volumes, the two detection schemes did not give significantly different results.

The impact of number of lanes on signal timing affected efficiency as it relates to average delay. The delay improvements due to implementation of lane-by-lane detection are shown in Figure 9.

The average delay improvement realized when utilizing lane-by-lane detection became more prominent with the increase in number of lanes. The maximum delay improvements for the two-, three- and four-lane cases were 7.0, 5.7 and 3.3 seconds, respectively. It should also be noted that the lane volume at which the delay improvement reached the maximum was lower for the scenario with the highest number of lanes. For example, according to Figure 9, the largest improvement for the four-lane model was at a lane volume of approximately 420 vph, while the highest delay improvement for the two-lane model appeared around 480 vph.

The analysis regarding the effect of the number of through lanes on the approach illustrates that number of lanes is an important factor influencing the performance of lane-by-lane detection. For approaches with multiple lanes, lane-by-lane detection should be recommended for its superior efficiency in signal control over the single-channel scheme.

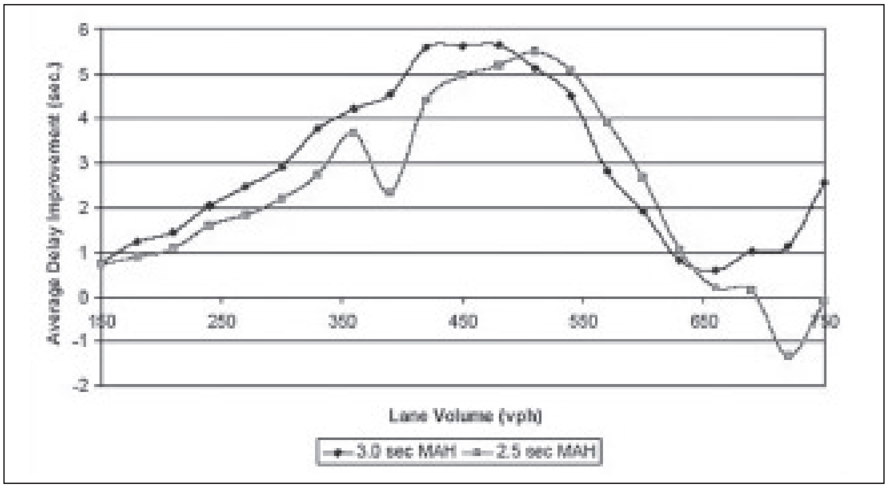

Figure 6. Delay improvement by using lane-by-lane detection with 2.5- and 3.0-second MAH.

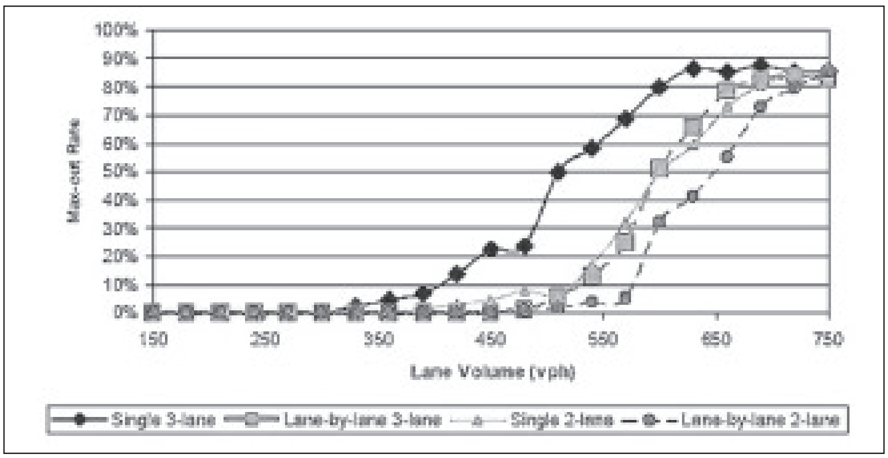

Figure 7. Max-out rates under the two detection schemes with two and three lanes.

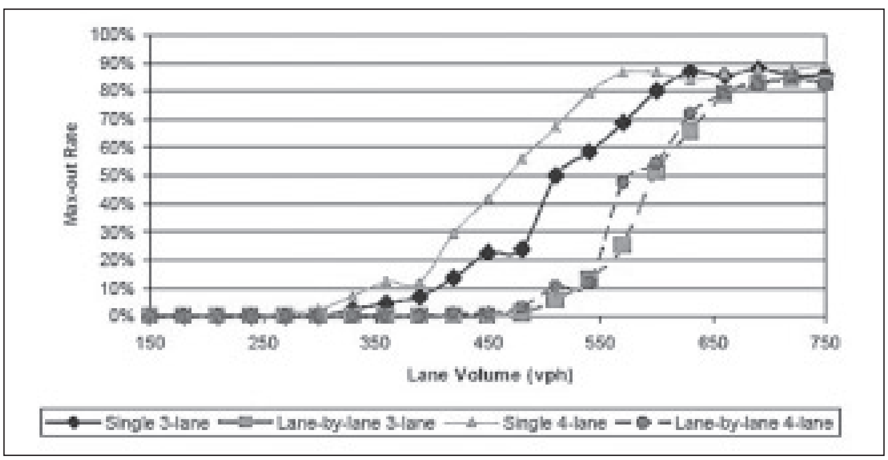

Figure 8. Max-out rates under the two detection schemes with three and four lanes.

SUMMARY AND CONCLUSIONS

From a traffic operations point of view, proper allocation of green time for each phase is critical to the efficient performance of actuated signalized intersections. Single-channel detection and lane-by-lane detection are two schemes that govern the green extension portion of an actuated signal phase. This paper focused on utilizing the VAP language to build a VISSIM module to analyze the effects of the two detection schemes on the performance of a fully actuated signalized intersection. The measures of effectiveness used in the evaluation included vehicle delays and the percentage of cycles when the actuated phases reached maximum.

This paper analyzed the gap-out logic and performed simulation runs of the green extension in the form of max-out rate with the two detection schemes under 21 traffic volume scenarios. Lane-by-lane detection was observed to more easily reach the gap-out condition and provided efficient signal timing solutions. The effect of these detection schemes on overall intersection delay was found to be minimal, with more significant delay improvements noticed under moderate traffic volume conditions.

Two scenarios related to the MAH of 2.5 seconds and 3.0 seconds were analyzed. It was found that a 2.5-second MAH was able to produce better intersection performance compared to a 3.0-second MAH under the same vehicle detection scheme. The average delay improvement using a 2.5-second MAH was similar to the 3.0-second result, except the volume at which the delay improvement reached its maximum was a little higher in the 2.5-second MAH case. The overall improvements were not found to be significantly different between the two scenarios.

The number of lanes greatly affected the difference of max-out rate and efficiency under the two detection schemes. Lane-by-lane detection with four lanes showed the most significant improvement over single-channel detection among the two-, three- and four- lane scenarios. This indicates that lane-by-lane detection can provide more significant improvement for approaches with more lanes.

Based on the results of this study, it can be concluded that lane-by-lane detection greatly benefits traffic operations at actuated signalized intersections, especially under moderate traffic volumes and on multilane approaches. The benefit is mainly reflected by minimizing the possibility of a phase max-out. However, the effect on overall intersection delay is not significant.

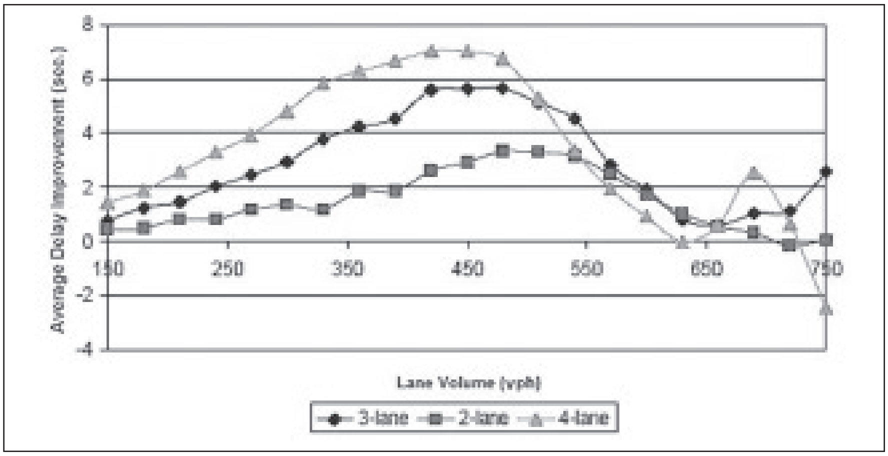

Figure 9. Delay improvement by using lane-by-lane detection with different number of lanes.

The study used microscopic simulation to evaluate the efficiency and impacts associated with lane-by-lane detection. However, microscopic models are limited when attempting to analyze a large number of scenarios with varying parameters. Development of an analytical model would be a valuable avenue for further research. The tools developed in this study could be used to validate future analytical models.

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XUAN WANG

is a research assistant and has been pursuing a Ph.D. in transportation engineering at the University of Nevada, Reno since January 2006. Her advisor is Dr. Zong Tian. She has won several awards from ITE during her studies, including best student paper awards from District 6 and the Intermountain Section, and the Ellis Mathes Scholarship. She obtained her master's degree in transportation engineering from Beijing Jiaotong University in China. She is a student member of ITE.