Impacts of Detector and Controller Settings at Actuated Signalized Intersections

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Abstract: This research explored the effects of detector setback and controller settings under different speed and volume levels. The purpose of this research was to provide a better understanding on how these actuated traffic signal control parameters can be optimized towards a better performance under different traffic conditions. The results of this research showed that there is a wide range of different parameter combinations that can yield statistically similar results, whereas certain settings can cause significantly poor performance compared to the best one observed. In general, the detector setback and the extension time are critical for lower volumes, extension time plays the biggest role for higher volumes and minimum green time does not generally have a significant effect, except for very low volumes. As volumes are higher, the range of acceptable combinations is wider. There are certain settings that can be used unchanged for different volume and speed levels as safe choices.

Key Words: Actuated Traffic Signal, Actuated Control, Detector Setback, Controller Settings

1. INTRODUCTION

Various types of vehicles have occupied the roads throughout history and there traditionally has been a way of managing their passage through intersections one way or another. It was not until traffic started to grow substantially and the proper technology was introduced that traffic lights as a traffic management tool were invented. The first traffic light that in a way resembled today’s traffic signals’ functions was introduced back in 1868, in London (Gordon, 1971). Popular railway engineer of the time R. Knight used red and green gas lamps and used a lever to turn the appropriate light to the direction of traffic. The United States of America was the first place to see electric traffic lights in 1912 and 1914. The lights featured green and red color and were installed in Utah and Ohio, respectively (Gordon, 1971).
Since then progress has been made in the area of traffic signals. Soon after the 1920s traffic control signals were automated, no more needing a human operator. The introduction of actuated traffic signals a few years later meant a whole new era for the field of traffic signal control. The basic components for an actuated traffic signal are the detectors, which are used to detect incoming vehicles, the traffic lights and a controller that is connected to both and, offering various different settings, uses the traffic demand information from the detectors to define the green and red times for each movement.

The detectors may take different forms from inductive loop detectors to modern video vehicle recognition systems but the question of how far behind the stop bar the actuations should be measured remains a matter of ongoing research. Additionally, the extension time that each actuation grants to the passing vehicle and the minimum green after the start of each green phase have traditionally been associated with the detector setback and the exact way of determining their values is not universally agreed.

This paper focused on exploring the effects of the detector setback, the extension time and the minimum green time on the performance of a single approach of an intersection with fully actuated traffic signal control under various speed and volume conditions. The objective was to determine whether and how the performance is affected by the above parameters, under different volume levels and to compare the performances with the current best practices. Specific recommendations were made under the knowledge of the project’s limitations and constraints and only as certain statistical tests of reliability allowed.

2. LITERATURE REVIEW

Several different approaches on selecting detector locations and settings have been introduced from time to time. In general, there is no mutual consent on the methodology used to determine the above characteristics and so they vary from place to place, according to the priorities and decisions of local traffic agencies. However, for all of the different approaches, it can be ascertained that the detector locations and settings are related to the approach speeds and/or traffic demand at the intersection. In this part, a few existing methodologies on selecting detector setback, extension time and minimum green are presented.

2.1 Detector Setback

2.1.1 The FHWA guidelines

The Traffic Control Systems Handbook, issued by the Federal Highway Administration (FHWA, 2005), offers some guidelines on the detector locations.

The general idea that FHWA refers to as a technique for determining detector locations is the one that directly correlates allowable gap (passage time) with the detector’s distance from the stop bar. Usually this gap is set to 3 to 4 seconds, so that the detector is placed 3 to 4 seconds of travel time behind the stop line. FHWA’s range is 3 seconds for speeds 15 to 25 mi/h and 3.5 seconds for speeds 30 to 40 mi/h. However, the setback is not to exceed 170 ft.

2.1.2 Minnesota Department of Transportation guidelines

Minnesota Department of Transportation (2008) has also set its own guidelines for detector
locations based on approach speeds. Their setback distance for a single detector varies from 120 ft at 30 mph to 625 ft at 65 mph.

**Methodologies involving braking**

Several agencies use the following simple formula derived from Physics laws of motion to calculate the detector set-back:

\[ D_i = A \cdot V_i + \frac{V_i^2}{2 \cdot B} \]

A and B are factors that can vary and depend on the method used. In the real world, A should represent “time” and B should represent “deceleration”, while \( V_i \) is the speed. That way, \( A \cdot V_i \) represents the reaction distance and \( \frac{V_i^2}{2 \cdot B} \) accounts for the braking distance to stop. If D is meant to be measured in feet, V would be feet per second and B would be feet per square seconds. It is of interest to note that the suggested A and B values are not consistent among agencies including AASHOT, Fisher, California, and ITE. For example, ITE uses 3.0 and 22.0 for A and B, respectively, while AASHTO uses 2.5 for A and 9-12 for B (Abbas, 2003; Traffic Operations Program, 2002).

**Comparison for detector setback**

As can be easily understood, all the above methods do not converge into common suggestions. Table 1 illustrates this for the single detector methods:

<table>
<thead>
<tr>
<th>Detector Setback (ft)</th>
<th>FHWA</th>
<th>AASHTO (B=12)</th>
<th>AASHTO (B=9)</th>
<th>Fisher</th>
<th>ITE</th>
<th>CADOT</th>
<th>MNDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>mi/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>109.19</td>
<td>121.14</td>
<td>87.02</td>
<td>107.56</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>25</td>
<td>80</td>
<td>147.69</td>
<td>166.36</td>
<td>122.22</td>
<td>140.56</td>
<td>98.43</td>
<td>--</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>190.67</td>
<td>217.56</td>
<td>162.80</td>
<td>176.00</td>
<td>147.64</td>
<td>120</td>
</tr>
<tr>
<td>35</td>
<td>135</td>
<td>238.13</td>
<td>274.73</td>
<td>208.76</td>
<td>213.89</td>
<td>180.45</td>
<td>180</td>
</tr>
<tr>
<td>40</td>
<td>170</td>
<td>290.07</td>
<td>337.88</td>
<td>260.09</td>
<td>254.20</td>
<td>229.66</td>
<td>250</td>
</tr>
<tr>
<td>45</td>
<td>--</td>
<td>346.50</td>
<td>407.00</td>
<td>316.80</td>
<td>297.00</td>
<td>278.87</td>
<td>300</td>
</tr>
</tbody>
</table>

### 2.2 Extension Time

When an actuation occurs, the green time is extended by the amount of the preset extension time (also known as passage or gap-out time). If another vehicle is detected, present vehicle interval timing is terminated and a new extension time is graced. This can go on until green time reaches its maximum value set by the given maximum green. Also, if the gap between two successive cars is longer than the given extension time, the phase is gapped out, yellow is initiated and no new actuation can extend the green.

Minnesota Department of Transportation (2008) suggests a range of 2.0-8.0 seconds and
computes the exact value by the formula:

\[
\text{Passage Time} = \frac{D}{1.47 \cdot S}
\]

D = Distance from the stop line to back detector, if single point detection. Distance (greatest
distance) between stop line and/or detectors, if multiple detection.
S = Posted speed limit in mph

Australian practice suggests passage times within the range of 2.5-4.0 seconds for through and
left-turn movements and 2.0-3.0 for arrow-controlled right-turn movements (Akcelik, 2003).

2.3 Minimum Green

Although minimum green has little to do with the actuation itself, its values are greatly
affected by the detector location. Minimum green is the shortest possible vehicle green time,
before any added initial or vehicle extensions. Its main role is to provide for service of number
of cars that are potentially stored between detector and stop line or the number normally
stopped if a single detector is located a significant distance from the stop line (University of
Idaho, 2010).

FHWA Handbook suggests the following for calculating minimum green:

- Start-up delay of 4 seconds
- Average headway between discharging vehicles of 2 seconds
- Minimum green time at least \((4 + 2 N)\), where \(N\) is number of vehicles between
detector and stop line.

\(“N”\) is computed by assuming an average vehicle length of 26 ft (7.9 m). For detectors
located approximately 120 ft (36.6 m) or more from the stop line, minimum green may equal
14 seconds or longer.

Another method for determining minimum green is proposed by the University of Idaho
(2010). An equation correlating minimum green with detector location, headway, startup-lost
time and vehicle length is formed, as following:

\[
d = \left( g_{\text{min}} - t_s \right) \cdot \frac{L_v}{h}, \quad g_{\text{min}} = \frac{d \cdot h}{L_v} + t_s
\]

Where:

- \(g_{\text{min}}\) = minimum green time (sec), \(d\) = distance from detector to stop bar (ft), \(t_s\) = Startup time
  (sec), \(L_v\) = Vehicle Length, and \(h\) = Headway (sec).

For the above equation, the values that are generally used are: \(t_s = 4\) sec, \(L_v = 20\) ft, \(h = 2\) sec.

Although a case of a stop-bar detector would yield a 6-seconds minimum green time, it is
suggested by the University of Idaho that the minimum value for \(g_{\text{min}}\) should be as much as 10
seconds.

There is also a safety element involved in determining the minimum green time, since drivers
expect the signal to remain green for a "reasonable" time, and a green interval which is unduly
short leads to erratic behavior and rear-end collisions (Akcelik, 2003). Motor cycles and
passenger cars have greater acceleration capabilities than trucks and, in the interests of safety,
minimum green time should be related to the slowest vehicle likely to use the intersection
within 95 percent probability (5th percentile speed) (Akcelik, 2003). In Australian practice, a 4-10 seconds minimum green time is usually set for stop line detectors, increased by 0.5-2.0 seconds for the case of advance detectors (Akcelik, 2003).

### 2.4 Summary

This literature review section presented various guidelines on detector setback, extension time, and minimum green time developed by several agencies. It clearly shows that these guidelines are not consistent and certainly needs comprehensive evaluations considering all elements of the traffic signal timing plan such as volume, speed, etc.

### 3. METHODOLOGY

#### 3.1 The Intersection

A four-leg intersection was modeled in VISSIM 5.0 simulation software. The through links are 1200-1300 ft long and intersect each other at about the 2/3 of their length, beginning from their traffic input points. Left turns for all directions were attributed an exclusive turn bay of approximately 360 ft.

The intersection is designed to feature fully actuated signal control, receiving actuation calls from detectors for through and left movements. A detector was placed in every lane, giving calls for the respective movement. The detectors were 20 ft long and were initially put at the stop bar for all movements. It is generally understood that the detector length would have little impact on the intersection performance. Right turns were not permitted on red, so that this research applies to a broader set of traffic rules around the world.

#### 3.2 Signal Control

The NEMA emulator controller for VISSIM 5.0 was selected to serve as the intersection’s controller. The choice was made because of the emulator’s non-encrypted input text files and the convenience of altering the signal control settings for the creation of multiple different scenarios later. The phase numbers of NEMA were followed and thus the detector numbers were associated with the appropriate phases. To ensure the reliability of NEMA emulator controller, the performances of the ASC/3 software in the loop controller and the NEMA emulator controller were compared and found to be acceptable.

#### 3.3 The simulation

The simulation for each scenario was run 10 times with varying random number seeds to capture possible variations because of the certain level of the software’s stochastic behavior. The total simulation period for each replication run was 2100 seconds (35 min), allowing the first 300 seconds (5 min) to serve as a warm-up time. Simulation resolution was set to 5 time steps/simulation second.

#### 3.4 Experimental design

For each case study a number of different settings’ scenarios were considered. The settings
subject to change were the detector setback from the stop bar, the extension time and the minimum green.

Maximum green times for every phase were estimated using the TRANSYT-7F software according to volume inputs, using the Genetic Algorithm optimization method and the control delay as the objective function to be minimized. As such, maximum green was not part of the experimental design’s varying settings. As the geometry was fixed for all the cases, a fixed yellow time of 3 seconds and a red clearance time of 2 seconds were set assuming little impacts on these with two approach speeds of 35 and 45 mph. Red lock was also selected for placing presence calls under a red phase but no recall options were selected.

For every case study a number of different settings scenarios were developed. The parameters, namely detector setback, extension time and minimum green, were taking specific values between certain ranges and all possible combinations were considered. Table 2 shows the ranges for every parameter and the increments for the accepted values.

Table 2 Settings, ranges and increments for the experimental design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Increment</th>
<th>Number of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Setback (ft)</td>
<td>0-200</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Extension Time (sec)</td>
<td>2-7</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Minimum Green (sec)</td>
<td>4-15</td>
<td>1</td>
<td>12</td>
</tr>
</tbody>
</table>

The settings were changed only for the Southbound Through direction. The rest of the movements kept the same settings with a stop bar detector, a 2-second extension time and a 5-second minimum green as the minimum requirements for call placement for every movement. This was selected in order to capture the isolated and individual effects of the different settings on one direction, keeping outside as many external parameters as possible. As such, a total number of 11x6x12=792 combinations were considered for every case study. The average vehicle delay for the southbound-through movement was selected as the main performance measure.

3.5 Case Studies

Different volume and speed levels were considered in the process of defining the various case studies. This simulation experiment mainly refers to typical arterial intersections and the performance of the settings under different volume levels is of great interest. Thus, speed levels of 35 mph and 45 mph and volume levels of 100 vphpl (light traffic), 300 vphpl (light-moderate traffic), 500 vphpl (moderate-heavy traffic), 700 vphpl (heavy traffic) were considered. As such, a total of 8 different case studies were considered. For each case study, speed and volume levels apply to all approaches and movements.

Again, the homogeneity of volumes and speeds per lane for each case study was based on the logic of isolating the effects of the main changing variables (detector setback, extension time, minimum green).

Speeds were thought to be set by the speed limit in VISSIM for each approach. However, a variation of ±5 mph around the posted speed limit was considered.
Each case study was tested under the 792 different settings combinations for detector setback, extension time and minimum green mentioned above.

3.6 Limitations and constraints

The main limitations and constraints for this research and the use of its findings lie within the software used (VISSIM 5.0) and the methodology followed.

The stochastic nature embedded in VISSIM 5.0 simulation is of concern. This concern was partly addressed by performing multiple replications for each scenario, using the average of them for further evaluations and then performing statistical tests (t-tests) to determine which results can be considered similar. However, different simulation software packages might well feature smaller variations among replications and give the opportunity to distinguish narrower ranges of acceptable parameter combinations as best ones for each case study. All results are contingent upon VISSIM 5.0’s simulation capabilities, accuracy and the various default parameters for drivers’ behavior that remained unchanged.

Additionally, the case studies selected are very specific in terms of speed and volume levels. Equal volumes for all approaches are not usually the case for real intersections and they were assumed just for research purposed and in an effort to isolate the parameters’ effect on performance. High volumes on left turns might cause spillbacks behind the storage bays and thus affect the flow of through movements from upstream. However, the fact that the approach features 3 lanes and also the proper positioning of the routing decision points generally gave good maneuvering opportunities to the vehicles. What is more, the fixed parameters for the other movements also serve in favor of the isolation of the effects of the single-movements’ parameters but may shift the results if changed.

4. CASE STUDIES AND EVALUATION

4.1. Case Study Results

As noted, the case studies were run in 10 replications for each of all combinations (i.e., 792 cases) of detector setback, extension time and minimum green. After collection of the results, the general picture for the southbound-through average vehicle delays and the variations between the replications for each combination scenario is summarized in Table 3. Delay values for each combination are represented by the average among the 10 replications. Standard deviations refer to the ones observed among the 10 replications of each parameter combination scenario.

From the first view it is obvious that the changes of the settings of detector setback, extension time and minimum green (which are the only variables that change throughout the set of runs within the same case study) can indeed cause some differences in performance. The range of observed delays varies among the case studies.
### Table 3 Summary of delays and variations

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
<th>Case Study 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>13.27</td>
<td>35.65</td>
<td>97.91</td>
<td>127.15</td>
</tr>
<tr>
<td>Max</td>
<td>19.4</td>
<td>63</td>
<td>123.61</td>
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</tr>
<tr>
<td>Average</td>
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<td>39.9</td>
<td>110.19</td>
<td>137.98</td>
</tr>
<tr>
<td>95% Perc.</td>
<td>17.55</td>
<td>47.45</td>
<td>115.7</td>
<td>137.98</td>
</tr>
<tr>
<td>10% Perc.</td>
<td>14.59</td>
<td>37</td>
<td>104.36</td>
<td>130.48</td>
</tr>
</tbody>
</table>

### Table 4 Two-way ANOVA results for all case studies

<table>
<thead>
<tr>
<th>Case Studies</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35mph - 100vphpl</td>
<td>35mph - 300vphpl</td>
<td>35mph - 500vphpl</td>
<td>35mph - 700vphpl</td>
<td>45mph - 100vphpl</td>
<td>45mph - 300vphpl</td>
<td>45mph - 500vphpl</td>
<td>45mph - 700vphpl</td>
</tr>
<tr>
<td>Source</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
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<td>0.000</td>
<td>0.000</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
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<td>0.000</td>
<td>0.000</td>
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<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.999</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.999</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Source</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
</tr>
<tr>
<td>Setback</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.485</td>
<td>0.001</td>
</tr>
<tr>
<td>MinGreen</td>
<td>0.000</td>
<td>0.000</td>
<td>0.978</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
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</tr>
<tr>
<td>Interaction</td>
<td>0.005</td>
<td>0.000</td>
<td>1.000</td>
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<td>0.005</td>
<td>0.000</td>
<td>1.000</td>
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<tr>
<td>Source</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
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<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
<td>P-Value</td>
</tr>
<tr>
<td>Setback</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<tr>
<td>MinGreen</td>
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<td>0.000</td>
<td>0.690</td>
<td>0.996</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.994</td>
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<tr>
<td>Interaction</td>
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<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The primary concern was the exploration of the effects of each variable and their interactions towards performance. Two-way ANOVA (ANalysis Of VAriance) tests at a 95% confidence level (alpha level $\alpha=0.05$) were made considering the southbound throughput delay as response and the possible pairs of the three parameters as factors. The null hypothesis assumes that there is no significant difference in delays attributed to the source factor (no significant effect) and is accepted when the p-value is greater than the selected alpha level ($\alpha=0.05$). If the p-value is smaller than the alpha level, the null hypothesis is rejected and it is assumed that the source factor has a significant effect on performance. Results for the p-values are shown in Table 4, below.
Table 4 shows that detector setback and extension time have an effect on performance under all tested volume levels as individual and interacting factors. Their interaction, though, does not have an effect under low volumes. The minimum green has an effect on performance only for the lower two volume levels as an individual factor and interacting with the setback. The interaction between extension time and minimum green does not have an effect on performance for any tested volume level.

Each volume level shows different sensitivity and trends in terms of how the performance is affected by each parameter’s values. The following Figure 1 shows the interaction plots. The “y” axis represents southbound through delays. Data points represent the average values of observations (delays) that result from a given pair of parameters. For example, the top row plots show how detector setbacks (one line connecting the data points for each setback) perform when combined with different extension times and minimum green times (data points). The other rows follow the same logic for extension times and minimum greens.
(b) Case study 2

(c) Case study 3
However, several combinations would yield similar delays. Given the variations among the replications for each scenario, those differences in delays may not be statistically significant. Thus, it was decided to perform a proper t-test between the best observed performance (lowest delay) and every other observation. For the t-test purposes all the observations from the simulation replications for each scenario were used. The two-sample t-test was performed at a 90% significance level using Minitab 15.1. This resulted into a range of accepted parameter combinations for each volume level. As the volume level is higher, this range is also wider.

4.2 Comparison with current practices

As mentioned before in the introduction and the literature review, current practices that involve all three parameters of detector setback (single detector), extension time and minimum green do not take into consideration different volume levels and guidelines are associated with approach speeds. Additionally, minimum green is loosely associated with detector setback and not every set of guidelines includes that clearly in its suggestions, except from FHWA (Gordon and Tighe, 2005).

The following Table 5 shows several guidelines also presented in the literature review as a summary of detector setback and extension time pairs for a posted speed limit of 35 mph. For the cases that use braking for the detector setback calculation, extension time is noted as the sum of the reaction time plus the time needed for the vehicle to stop, after the brakes are applied (using the basic equations of motion).
Table 5 Current practices on detector setback-extension time (35mph)

<table>
<thead>
<tr>
<th></th>
<th>35 mph</th>
<th>Detector Setback (ft)</th>
<th>Extension Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHWA</td>
<td>135</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>MNDOT</td>
<td>180</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>CADOT</td>
<td>180.45</td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Fisher</td>
<td>208.76</td>
<td></td>
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</tr>
<tr>
<td>ITE</td>
<td>213.89</td>
<td></td>
<td>5.3</td>
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<tr>
<td>AASHTO (B=12)</td>
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<td>6.8</td>
</tr>
<tr>
<td>AASHTO (B=9)</td>
<td>274.73</td>
<td></td>
<td>8.2</td>
</tr>
</tbody>
</table>

The recommended guidelines in Table 5 were evaluated for different volume levels based on this research’s proposed parameter combinations. Minimum green was not taken into consideration due to lack of specific guidelines from every agency and it is assumed that it can be selected properly once the detector setback and the extension time are determined. Table 6 depicts the evaluation for a posted speed limit of 35 mph. Checked (✓) boxes indicate guidelines that fall within the accepted ranges of this research for each volume level. For the case of 45mph all current practices fall out of the experiment’s detector setback range and no comparisons were made.

Table 6 Current practices compliance to accepted combinations (35mph)

<table>
<thead>
<tr>
<th>Volume (vphpl)</th>
<th>FHWA</th>
<th>MNDOT</th>
<th>CADOT</th>
<th>Fisher</th>
<th>ITE</th>
<th>AASHTO (B=12)</th>
<th>AASHTO (B=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>300</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>⚹</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>500</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>⚹</td>
<td>✓</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>700</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>⚹</td>
<td>✓</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

4.3 Common settings for all volumes

Based on the results of this research, there are a few parameter combinations that fall within the acceptable ranges for all volume levels, even though they might not yield the absolute best average delay for every case. Those parameter combinations are shown in Table 7.

Table 7 Accepted parameter combinations for all volume levels

<table>
<thead>
<tr>
<th></th>
<th>35 mph</th>
<th>Setback</th>
<th>Ext Time</th>
<th>Min Green</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>5.0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>6.0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>7.0</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>45 mph</th>
<th>Setback</th>
<th>Ext Time</th>
<th>Min Green</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>4.0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4.0</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5.0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>6.0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>4.0</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>
5. CONCLUSIONS AND RECOMMENDATIONS

The parameters of detector setback, extension time and minimum green indeed can have a significant effect on performance in terms of approach or intersection delay. Detectors placed closer to the stop bar (until about 100 ft further back), extension times of 4 - 7 seconds and minimum greens of 10 - 15 seconds found to be a safe choice for a variety of volume levels, even though they may not yield the absolute best performance for each case.

Volume should be considered in determining detector and controller setting parameters, since different parameter combinations yield the best performance for varying volume levels. Current practices provide good guidelines for certain volumes but not for all. Among all suggestions, the ones of MNDOT, CADOT and ITE are closer to the best settings resulted from this research, but only when it comes to medium-high volumes.

Practitioners should consider implementing the findings of this research. Table 11 provides safe guidelines for satisfactory performance under different volume levels. If detector setback and controller settings were dynamically updated with varying volumes and operational speeds, then those settings found in Table 8 (and the settings for the 45 mph cases that are available but not included in this paper) shall be used.

This research provides motivation for further research based on the general observations that were made. Further research may include validation of this research’s findings by conducting field experiments on real intersections. Different traffic volume combinations from all approaches may also be considered, in order to capture more realistic traffic conditions. Finding the best settings for a single movement (e.g., southbound through) does not necessarily mean that those could be applied on all approaches in an effort towards better overall intersection performance. Additionally, including more controller options in the research might offer valuable findings. Different settings for maximum green, recall modes, locking/non-locking memory and other parameters discussed in literature review may lead to new optimal combinations for detector setback, extension time and minimum green and also better performance.

ACKNOWLEDGMENTS

This work was partly supported by the National Research Foundation of Korea grant funded
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Administration
California Department of Transportation