Green Extension and Traffic Detection Schemes at Signalized Intersections

Zong Tian and Thomas Urbanik

This paper provides analyses of green extensions associated with two vehicle detection schemes for actuated signal control: the current single-channel detection and the emerging lane-by-lane detection. The current single-channel detection has all detectors across all lanes on a particular approach providing a single input to a signal phase. Lane-by-lane detection, however, monitors headways and gaps on a lane-by-lane basis. A simulation model was developed to analyze both detection schemes. With the simulation model, green extensions by the two detection schemes were compared over a wide range of traffic scenarios. On the basis of study results, it was found that the two detection schemes do not produce significantly different green extensions under normal traffic flow conditions. For the various factors examined, maximum allowable headway (also passage time) is found to be more sensitive compared with other factors such as arrival headway patterns and lane volume distribution. Although the difference between the two detection schemes in average green extension is generally minimal, large differences do exist among certain cycles, and the actual impact on signal operations could be more significant; this would need further evaluation with other standard traffic simulation models.

At signalized intersections with multilane approaches and actuated control, vehicle detectors are usually placed in each individual lane. Currently, the detectors across all lanes on a particular approach are linked together and are channeled to the same signal phase for controlling the phase duration. When any of the detectors detects a vehicle, the controller's gap-out timer resets and the phase (green) extends. Such a detection scheme makes it difficult to gap out a phase based on the desired headway or gap, especially when an approach has more than one lane. The unnecessary green extension directly affects the efficiency of signal operations, in which the extra green could be allocated to better serve other traffic movements. Ideally, a signal phase should terminate when a gap-out is reached for each lane individually; this suggests a new detection scheme, namely, the lane-by-lane detection (*1*).

The primary objective of this paper is to evaluate how the two types of detection schemes would affect the phase extension at actuated traffic signals, which is a major parameter affecting signal operations. The evaluation is focused on comparing the amount of green extension with the two detection schemes: the current single-channel detection and the lane-by-lane detection. Green extension is part of the green interval of a signal phase beyond the minimum green or the saturated portion of the green that clears the standing queues. Estimation of green extension is an essential element for capacity and delay calculations at signalized intersections (*2*). Although some methodologies are available to estimate green extension based on the current single-channel detection scheme, the effect of the alternative schemes on multilane approaches needs to be studied (e.g., lane-by-lane detection in this study).

This paper is organized as follows. In the next section, a review of the two detection schemes and the related traffic control features is provided. Examples are given to illustrate the differences between the two detection schemes. A review of the existing analytical models for green extension estimation is also provided. The paper then focuses on the development of a simulation model for estimating green extension based on the lane-by-lane detection scheme. By using the simulation model, analyses of the two detection schemes are conducted on the basis of various traffic scenarios. Finally, a summary and conclusions are provided.

DETECTION SCHEMES AND ACTUATED SIGNAL OPERATIONS

To understand how the two detection schemes affect the green extension, a review of actuated signal control is provided, including some common terms related to vehicle detection and signal controller operations. Next, examples illustrating the differences between different detection schemes are provided.

Passage Time and Maximum Allowable Headway

Figure 1 illustrates a typical detection layout at a single-lane approach using a single detector located upstream of the stop bar. A detector can be set up with either a pulse mode or a presence mode. In a pulse mode, the detector produces a pulse signal the moment a vehicle passes the detector, and then the detector turns off. The gap-out timer in the signal controller starts immediately after the pulse signal is produced. In a presence mode, the detector remains activated as long as the vehicle stays on the detector. The gap-out timer starts only after the vehicle leaves the detector. The remaining discussions are based on detector operation with the presence mode, which is a preferred mode in field operations. The reason that presence mode is preferred over the pulse mode is that pulse mode will not work properly when the lane is blocked downstream.

In actuated signal operations, a phase terminates (gaps out) when a gap larger than the phase passage time is encountered. As one of the major signal control parameters, the phase passage time has also been referred to with the following terms: passage gap, vehicle interval, preset gap, and vehicle extension. Equation 1 shows the relationship between all variables in Figure 1.

Z. Tian, Department of Civil and Environmental Engineering, University of Nevada–Reno, Reno, NV 89557. T. Urbanik, Civil and Environmental Engineering, University of Tennessee, 219-B Perkins Hall, Knoxville, TN 37996-2010.

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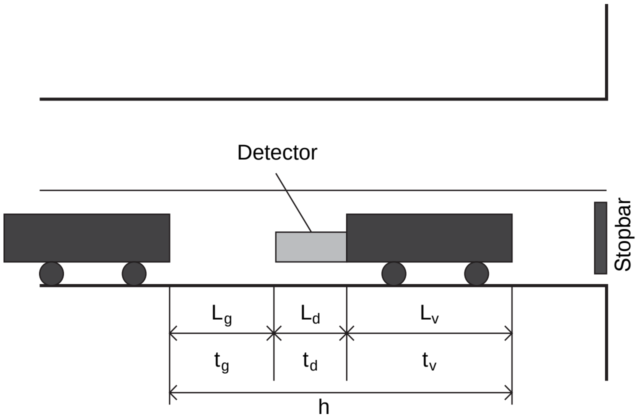

FIGURE 1 Vehicle detection layout and related variables. (L_g = distance gap, L_d = detector length, L_v = vehicle length, t_g = time gap, t_d = time to traverse detector length, t_v = time to traverse vehicle length, and h = time headway.)

$$h = t_g + t_d + t_v = t_g + \frac{L_d + L_v}{S} \qquad (1)$$

In Equation 1, S is the vehicle speed in feet per second, and t_g equals L_g/S. All other variables are defined in Figure 1. In Equation 1, if the time gap (t_g) is set equal to the passage time in the controller, the resulting headway (h) is called the maximum allowable headway (MAH). The MAH is the maximum headway in the traffic stream that would keep the phase extending without gapping out. If the vehicles are the same length and travel at the same speed, the MAH and the passage time differ at a constant value, which equals the time that a vehicle traverses the distance of the detector length and the vehicle length. When the detector is in pulse mode, the MAH equals the passage time. In the following discussions, uniform vehicle length and travel speed are assumed; therefore, the analyses are focused on examining the vehicle headways rather than the time gap.

Types of Detection Schemes

Current practice in vehicle detection is to have all detectors in individual lanes on a particular approach providing a single input into the same signal phase. For example, if there are three lanes on an approach and the associated signal phase is Phase 2, there will be three detectors, one in each lane, and all three detectors will be wired together to provide actuations for Phase 2. For that reason, the current detection is called single-channel detection. The controller sees the combined gaps and headways across all 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 current single-channel detection scheme may therefore result in unnecessary green extension and thus may not be efficient from the operation's point of view. For example, while traffic in individual lanes exceeds the MAH, the controller may see the combined headways less than the MAH, and thus the phase will not gap out.

Another detection scheme, called lane-by-lane detection, is configured to monitor the gaps and headways on a lane-by-lane basis. When all lanes reach gap out, the phase would terminate.

The following examples illustrate the differences between the two detection schemes. Table 1 shows a sample of vehicle arrivals and the associated headways in each lane. The MAH, $h = 3.0$ s, is assumed in the examples, that is, when a headway is greater than 3.0 s, a gap-out condition is reached and the phase terminates.

TABLE 1 Vehicle Arrivals and Headways on Two-Lane Approach

Lane 1 Arrival Time	Headway (s)	Lane 2 Arrival Time	Headway (s)
1.8		1.2	
3.3	1.5	3.1	1.9
4.8	1.5	4.6	1.5
8.4	3.6 (>3.0)	6.1	1.5
12.0	3.6	10.3	4.2 (>3.0)
17.8	5.8	12.9	2.6
22.8	5.0	14.4	1.5
25.0	2.2	15.9	1.5
27.3	2.3	17.4	1.5
30.5	3.2	19.1	1.7
32.0	1.5	20.8	1.7
33.6	1.6	23.1	2.3
35.1	1.5	24.6	1.5
		32.6	8.0

Case 1. Current Single-Channel Detection

To determine when gap out occurs and the resulting green extension time with the single-channel detection, the arrival times in both lanes are sorted in sequence, and the headways are calculated (see Table 2). The numbers in bold italic represent the vehicles in Lane 2.

For the data shown in Table 2, a gap-out condition would occur at 27.3 s when the following headway is 3.2 s (>3.0). So the phase

TABLE 2 Combined Vehicle Arrivals and Headways on Two-Lane Approach

Combined Arrival			Combined Arrival		
No.	Time	Headway (s)	No.	Time	Headway (s)
1	***1.2***		15	17.8	0.4
2	1.8	0.6	16	***19.1***	1.3
3	***3.1***	1.3	17	***20.8***	1.7
4	3.3	0.2	18	22.8	2.0
5	***4.6***	1.3	19	***23.1***	0.3
6	4.8	0.2	20	***24.6***	1.5
7	***6.1***	1.3	21	25.0	0.4
8	8.4	2.3	22	27.3	2.3
9	***10.3***	1.9	23	30.5	3.2 (>3.0)
10	12.0	1.7	24	32.0	1.5
11	***12.9***	0.9	25	***32.6***	0.6
12	***14.4***	1.5	26	33.6	1.0
13	***15.9***	1.5	27	35.1	1.5
14	***17.4***	1.5			

would terminate at 30.3 s (27.3 + 3.0). For this particular example, the lane-by-lane detection results in 21.2 s (i.e., 30.3 – 9.1 = 21.2) less green extension than the current single-channel detection.

Case 2. Lane-by-Lane Detection

In the case of lane-by-lane detection, the headways in each lane are monitored independently by the detectors, and the phase would gap out when both lanes reach gap out. As shown in Table 1, Lane 1 first reaches gap out after the arrival at 4.8 s when the following headway is 3.6 s (>3.0), and Lane 2 reaches gap out after the arrival at 6.1 s when the following headway is 4.2 s (>3.0). Therefore, a gap-out condition would occur at 6.1 s, and the phase would terminate at 9.1 s (6.1 + 3.0).

Figure 2 provides a graphical presentation of the examples above. In Figure 2 the vehicle arrivals in each lane as well as the combined arrivals of both lanes are shown. The gap-out conditions are indicated by the location at which the headways are greater than the MAH of 3.0 s.

The examples above may not represent typical vehicle arrival patterns. Detailed investigations of the two types of detection schemes will be conducted later using the simulation model developed in this study.

GREEN EXTENSION ESTIMATION

Analytical Models

Several research efforts have been conducted in the past on estimating green extension for actuated signal controls (*3*–*6*). Appendix B in Chapter 16 of the *Highway Capacity Manual* (HCM 2000) documents a methodology of estimating green extension for actuated traffic signals (*2*). The methodology was primarily the work done by Akcelik (*5*). The following provides a brief summary of the methodology.

The green extension beyond the time of queue clearance depends on the MAH (h) and the vehicle arrival headways. The number of headways that the controller would be expected to hold forms a geometric distribution.

$$P_n = p^n(1-p) \tag{2}$$

where P_n equals the probability of extending n headways before experiencing a headway greater than the MAH (h), and p equals the probability of having a headway less than the MAH (h).

$$p = P(t < h) = \int_0^h f(t)\,dt \tag{3}$$

where $f(t)$ is the probability density function of the vehicle arrival headway distribution.

The average number of headways the controller holds [$E(n)$] can be obtained from the characteristics of a geometric distribution.

$$E(n) = \frac{p}{1-p} = \frac{\int_0^h f(t)\,dt}{\int_h^\infty f(t)\,dt} \tag{4}$$

The average green extension time would be the product of $E(n)$ and $\bar{T}$, the average length of headways less than h.

$$\bar{T} = \frac{V\int_0^h tf(t)\,dt}{V\int_0^h f(t)\,dt} \tag{5}$$

where V = traffic volume (vehicles per hour).

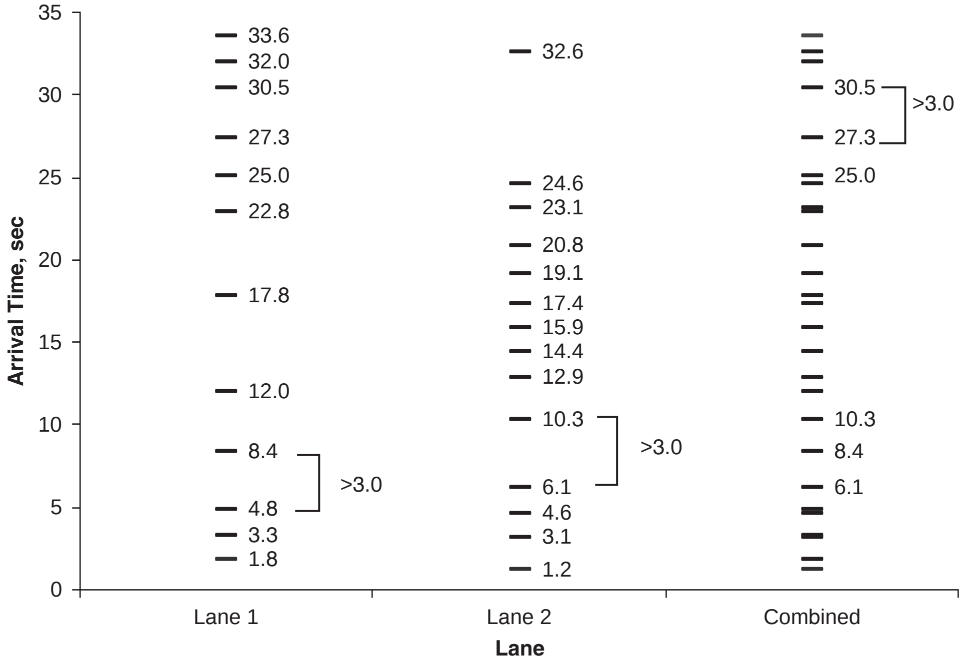

FIGURE 2 Vehicle arrivals by lane and combined.

The numerator in Equation 5 is the total time of those headways less than *h*, and the denominator is the number of headways that are less than *h*. From Equation 5

$$\bar{T} = \frac{\int_0^h tf(t)}{\int_0^h f(t)dt} \tag{6}$$

So the expected green extension (Φ_e) can be obtained from Equation 7:

$$\Phi_e = E(n)\times\bar{T} = \frac{\int_0^h tf(t)}{\int_h^\infty f(t)dt} \tag{7}$$

The actual termination point of the green is *h* beyond Φ_e. When *h* is considered as a portion of the green extension, Equation 7 becomes

$$\Phi_e = \frac{\int_0^h tf(t)}{\int_h^\infty f(t)dt} + h \tag{8}$$

With the type of vehicle known, arrival headway distribution, Φ_e, can be obtained.

One of the commonly used headway distributions is the so-called Cowan's M3 model (*7*), as given by the following equation for its probability density function.

$$f(t) = \begin{cases} \lambda\alpha e^{-\lambda(t-\Delta)} & \text{for } t \geq \Delta \\ 0 & \text{for } t < \Delta \end{cases} \tag{9}$$

where

α = proportion of free (nonplatoon) vehicles,
Δ = minimum headway (s), and
λ = model parameter in vehicles per second, determined on the basis of Equation 10.

$$\lambda = \frac{\alpha V}{3,600 - \Delta V} \tag{10}$$

Cowan's M3 model represents a generalized headway distribution with platoon characteristics. The other types of headway distributions, such as the negative exponential distribution (M1) and the shifted negative distribution (M2), are special cases of Cowan's M3 distribution. Cowan's M3 model has been widely used by researchers in conducting traffic studies (*8*).

With Cowan's M3 headway distribution, Equation 8 becomes

$$\Phi_e = \frac{3,600 e^{\lambda(h-\Delta)}}{\alpha V} - \frac{1}{\lambda} \tag{11}$$

with the negative exponential distribution, where $\alpha = 1$ and $\Delta = 0$.

$$\lambda = \frac{V}{3,600} \tag{12}$$

$$\Phi_e = \frac{3,600}{V}\left(e^{\frac{Vh}{3,600}} - 1\right) \tag{13}$$

with the shifted negative exponential distribution, where $\alpha = 1$.

$$\Phi_e = \frac{3,600}{V}\left[e^{\frac{V}{3,600-\Delta V}(h-\Delta)} - 1 + \frac{V\Delta}{3,600}\right] \tag{14}$$

Figure 3 illustrates the green extensions based on the two types of headway distributions: the negative exponential distribution and the shifted-negative exponential distribution. An MAH of 3.0 s is used in the figure. As can be seen, there is no significant difference in green extensions when the volume is less than 1,000 vehicles/h in a single lane. The amount of green extension is also minimal with less than 5 s. The constant 3.0 s is included. What it really indicates is that a gap-out condition can be easily reached with an MAH of 3.0 s and a traffic volume at 1,000 vehicles/h/lane or less, which is typically

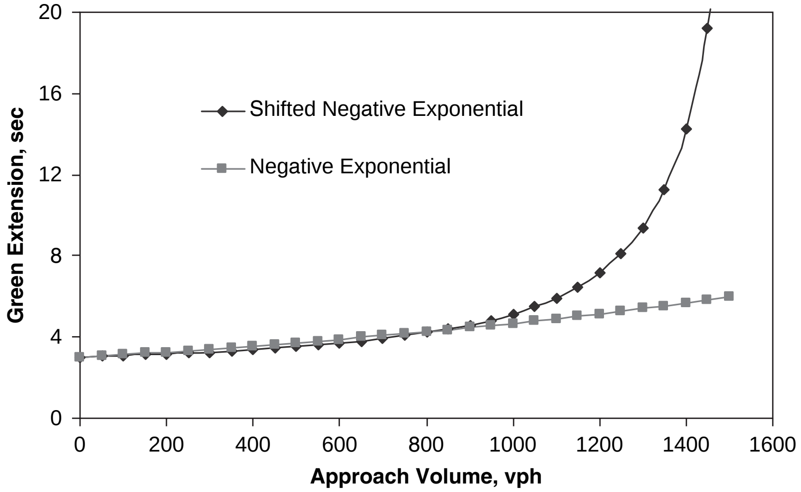

FIGURE 3 Green extensions with two types of headway distributions: negative exponential and shifted negative exponential (Δ = 2.0 s; *h* = 3.0 s).

found in the field. Significant differences can be noticed between the two headway distributions under high-volume conditions, when the lane basically reaches saturation, and gap out becomes difficult.

Simulation Analysis

The green extension model by Akcelik presented above was based on the following major assumptions:

- Single-channel detection scheme and
- Uniform vehicle length and travel speed.

Although it is possible to develop an analytical model based on the lane-by-lane detection scheme, capturing the effect of nonuniform vehicle length and varying speed may be difficult to accomplish in an analytical model. As the first step in addressing the lane-by-lane issue in this study, a microscopic simulation model was developed. The model was written in Visual Basic in Excel, and it provides estimates on green extension by the two detection schemes. The current version of the simulation model is still limited to modeling the case of uniform vehicle length and travel speed. However, the authors believe this preliminary study can nevertheless provide good insights into the lane-by-lane detection scheme. Incorporating nonuniform vehicle length and travel speed will be accomplished in future developments of the model if deemed necessary.

Major inputs of the model include approach volume, number of lanes, traffic-volume distribution by lane (also referred to as lane utilization in HCM 2000), maximum allowable headway, and parameters α and Δ for defining the headway distribution. The simulation model generates random vehicle arrivals based on specified headway distributions and calculates the green extensions for the two detection schemes. Each simulation run generates a total of 200 green extension times, representing 200 cycles of actual signal operations.

The simulation model is first compared with the theoretical model by Akcelik for model validity. Figure 4 shows the green extension results from the two models, which are based on the negative exponential headway distribution and the shifted negative exponential distribution with $\Delta = 2.0$ s. The traffic volume ranges between 0 and 1,500 vehicles/h on a single-lane approach. Results in Figure 4 indicate that the two models match very well as indicated by the high R^2 value of 0.977.

Simulation Results

With the lane-by-lane simulation model, various analyses are conducted to evaluate the two types of detection schemes. Results from the analyses are presented next.

Figure 5 compares the green extensions of the two detection schemes from a particular simulation run: three-lane approach with an approach volume of 1,600 vehicles/h, an MAH of 3.0 s, and a shifted negative exponential distribution in each lane with a Δ of 2.0 s. Each data point represents the green extension for the two detection schemes from a particular cycle. There are a total of 200 data points (cycles) in the figure.

The data in Figure 5 indicate that the single-channel detection always results in green extensions that are either the same or larger than the lane-by-lane detection. Although the difference can be as high as 24 s (e.g., 29 s versus 5 s) for a particular cycle, the average difference in green extension is only about 2.3 s. That can be explained by the distribution data shown in Figure 6, in which the distribution of the differences in green extension is plotted.

As can be seen from Figure 6, the two detection schemes result in the same green extension in about 60% of the cycles. The difference exceeding 15 s occurs only in about 3% of the cycles. This particular data set indicates that the two detection schemes may not be sensitive to the average green extension; that is, the two detection schemes may not produce significantly different capacity results.

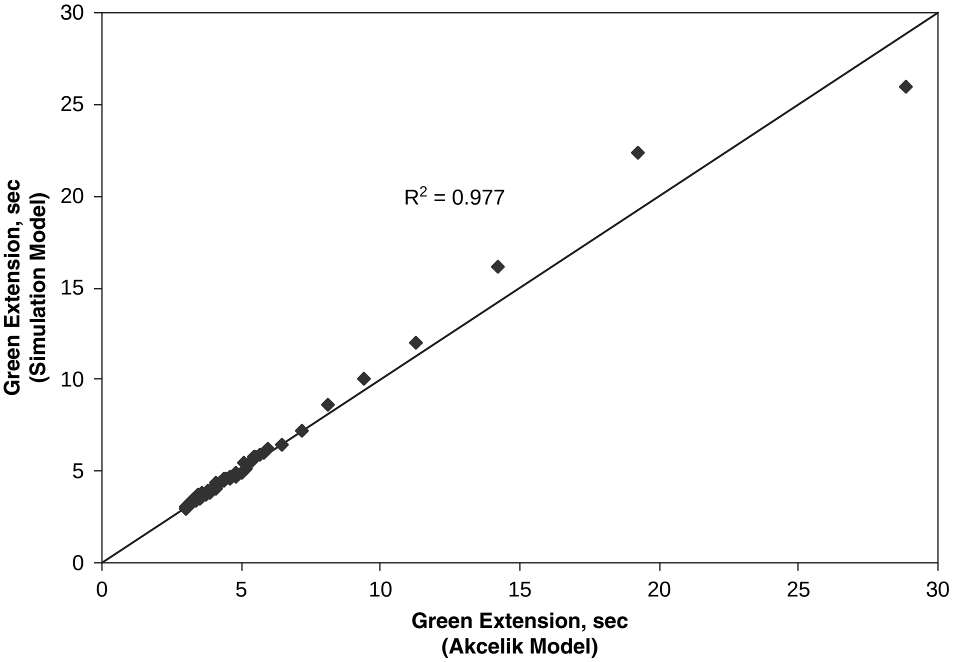

FIGURE 4 Comparison between simulation and Akcelik model.

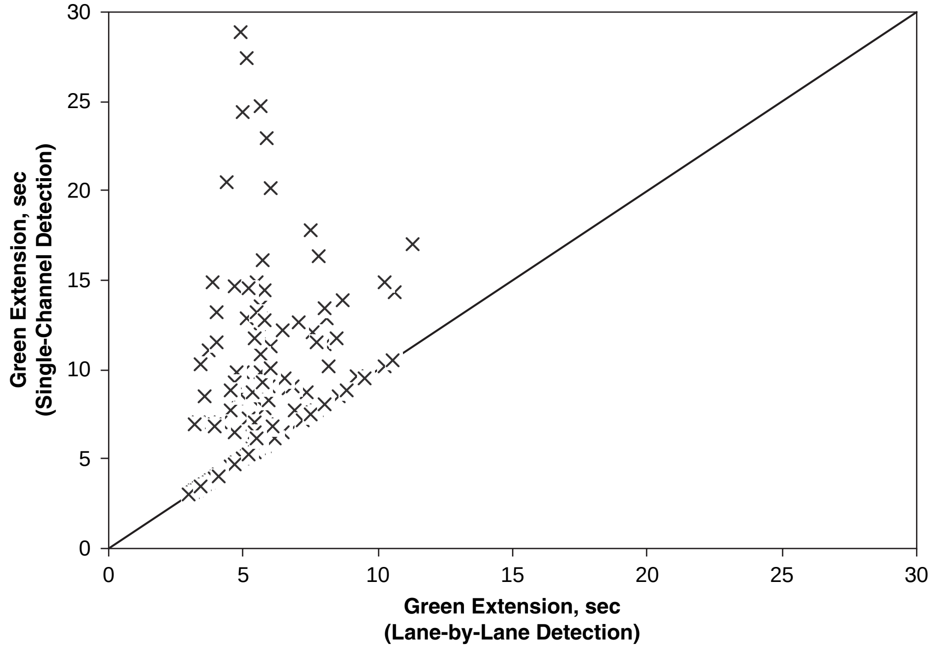

FIGURE 5 Comparison of green extension by both detection schemes.

However, because significant differences do exist in some cycles, the actual impact on signal operations may be more dramatic than what is indicated by the average green extension. For example, excessive green extension in one cycle may result in oversaturation for the other movements, which would result in unserved demands and residual queues. The residual queues could significantly affect the subsequent cycles, which is not reflected by the average green extension. Such potential impacts may be better addressed by using other specialized traffic simulation models, which is beyond the scope of this study.

The effect of the number of lanes on the approach is presented in Figure 7 and Figure 8. Figure 7 illustrates the difference in green extension between the two detection schemes when the approach volume is the same, and Figure 8 illustrates the difference when the lane volume is the same. An MAH of 2.5 s was used to generate the results in both figures.

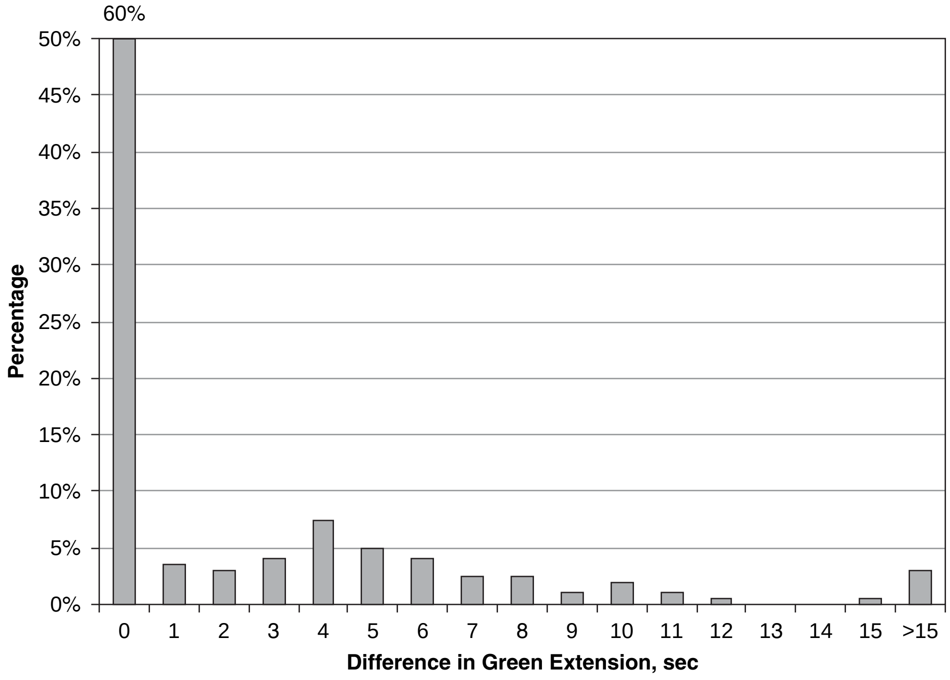

FIGURE 6 Distribution of difference in green extension by both detection schemes.

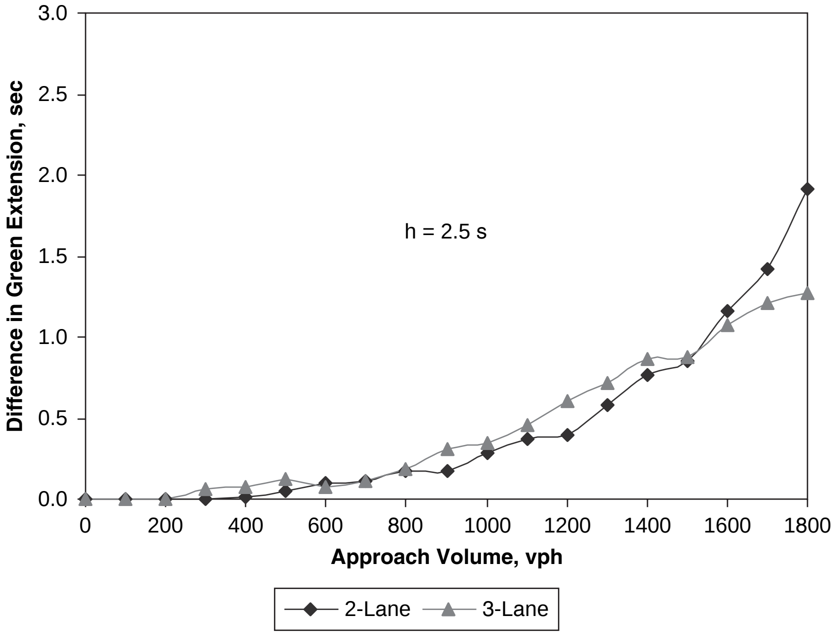

FIGURE 7 Effect of number of lanes on green extension with same approach volume.

Figure 7 indicates that the difference in green extension by the two detection schemes is negligible between two-lane and three-lane approaches with the same approach volume. However, when each lane has the same volume as shown in Figure 8, the difference in green extension by the two detection schemes is higher for a three-lane approach than for a two-lane approach, although the magnitude of the difference may still not be very large. For example, when each lane has a volume of 600 vehicles/h/lane, the difference for a three-lane approach is about 1.27 s, and 0.39 s for a two-lane approach. The difference becomes significant with an increase in traffic volumes. However, volumes higher than 600 vehicles/h/lane may be rarely experienced in the field. Both Figure 7 and Figure 8 indicate that the lane-by-lane detection would benefit more in reducing green extension times with the increase in traffic volumes.

Figure 9 illustrates the effect of MAH on the two detection schemes based on a two-lane approach. Three MAH settings are examined: 2.5, 3.0, and 3.5. Figure 9 indicates that with the increase of MAH (also the passage time), the difference in green extension between the two detection schemes increases. Again, the difference may not be significant. For example, with volumes less than

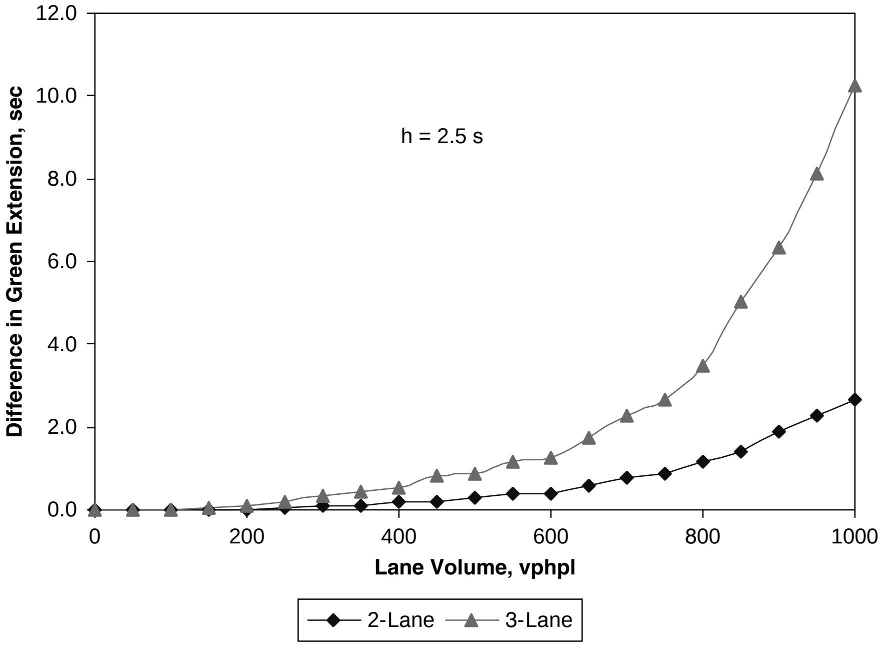

FIGURE 8 Effect of number of lanes on green extension with same lane volume.

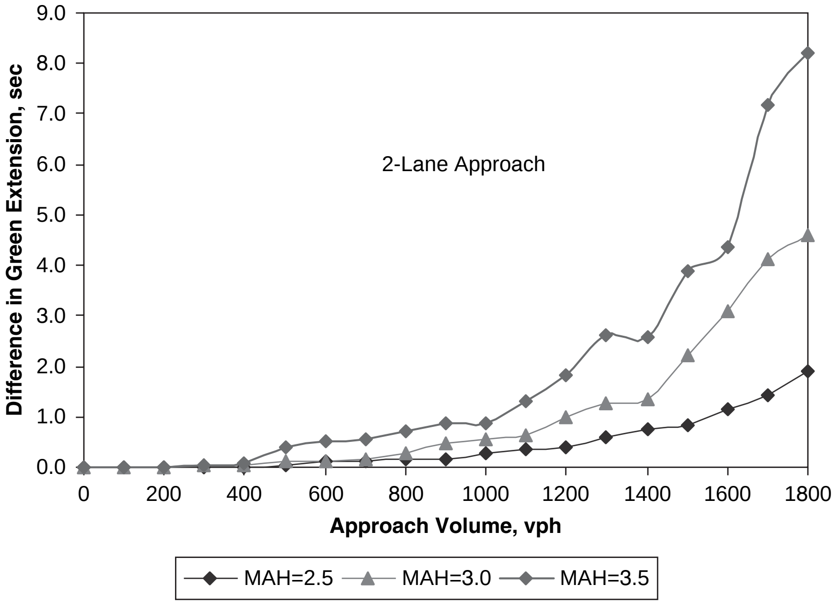

FIGURE 9 Effect of MAH on green extension.

1,400 vehicles/h, the average difference in green extension is less than 3.0 s.

Figure 10 illustrates the effect of lane volume distribution on the two detection schemes based on a two-lane approach. Three volume splits are examined: 50/50, 30/70, and 10/90. As shown in Figure 10, the lane distribution does not exhibit a significant impact on the two detection schemes. The difference in green extension is slightly higher with more even volume distribution when the approach volume is below 1,400 vehicles/h; that is, the lane-by-lane detection would benefit more with even volume distribution, but the difference is minor.

Figure 11 illustrates the effect of headway distribution on the two detection schemes. The data shown in Figure 11 are generated on the basis of a two-lane approach with a MAH of 3.0 s. Two types of headway distributions are assumed: the shifted negative exponential distribution (M2) and Cowan's M3 distribution with $\alpha = 0.5$. Cowan's M3 distribution represents vehicle arrivals with more platoons than in the M2 distribution. Figure 11 indicates that the lane-by-lane detection would benefit more in reducing green extension times with platoon arrival patterns when the approach volume is below 1,400 vehicles/h. When the volume is higher than 1,400 vehicles/h, the lane-by-lane detection would benefit more with more random (fewer platoons) arrivals. Once again, the difference is minimal.

Overall, the two detection schemes exhibit only minor differences in regard to the average green extension under normal traffic volume conditions. The difference becomes more significant with an increase in traffic volumes.

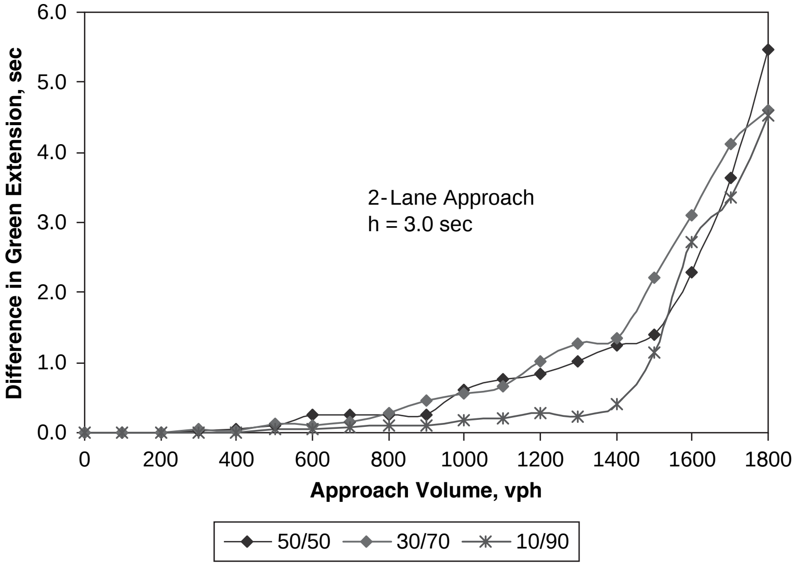

FIGURE 10 Effect of lane volume distribution on green extension.

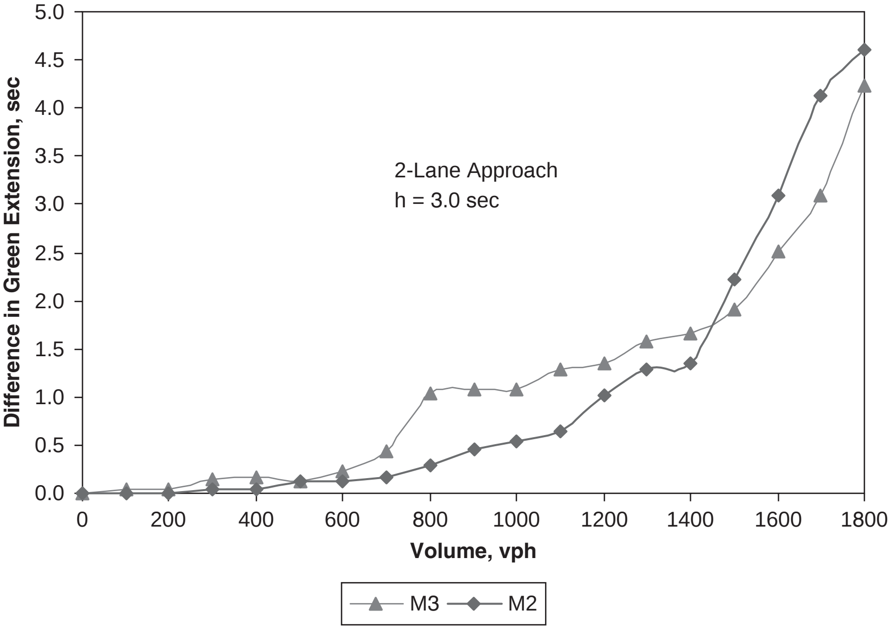

FIGURE 11 Effect of headway distribution on green extension.

SUMMARY AND CONCLUSIONS

Effectively allocating the green times among conflicting movements is critical to the efficiency of traffic signal operations. With actuated signal control, the green extension portion of a phase relies mainly on the detection schemes. Two detection schemes are evaluated using a simulation model developed in this study: the current single-channel detection and the emerging lane-by-lane detection. The analyses are focused on comparing the difference in green extension by the two detection schemes over a wide range of traffic scenarios. All analysis results are based on two-lane and three-lane approaches with uniform vehicle length and travel speed. Major conclusions from this study are summarized below:

- In general, the difference in average green extension is not significant for the two detection schemes under normal traffic volume conditions. The difference becomes more significant only under very high volume conditions, which may not be encountered frequently in the field. Therefore, the type of detection scheme may not have a significant impact from the point of view of capacity calculations. However, significant differences do exist during certain signal cycles, in which its result could significantly affect subsequent cycles in actual operations. Such a compounding impact due to oversaturated phases in some cycles is not addressed in this current study.
- Among the various factors analyzed, the maximum allowable headway is found to be more sensitive to the difference in green extension than to other factors, such as lane volume distribution, arrival patterns, and number of lanes. Because the maximum allowable headway is more sensitive to the detection technologies (e.g., video versus loop) and the vehicle types (e.g., length, height, and speed), a further examination of the effect of vehicle length and speed is worth exploring.
- This study is considered as a preliminary step to exploring the issues associated with the lane-by-lane detection scheme. There are several areas identified from this study that need further research. In summary, these areas include comprehensive evaluations using specialized traffic simulation models and the effect of vehicle length and travel speed. An analytical model based on lane-by-lane detection may be developed and incorporated into the highway capacity analysis procedures for actuated signal operations.

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