TRAFFIC RESPONSIVE SIGNAL SYSTEMS TO ADDRESS RAIN-RELATED CONGESTION

by

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A THESIS

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TRAFFIC RESPONSIVE SIGNAL SYSTEMS TO ADDRESS RAIN-RELATED CONGESTION

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CIVIL ENGINEERING

ABSTRACT

Rainy conditions typically have an impact on the behavior of drivers and in turn can affect traffic flow characteristics in transportation networks. As a result, signal timing plans developed for dry conditions may be unsuitable or sub-optimal during periods of rain, and changes in such plans may be desirable to account for changes in environmental conditions. Current technology in the field of traffic signal control and communications make it possible to change the signal controller settings remotely, a capability that offers opportunities for signal timing adjustments during rain conditions. This study explores the feasibility and benefits of implementing alternative signal-timing plans during rainy conditions. The current study has two main objectives: a) Assess the impacts of rain events on traffic flow parameters, and b) evaluate the benefits of implementing changes in signal timing plans in response to rainy conditions.

The study objectives were addressed through a case study in Birmingham, AL, that collected and analyzed traffic and signal data under dry and rainy conditions. More specifically, traffic volumes and speeds were collected under normal and rainy conditions at a study corridor located on Alabama Highway 79 (HWY 79) in Birmingham. Statistical analysis revealed that traffic volumes during rainy conditions were typically decreased by 4% in the peak hour and that the 85th percentile speeds were reduced by an average of 7% during rain. Special signal-timing plans tailored for rainy conditions were developed for a nine-intersection study corridor using the simulation and signal
optimization model called Synchro. The likely benefits of implementing these special-timing plans were then determined in greater detail using a microscopic simulation model called SimTraffic.

The results from the study indicated that the average delay per vehicle could be reduced by up to 31 seconds/vehicle by replacing the regular signal-timing plan with a weather-specific timing plan. With the assumptions made in this study the annual benefits may vary from $20,300 to $81,900 per year, depending upon the duration and timing of the rainfall.

Keywords: Traffic Responsive Systems, Rain - Related Congestion, Sim Traffic, Synchro
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<th>Description</th>
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<td>ALDOT</td>
<td>Alabama Department of Transportation</td>
</tr>
<tr>
<td>AIMSUN</td>
<td>Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks</td>
</tr>
<tr>
<td>BTS</td>
<td>Bottle Traffic Simulator</td>
</tr>
<tr>
<td>CCTV</td>
<td>Closed Circuit Television</td>
</tr>
<tr>
<td>CLCS</td>
<td>Closed-Loop Control Systems</td>
</tr>
<tr>
<td>CORFLO</td>
<td>Corridor Flow Simulation Software</td>
</tr>
<tr>
<td>CORSIM</td>
<td>Corridor Simulation</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
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<tr>
<td>FREQ</td>
<td>Freeway Corridor Simulation Model</td>
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<tr>
<td>FC</td>
<td>Fuel Consumption</td>
</tr>
<tr>
<td>HCM</td>
<td>Highway Capacity Manual</td>
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<td>HWY 79</td>
<td>Highway 79</td>
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<tr>
<td>I-84</td>
<td>Interstate-84</td>
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<tr>
<td>Mn/DOT</td>
<td>Minnesota Department of Transportation</td>
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<td>MOE’s</td>
<td>Measures of Effectiveness</td>
</tr>
<tr>
<td>MUTCD</td>
<td>Manual for Uniform Traffic Control Devices</td>
</tr>
<tr>
<td>PARAMICS</td>
<td>Parallel Micro Scopic Traffic Simulator</td>
</tr>
<tr>
<td>PD</td>
<td>Percentile Delay</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>-------------</td>
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<tr>
<td>PASSER</td>
<td>Progression Analysis and Signal System Evaluation Routine</td>
</tr>
<tr>
<td>SCOOT</td>
<td>Split Cycle Offset Optimization Technique</td>
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<tr>
<td>TBC</td>
<td>Time Based Coordination</td>
</tr>
<tr>
<td>TRANSYT</td>
<td>Traffic Network Study Tool</td>
</tr>
<tr>
<td>TSIS</td>
<td>Traffic Software Integration System</td>
</tr>
<tr>
<td>UTC</td>
<td>Urban Traffic Control Center</td>
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<tr>
<td>UTCS</td>
<td>Urban Traffic Control Systems</td>
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<tr>
<td>VISSIM</td>
<td>Verkehr In Städten – SIMulation (Traffic in cities – simulation)</td>
</tr>
<tr>
<td>WATSim</td>
<td>Wide Area Traffic Simulation</td>
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1. INTRODUCTION

1.1. Problem Statement

Inclement weather changes pavement conditions and driver behavior, which can have an impact on traffic flow parameters. Driver behavior is the outcome of both human factors and factors related to the driving environment (17). Field observations indicate that during rainy conditions drivers cause increases in startup lost times and headways and maintain wider gaps between successive moving vehicles. As a result, adverse weather conditions often reduce vehicle speeds and vehicle throughput. Since adverse weather conditions change traffic flow parameters, timing plans developed for dry conditions may not efficiently serve traffic demand under rainy conditions.

In the past, the implementation of specialized signal timing plans for inclement weather conditions was impractical, because it required a traffic operator to manually change the settings of the signal controllers in the field. But technological developments in the field of traffic signal control and communications have made it possible to quickly change controller settings from a remote location (for example, a traffic control center). In Alabama, almost all new coordinated systems installed by the Alabama Department of Transportation (ALDOT) include a master controller and communications hardware that enable this type of manipulation. In most cases, the basic requirement for traffic responsive operation is the installation of a few sensors at key locations and proper programming of the master controller.
This research seeks to understand the impact of rainy conditions on traffic flow parameters and evaluate the effectiveness of rain-specific signal plans.

1.2. Goals and Objectives

This study investigates the feasibility and potential benefits of implementing special signal timing plans for rainy conditions. The main objectives of the study are as follows:

- To determine the impacts of rain on traffic flow parameters (i.e., Traffic volumes, speeds, headways, and saturation flow rates) at signalized intersections.
- To develop a special signal-timing plan for rainy conditions using a signal optimization model for intersections.
- To evaluate the cost-effectiveness of implementing special timing plans for rain conditions.

The report is organized in seven chapters as follows:

- *Chapter 1* introduces the research problem considered in this study and outlines the study’s goals and objectives.
- *Chapter 2* provides a detailed literature review of past research in assessing the impact of inclement weather on traffic flow parameters and the feasibility of implementing special timing plans for inclement weather.
- *Chapter 3* describes the study methodology and introduces basic concepts related to signalization and traffic simulation modeling.
• Chapter 4 discusses the case study and provides details of site location, data collection, and data analysis.

• Chapter 5 provides some background on simulation modeling and signal optimization for normal and rainy conditions and summarizes the results from the simulation analysis.

• Chapter 6 describes the cost/benefit analysis and related results.

• Chapter 7 summarizes the main conclusions derived from the study and provides some recommendations for future research.
2. LITERATURE REVIEW

A review of earlier studies identified in the literature indicate that weather events such as rain, snow, fog, high winds, and extreme temperatures can reduce roadway capacity (8) and also affect driver behavior, roadway safety, and mobility. Rain and snow reduce the pavement friction while driver visibility is reduced due to rain and windshield water spray. Figure 1 shows a typical view from the driver’s seat for motorists when it is raining.

In addition, lane obstruction and infrastructure damage may also occur due to standing (logged) water and heavy rain (9). This leads to an increase in crash risk and frequency. Weather events also influence transportation system productivity by increasing operation and maintenance costs for public works agencies, traffic management agencies, emergency management agencies, and commercial vehicle operators (19).

The traffic flow parameters affected by inclement weather conditions include traffic volumes, speeds, and densities. Table 1 lists impacts of weather events on roads and traffic (9). The Highway Capacity Manual (HCM) 2000 (Chapter 22) provides information regarding speed and capacity reductions due to rain or snow of light and heavy intensities (10). The manual documents reductions in capacities between 0% and 15%, and reductions in speeds due to light and heavy rains of 2%–14% and 5%–17%, respectively (10,12).
Figure 1. View from Driver’s Seat When Raining (34)

Table 1. Impacts of Weather Events (9)

<table>
<thead>
<tr>
<th>Weather Events</th>
<th>Roadway Environment Impacts</th>
<th>Transportation System Impacts</th>
</tr>
</thead>
</table>
| Rain, Snow, Sleet, Hail & Flooding | • Reduced visibility  
• Reduced pavement friction  
• Lane obstruction & submersion  
• Reduced vehicle stability & maneuverability  
• Increased chemical and abrasive use for snow and ice control  
• Infrastructure damage | • Reduced roadway capacity  
• Reduced speeds & increased delay  
• Increased speed variability  
• Increased accident risk  
• Road/bridge restrictions & closures  
• Loss of communications/power services  
• Increased maintenance & operations costs |
| High Winds                      | • Reduced visibility due to blowing snow or dust  
• Lane obstruction due to wind-blown debris & drifting snow  
• Reduced vehicle stability & maneuverability | • Increased delay  
• Reduced traffic speeds  
• Road/bridge restrictions & closures |
| Fog, Smog, Smoke & Glare        | • Reduced visibility | • Reduced speeds & increased delay  
• Increased speed variability  
• Increased accident risk  
• Road/bridge restrictions & closures |
| Extreme Temperatures & Lightning | • Increased wild fire risk  
• Infrastructure damage | • Traffic control device failure  
• Loss of communications & power services  
• Increased maintenance & operations costs |
In a study by Perrin et al, in Salt Lake City, Utah, over 30 hours of data were collected on 14 different inclement weather days. Table 2 shows free-flow speed and saturation flow reductions in adverse road weather conditions based on this analysis. The study reports an increase of 5% in start-up delay times on wet pavements along with an 8% increase in pedestrian crossing times (13).

Table 2. Free-Flow Speed and Saturation Flow Reductions in Adverse Road Weather Conditions

<table>
<thead>
<tr>
<th>Road Weather Conditions</th>
<th>Percentage Reduction in Speed</th>
<th>Percentage Reduction in Saturation Flow Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rain</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Wet and Snowing</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Wet and Slushy</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td>Wheel Path Slush</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Snowy and Sticky</td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

The Federal Highway Administration (FHWA) considered different studies and stated that the weather events can reduce the arterial mobility and reduce the effectiveness of traffic signal timing plans (19). From their study, it was revealed that the average arterial volumes decreased by 15 to 30% depending upon road weather conditions and time of the day, and reduction in travel speeds ranged from 10 to 25% on wet pavement, and 30 to 40% with snow and slushy pavement. Saturation flow rate reductions ranged from 2 to 21%. Travel time delay and start-up delay increased from 5 to 50% depending upon the severity of the weather event.
A study performed for the Minnesota Department of Transportation (Mn/DOT) in 1999 evaluated the impact of adverse weather (snow and sleet) on a signalized corridors and developed weather-related timing plans to improve traffic operations. The study area consisted of five coordinated, actuated traffic signals along a three-mile section of expressway in the Minneapolis/St. Paul metropolitan area. During winter, travel time, speed, volume and occupancy data, as well as start-up delay and saturation flow rate measurements, were collected during peak periods in normal and adverse weather conditions. When compared with normal days, traffic volumes during adverse weather events were 15% to 20% lower during the afternoon peak period (3:00 - 8:00 PM) and 15% to 30% lower in the peak hour (5:00 - 6:00 PM). During inclement winter weather conditions, average speeds decreased from 44 mph to 26 mph, a reduction of 40%. Start-up delay increased from 2 seconds to 3 seconds during adverse weather and saturation flow rates decreased from 1800 vehicles per lane per hour (vplph) to 1600 vplph, (14).

In another research study, Stern et al. examined weather impacts on 33 bi-directional road segments in the Washington, D.C. metropolitan area from December 1999 to May 2001. Of these thirty-three segments, eighteen segments were freeways totaling 472 miles, and 15 segments were major arterials covering 239 miles. Reported travel time data and weather observation data were combined and used in a two-step regression analysis to predict travel time impacts under adverse road weather conditions. Initially, travel times were regressed against the weather variables of precipitation intensity (none, light rain/snow, heavy rain, or heavy snow/sleet), along with pavement condition (dry, wet, snowy, or icy), wind speed (<30 mph or ≥30 mph), and visibility (≥0.25 miles or <0.25 miles). In the second step, linear regression models for each road
segment were reduced and used to predict normal travel time as well as increased travel time due to weather. Results showed that the average impact of precipitation in peak period was at least an 11% increase in travel times \((12, 15)\).

In major cities in the UK, traffic is monitored and controlled from Urban Traffic Control (UTC) centers, with the help of color closed circuit television (CCTV) and with a traffic operation system known as Split Cycle Offset Optimization Technique (SCOOT). A study performed by Gillam and Withill collected traffic data for 149 links from the Leicestershire UTC computers (from March 1991 to November 1991) \((16)\). The analysis revealed that, for the wet road conditions, link journey times tend to be 10 – 13% greater than that for dry roads. Moreover, a 6% reduction was observed in saturation flow rates during wet days compared to dry days \((16)\).

A study by Agarwal et al \((11)\) assessed the changes in capacity and operating speeds during different weather conditions. In their study, researchers related weather’s relative intensity (inches of rain or snow fall per hour) to traffic flows. Long-term traffic data (volumes and occupancies) were collected for four years, from January 2000 to April 2004. For analysis, the traffic data and weather data were combined using constraints of similar date, hour, and time intervals. Capacity and average operating speeds of freeways were determined according to rain intensity, for e.g., rain \((0, \text{less than } 0.01, 0.01-0.25, \text{and greater than } 0.25 \text{ inches of rainfall/hour})\) and compared to the values provided in the HCM 2000 \((10)\). Results from this comparison are shown in Table 3.

Unrau and Andrey (1998) studied drivers’ response to rainfall under congested and uncongested conditions for traffic flow, during both day and night times. Their study
corridor was along Gardiner Expressway at Waterloo, Ontario, Canada. This is a six-lane highway with an average daily vehicle count of 90,000 vehicles. The traffic flows, average speeds, and vehicle occupancies were collected with the help of double-loop detector systems.

Table 3. Comparison of the Percentage Reductions in Capacity and Average Operating Speeds with HCM 2000 (11)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Assumed corresponding categories from HCM 2000</th>
<th>Capacities (% Reductions)</th>
<th>Average Operating Speeds (% reductions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HCM 2000</td>
<td>Their Study</td>
</tr>
<tr>
<td>Rain (in/hr)</td>
<td>0 – 0.01</td>
<td>Light</td>
<td>0</td>
<td>1– 3</td>
</tr>
<tr>
<td></td>
<td>0.01 – 0.25</td>
<td>Light</td>
<td>0</td>
<td>5 – 10</td>
</tr>
<tr>
<td></td>
<td>&gt;0.25</td>
<td>Heavy</td>
<td>14-15</td>
<td>10 – 17</td>
</tr>
</tbody>
</table>

Regression analysis was performed to determine the relationships between speed, volume, and occupancies under dry and wet conditions for both congested and uncongested conditions, and the results are shown in Table 4 (17).

A study by Liang et al observed the effects of visibility and other environmental factors on driver speed. The study corridor was 160 km long, beginning at the junction of Interstate - 84 (I-84) and I-86 in Idaho and extending southeast to the junction of I-84 and I-15 in Utah. The primary focus of the test was on a 25-km section in the northernmost part of the project area. Traffic data (including number of lanes, time, speed, and length of each vehicle), visibility data, and weather data were collected from different locations along the corridor.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Night Uncongested</th>
<th>Day Uncongested</th>
<th>Day Congested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rain</td>
<td>Dry</td>
<td>Rain</td>
</tr>
<tr>
<td>Minimum</td>
<td>48.6</td>
<td>65.6</td>
<td>51.4</td>
</tr>
<tr>
<td>Lower Quartile</td>
<td>82.8</td>
<td>85.7</td>
<td>68.9</td>
</tr>
<tr>
<td>Median</td>
<td>87.5</td>
<td>90</td>
<td>77.8</td>
</tr>
<tr>
<td>Upper Quartile</td>
<td>94.8</td>
<td>96.6</td>
<td>85.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>110.2</td>
<td>115.7</td>
<td>100.5</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>85.2</td>
<td>87.7</td>
<td>75.4</td>
</tr>
<tr>
<td>Average Speed (km/h)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>1.9</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Lower Quartile</td>
<td>5.4</td>
<td>5.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Median</td>
<td>12.4</td>
<td>11.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Upper Quartile</td>
<td>24.8</td>
<td>21.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>99.7</td>
<td>149.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>8.3</td>
<td>7.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Physical Time Gap (sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>3</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>Lower Quartile</td>
<td>12</td>
<td>14</td>
<td>84</td>
</tr>
<tr>
<td>Median</td>
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<td>25</td>
<td>98</td>
</tr>
<tr>
<td>Upper Quartile</td>
<td>54</td>
<td>53</td>
<td>116.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>143</td>
<td>145</td>
<td>155</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>35.2</td>
<td>37.2</td>
<td>99.6</td>
</tr>
<tr>
<td>5 Min Volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0</td>
<td>2.4</td>
<td>2</td>
</tr>
<tr>
<td>Lower Quartile</td>
<td>6.1</td>
<td>6.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Median</td>
<td>7.6</td>
<td>7.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Upper Quartile</td>
<td>9.5</td>
<td>9.9</td>
<td>6.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>42.1</td>
<td>31.1</td>
<td>15.8</td>
</tr>
<tr>
<td>Weighted Mean</td>
<td>7</td>
<td>7.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Vehicle speeds under normal conditions (defined as sunny, clear days without wind and with excellent visibility) were measured, and these results were treated as the
baseline. During normal conditions vehicle speeds were fairly consistent throughout the day (between 95 and 112 km/hr, with a mean value of 104 km/hr).

Two inclement weather events where visibility was less than 0.8 km (1 km = 0.61 mile) were considered for the study. According to the analysis, vehicle speeds were reduced to 80 to 97 km/hr with a mean value of 92.5 km/hr, which was 10% lower than that of the base flow conditions (32).

In a study done by Maki, for the Mn/DOT, a simulation model was developed with a special signal-timing plan for snow and ice conditions. Simulation results indicated that weather-related signal timing plans were beneficial compared to normal signal timing plans as they led to vehicle delay time reductions of 8% per vehicle and an decrease in average stops of 6% per vehicle (14).

In a study by Gillant et al, a simulation model was developed to evaluate the potential impact of implementing new signal timing plans for inclement weather conditions using the TRANSYT-7F software. As Table 5 shows, vehicle delays increased under wet conditions when signal timings remained unchanged, but the increase in delay was smaller when signal timings were altered to account for wet conditions.

Based on the literature review, it was determined that traffic flow parameters (volumes, speeds, saturation flows, and headways, as well as travel times, increase during rainy conditions when compared to normal conditions. Also based on the literature review, it has been demonstrated that signal timing plans developed for inclement weather conditions are beneficial in reducing travel time, reducing the number of stops, reducing delays, and increasing fuel efficiency. However, most of these studies focused on winter weather conditions (snow and ice) when the benefits of signal timing changes
are likely to be more dramatic. The primary inclement weather event in the southern United States is rain, which tends to have smaller impacts on traffic flow and therefore smaller potential benefits resulting from modified signal timings. Furthermore, rain events in the South can be intense but of short duration. To date there have been no studies performed to identify the potential benefits of implementing rain-specific timing plans for the motoring public, nor have there been any studies to identify the cost-benefit of purely rain-related timing plans. This thesis is the first attempt at such a published study for Alabama.

<table>
<thead>
<tr>
<th>TRANSYI DETAILS</th>
<th>VEHICULAR DELAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM PEAK</td>
</tr>
<tr>
<td>‘DRY’ parameters and Timings</td>
<td>416</td>
</tr>
<tr>
<td>‘WET’ parameters, ‘DRY’ Timings</td>
<td>463</td>
</tr>
<tr>
<td>‘WET’ parameters and Timings</td>
<td>441</td>
</tr>
</tbody>
</table>
3. STUDY METHODOLOGY

3.1. Approach

This study investigates the potential impacts on traffic operations from the implementation of special signal timing plans developed specifically for rain events. To assess the likely benefits of the special timing plans, a nine-intersection corridor was selected along Highway 79 in Birmingham, AL. For developing the rain-specific signal timing plan, a macroscopic traffic simulation model, SYNCHRO 7 (Trafficware Corporation, 2001), was used. The benefits of implementing a special signal-timing plan were assessed through a microscopic simulation model, SimTraffic (Trafficware Corporation, 2001) which was used to simulate the performance of the study corridor with and without rain-specific timing plans.

The following sections provide details on traffic signal system components, signalization options, and traffic simulation models.

3.2. Traffic Signals

Traffic signals are electrically operated traffic control devices that control the vehicular and pedestrian traffic at an intersection. The main functions of traffic signals are to provide smooth flow of traffic and to increase the traffic-handling capacity of certain movements at an intersection (7).
Generally all traffic signal devices display red, yellow, and green lights to control vehicular traffic, and some traffic control devices are additionally equipped pedestrian crossing lights (with “WALK” and “DON’T WALK” light indications). All signals include a traffic signal cabinet containing the traffic signal controller and vehicle detection systems. Figure 2 illustrates the various traffic signal components (6).

Figure 2. Components of Traffic Signal (6)

A – Vehicular Traffic Signal Head
B – Pedestrian Signal Head
C – Traffic Signal Controller Cabinet
D – Vehicle Detectors
E – Video Imaging Detector

The following section defines the transportation terminology used in this study in reference to signal timing and design (3):
• **Cycle**: A signal cycle is one complete rotation through all of the indications provided.

• **Cycle length**: The cycle length is the time (in seconds) to complete one full cycle of indications.

• **Interval**: The interval is a period of time during which no signal indication changes.

• **Phase**: A signal phase consists of a green interval, plus the change interval (yellow time for given indication) and clearance interval (all-red time) that follow it. It is a set of intervals that allows a designated movement or set of movements to flow and to be safely halted before release of a conflicting set of movements (3)

• **Offset**: A time relationship, expressed in seconds or percent of cycle length, determined by the difference between the coordinated green phase and a system reference point

• **Split**: The portion of cycle length, in seconds or percent, allocated to the green, yellow, and all red intervals for a particular signal phase

• **Coordination**: A timing relationship between adjacent signals that allows traffic to progress smoothly through a corridor.

3.3. **Traffic Signal Operations**

Traffic signal operation aims at minimizing the delay experienced by the vehicles in their travel path and regulating vehicle movements to eliminate conflicts. There are
two major types of signal operation, namely pre-timed signal operation and actuated signal operation.

In a pre-timed signal operation, the phase sequence, cycle length, and all interval times are constant and do not change based on actual traffic and environmental conditions. One or more predetermined timing plans are available and are selected according to the time of the day to accommodate traffic based on historical traffic patterns.

On the other hand, in actuated signal operation, the system detects the vehicular movements on selected or all approaches, and the signal timing is adjusted, as needed, in response to the actual demand. This system uses detectors, commonly embedded into the pavement, to determine traffic demand. Figure 2 shows an example of an intersection set up with detectors for actuated signal operations (4).

Figure 3. Actuated Signal Set-Up for Intersections (4)
There are two types of actuated signal controllers, namely semi-actuated and fully actuated ones. A semi-actuated control is typically implemented at the intersection of a major and a minor street, with detectors placed only on the minor street approaches to the intersection. The major street is given the green display, which is interrupted only if the sensor detects a vehicle on the minor side street or when a preset maximum green time is reached. Fully actuated control systems employ detectors on all approaches to the intersection and are appropriate to intersections of streets that carry similar but fluctuating volumes. Thus sensors monitor all approaches and the cycle length, the maximum green, and the phase sequence are all determined according to competing demand from all approaches.

3.4. Traffic Signal Coordination

Traffic signal coordination is a method of establishing relationships between a series of signalized intersections that allow traffic to progress smoothly along the corridor with minimal stops. The main purpose of coordination is to maximize the utilization of the existing roadway infrastructure by assuring optimum travel speeds while reducing delay. This scheme works when the signals being coordinated have the same cycle length but not necessarily the same distribution of green, yellow, and red within the common cycle. The coordination plan has three main parameters: the cycle length, the phase splits, and the offset (i.e., the time difference between a reference time and the beginning of the first complete green phase thereafter), all of which play a vital role in building an effective coordination plan (30,31).
The most common coordinated signal systems in use are a) Time-Based Coordination (TBC), b) Urban Traffic Control Systems (UTCS), and c) Closed-Loop Control Systems (CLCS). The choice of coordination system depends on the available budget, resources, and feasibility of using a system in a particular area (23).

The TBC system operates on a time clock that is used to take actions automatically based upon the time of day and day of week. On the other hand, in UTCS and CLCS, traffic signals are interconnected using different types of communication mechanisms such as electric or fiber-optic cables. Hence both UTCS and CLCS can be traffic responsive while TBC cannot (23).

The coordination plans can be programmed at both the master and local controllers. These timing plans can be run at a certain time of day, day of week, or day of year. If the coordination system is set to closed loop operation, the local controller will run the programs indicated by the master controller. In this case, if a local controller loses communications with the master controller, the local controller will run a preset coordination plan from its database.

3.5. Traffic Simulation Models

A traffic simulation model is defined as “a computer program that uses numerical techniques to conduct experiments with traffic events on a transportation facility or system over extended period of time” (10,20). Traffic simulation models are the most powerful analytical tools available for the traffic analyst and/or engineer for conducting traffic-engineering operations analysis (20,21).
Simulation models allow the analyst to replicate the real-world conditions and perform experiments in a controlled environment without disrupting traffic operations. Once the model is set up, a traffic engineer can perform different experiments by controlling selected variables and can determine their variations and impacts on the system performance. Simulation models can be more useful than field methods, where control of certain parameters is impractical or impossible.

Some of the advantages of simulation models are as follows: (21)

- Simulation models are used where analytical approaches are not appropriate.
- Simulation models can study systems in real time, compressed time, and expanded time.
- Using these models, future scenarios can be simulated.
- Traffic simulation models avoid the disruption of traffic operations that can characterize field experiments.
- Faster results can be obtained than with field experiments.
- They are typically less expensive than field experiments (10,21).

Simulation models disadvantages include the following:

- Development of simulation models requires knowledge in various disciplines (traffic flow theory, computer programming and operation, probability, and statistical analysis).
- Simulation models require considerable input characteristics and data, which may be difficult or impossible to obtain.
- Results obtained from simulation model may vary for each run (10).
In general, traffic simulation models are divided into three groups i.e., microscopic, macroscopic and mesoscopic. Microscopic models describe traffic movements of individual vehicles and their interaction with each other. Such models use sets of rules (logic and formulas) to describe the vehicle behavior, such as vehicle acceleration, deceleration, lane changes, passing maneuvers, turning movement execution, and gap acceptance (10). Examples of popular microscopic traffic simulation models include Traffic Software Integrated System/Corridor Simulation (TSIS/CORSIM), SimTraffic, Advanced Interactive Microscopic Simulator for Urban and Non – Urban Networks (AIMSUN), Wide Area Traffic Simulation (WATSim), Verkehr In Stadtten – SIMulation (Traffic in cities – Simulation) (VISSIM), and Parallel Microscopic Traffic Simulator (PARAMICS) (10,22).

A macroscopic model, on the other hand, considers the traffic at a high level of aggregation as traffic flow rates (rather than individual vehicles) (14). The simulation model is often defined by various differential equations, which are similar to those used to describe shock wave phenomenon (10). These models, however, cannot analyze transportation improvements in many details like microscopic models. Examples of macroscopic simulation models include Bottleneck Traffic Simulator (BTS), Freeway Corridor Simulation Model (FREQ), Corridor Flow Simulation Software (CORFLO), Progression Analysis and Signal System Evaluation (PASSER), SYNCHRO, and Traffic Network Study Tool (TRANSYT-7F) etc (10,22).

Mesoscopic models fall between macroscopic and microscopic models, and typically model the movement of clusters (i.e., platoons) of vehicles based on equations that define how these clusters of vehicles interact. Simulation models of signalized
networks are often designed this way, since the vehicles tend to move in platoons that interact with other platoons and exhibit predictable changes in character over time and distance, as with platoon dispersion (10).

Although each model type has its own strengths and weaknesses, the model selection depends upon the type of application (10, 22), available resources, data needs and availability, and familiarity and expertise.

Traffic simulation was determined to be the right tool for developing and testing specific signal-timing plans for inclement weather condition in this study. Most of the traffic research studies that used simulation models, however, were based on normal weather conditions. There is paucity of literature on the development of special signal timing plans for adverse weather conditions. Table 6 shows few studies that used simulation models in this regard.

<table>
<thead>
<tr>
<th>Study No</th>
<th>Study by</th>
<th>Simulation Model(s) used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perin et al (2001)</td>
<td>CORSIM and SYNCHRO</td>
</tr>
<tr>
<td>2</td>
<td>Agbolosu-Amison</td>
<td>TRANSYT-7F and SYNCHRO</td>
</tr>
<tr>
<td>3</td>
<td>Maki (1999)</td>
<td>SYNCHRO</td>
</tr>
</tbody>
</table>

After a complete understanding of the model approaches, capabilities, and limitations, along with the availability of the models SYNCHRO, CORSIM, and VISTA, SYNCHRO 7 was selected for this study because it contains traffic signal optimization abilities and also incorporates SIM TRAFFIC for simulation. The following paragraphs offer some background on model capabilities and limitations for the selected models.
3.5.1. Overview of the SYNCHRO Model

Synchro is a macroscopic simulation model, developed by Trafficware, Ltd., and capable of modeling traffic flow and optimizing traffic signal timings. Synchro can optimize signal timing for either isolated or coordinated signals, under pre-timed or actuated operations. The model is user friendly and it can import multiple bit maps for background. The Link and Node icons are used to draw over an existing map to create the portion of the network. As an example, Figure (4) shows a bit map used for drawing a network for this study.

Once the network is established using links and nodes, the various input data are entered into the network through Lane, Volume, and Timing windows. The lane window options are used to enter information related to the lane sharing, lane geometrics and vehicle speed for each direction. Using the volume window in Synchro, the user can enter the volumes for each directional movement, conflicting pedestrians and bicycles, peak hour and growth rate factors, and heavy vehicles percentages. Last but not least, the Timing and Phasing window, allows coding of the current signal timings and coordination plans. Figure (5) shows an example of available windows in Synchro model for inputing information for a particular direction. One of the most important features of Synchro is that the user can visualize the geometric layouts, and edit the data on a map side bar. Figure (6) shows an example of the geometric layout of one of the study intersections along with turning movements.
Figure 4. Bit Map Used for Drawing Birmingham Network.
Figure 5. Input Windows for a One Direction in Synchro
Although not very detailed, Synchro is a well-accepted tool for optimizing signal timing. Synchro calculates the coordinatability factor, considering travel time, volume, distance, vehicle platooning, vehicle queuing, and natural cycle lengths (25). As far as optimization is concerned, Synchro minimizes the Percentile Delay (PD), which is the weighted average of the delay corresponding to the 10th, 30th, 50th, 70th, and 90th percentile volumes. For calculating PD, Synchro varies the traffic arrivals according to a Poisson distribution (24). One of Synchro’s features is the ability to select a range for cycle lengths with desired increment in cycle length and optimize the cycle lengths for either the entire network or a portion of network (zones). This can be done automatically or manually. Figure (7) shows a sample of an optimization window in Synchro.
As far as outputs are concerned, Synchro generates a report summarizing queue lengths and levels of service for each lane group, and pertinent measures of effectiveness (MOE) such as total delay, delay per vehicle, total travel time etc. Moreover, summary input data are available in this report. Figure (8) shows the window in Synchro model used to create the reports.

The Synchro version used for this study was Synchro Light. Synchro Light is limited to optimizing up to 10 intersections at a time, whereas Synchro allows for a large number of intersections (up to 9999 nodes). Another limitation of Synchro Light is that it does not allow for transfer of files to CORSIM (a popular microscopic simulation software supported by FHWA and a part of TSIS), but it can transfer files to SimTraffic which allows for additional analysis.
3.5.2. Overview of the SimTraffic Model

SimTraffic performs microscopic simulation and animation of vehicular traffic. An advantage of this model over its counterparts is its ability to be used in combination with Synchro. SimTraffic’s modeling philosophy is based on vehicle and driver performance characteristics developed by FHWA (21). More specifically, SimTraffic uses car following, driver type, and lane changing logic for realistic traffic simulations based on research findings over 20 years (21). SimTraffic has the capacity to model different types of intersection controls, and can manage various street geometries (including lane drops and turning bays), as well as a wide range of traffic flow.
conditions. The version of SimTraffic being used in our present study is Version 7.

Figure (9) shows an example of graphical visualization of an intersection in the study network using SimTraffic.

![Sim Traffic Window for Study Corridor](image)

Figure 9. Sim Traffic Window for Study Corridor
4. STUDY DESIGN

The study design involved the selection of the study area, data collection and analysis, and the selection of the simulation models. Details on these elements of the study design are provided in the following paragraphs.

4.1. Study Site Location and Characteristics

The study site selected for a case study analysis in this project is located in Birmingham, AL, and consists of nine intersections along HWY 79, starting from Pine Hill Rd to Carson Rd. This facility is managed by a CLCS, which includes traffic sensors, local controllers, a master controller, and a remote central controller.

The study site is an approximately 5 mile-long median divided highway section located in a suburban area. The mainline has typically two 12-ft lanes of traffic per direction with auxiliary lanes added near cross street locations and with a posted limited speed of 60 mph along the highway and 30 mph on the minor street roads. The corridor selected for this study is shown in Figure 10.
Figure 10. Study Area along HWY 79 in Birmingham, Alabama
4.2. Traffic Data Needs and Data Collection Approach

In order to meet the study objectives, a comparison of traffic flow characteristics with and without rain presence was performed using data collected from the study site.

The comparison focused on vehicle volumes and speeds. Vehicle volume refers to the number of vehicles passing through a point during a specified time period and is measured in vehicles per hour. Traffic speeds refers to the 85th percentile speed, which is defined as the speed at which 85% of the sample of free flowing vehicles are travelling at or below. Geometric and traffic control data were also gathered in support of simulation modeling needs, as detailed in Chapter 5.

More specifically, vehicle volumes and speeds were collected during normal and inclement weather conditions in the months of February and March of 2008. Due to unusually dry conditions during this season in the Birmingham region, there were only a few rain events that occurred during peak hours, which limited the size of the data collection.

Traffic volumes and speeds were collected using JAMAR tube counters that were set midway between Industrial Pkwy and Lawson Rd. The volumes and speeds at the Lawson intersection were collected over six weekdays under normal weather conditions and three weekdays under rainy conditions during morning peak conditions (7 AM to 9 AM).

It should be noted that vehicle headways and saturation flow rates were not measured directly in the field but were estimated. Saturation flow rate is the maximum hourly rate of traffic flow for a single lane under prevailing conditions, assuming that the green signal is available all the time and no lost time is experienced. The change in
vehicle volumes and speeds from normal to rainy conditions were analysed from the collected data.

4.3. Traffic Volume and Speed Data Analysis

4.3.1. Volume Analysis

As described previously, the volume was data comprised of two samples of dry volume and wet volume counts. The design volume considered for control studies was the peak hourly volume. The two-sample t-test was employed to determine whether the population means of dry volumes and wet volumes were different. $\mu_1$ and $\mu_2$ are the population means for the dry volume and wet volume, respectively. For a significance level of 5%, the following hypotheses were constructed to compare the means.

$$H_0 = \mu_1 - \mu_2 \leq 0$$

$$H_1 = \mu_1 - \mu_2 > 0$$

The results obtained are tabulated in Tables 7 and 8. From the tables we can conclude that the null hypothesis (i.e., that wet peak hour volumes may exceed or equal the dry peak hour volumes) is accepted. The percentage variation of dry to wet volumes is given in Table 9. Based on the results it is concluded that the volume is about 3 to 4% lower during the rainy conditions, as compared to the baseline conditions (dry peak hour volume).
Table 7. Comparison of Dry and Wet Peak Hour Volumes (HWY 79; Northbound)

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation</th>
<th>Population Mean</th>
<th>Sample Size</th>
<th>Degrees of freedom</th>
<th>t statistic</th>
<th>t statistic for p=0.05</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Condition</td>
<td>7.13</td>
<td>154.83</td>
<td>6</td>
<td>2</td>
<td>0.2259</td>
<td>2.9199</td>
<td>Null hypothesis may be possible.</td>
</tr>
<tr>
<td>Wet Condition</td>
<td>34.12</td>
<td>150.33</td>
<td>3</td>
<td>2</td>
<td>0.7859</td>
<td>2.0150</td>
<td>Null hypothesis may be possible</td>
</tr>
</tbody>
</table>

Table 8. Comparison of Dry and Wet Peak Hour Volumes (HWY 79; Southbound)

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation</th>
<th>Population Mean</th>
<th>Sample Size</th>
<th>Degrees of freedom</th>
<th>t statistic</th>
<th>t statistic for p=0.05</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Condition</td>
<td>122.0339</td>
<td>19.8578</td>
<td>6</td>
<td>5</td>
<td>0.7859</td>
<td>2.0150</td>
<td>Null hypothesis may be possible</td>
</tr>
<tr>
<td>Wet Condition</td>
<td>938.6667</td>
<td>898.333</td>
<td>3</td>
<td>5</td>
<td>0.7859</td>
<td>2.0150</td>
<td>Null hypothesis may be possible</td>
</tr>
</tbody>
</table>

Table 9. Mean Volume Comparison

<table>
<thead>
<tr>
<th></th>
<th>Dry Peak Hour Volume</th>
<th>Wet Peak Hour Volume</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound</td>
<td>154.8333</td>
<td>150.3333</td>
<td>3</td>
</tr>
<tr>
<td>Southbound</td>
<td>938.6667</td>
<td>898.3333</td>
<td>4</td>
</tr>
</tbody>
</table>

4.3.2. Speed Analysis

The speeds collected at the Lawson intersection for both northbound and southbound approaches were analyzed separately. For comparison of dry and wet speeds in peak periods, the 85th percentile speed was used for analysis. As the literature confirms, the 85th percentile speed is considered to be safe and reasonable for motorists under ideal conditions. Figures 11 through 14 show 85th percentile speeds for both dry and wet conditions for both approaches for HWY 79 at the Lawson Road intersection.
Figure 11. Graph Showing 85th Percentile Speed for HWY 79 (Northbound) under Dry Conditions

Figure 12. Graph Showing 85th Percentile Speed for HWY 79 (Northbound) under Wet Conditions
Figure 13. Graph Showing 85\textsuperscript{th} Percentile Speed for HWY 79 (Southbound) under Dry Conditions

Figure 14. Graph Showing 85\textsuperscript{th} Percentile Speed for HWY 79 (Southbound) under Wet Conditions
To facilitate comparisons, the 85th percentile speeds at the Lawson intersection for both approaches (North and South), under wet and dry conditions are summarized in Table 10.

Table 10. 85th Percentile Speeds at HWY 79 for both Approaches (North and South), and for both Wet and Dry Pavement Conditions

<table>
<thead>
<tr>
<th>Lawson Intersection</th>
<th>North Bound</th>
<th>South Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Condition</td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td></td>
<td>Pavement</td>
<td>Condition</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>85th Percentile Speed</td>
<td>63 mph</td>
<td>59 mph</td>
</tr>
</tbody>
</table>

Review of the speed results demonstrate that the speed during rainy conditions is decreased by almost 7% along both the northbound and southbound lanes.
5. SIGNAL TIMING PLAN FOR RAINY CONDITIONS

The impact of rain on traffic flow parameters at signalized intersections is discussed in Chapter 4. Given these findings, the next step in this study was to evaluate the likely benefits of implementing special timing plans for rainy conditions. The methodology is described in the following steps:

1. Selection of a model: Model selection required selection of an appropriate traffic analysis tool with the ability to optimize signal timings and determine Measures of Effectiveness (MOE) such as Total Delay, Delay Per Vehicle, and Total Travel Time.

2. Data Collection: Data required as inputs to the simulation model selected in Step 1 were collected in the field.

3. Analysis of study tasks: The simulation model developed in Step 2 was used to examine traffic operations for both wet and dry conditions for current and optimized signal timings. The impact of changes in traffic flow parameters (volumes, speeds and saturation flow rates) under wet conditions was studied by comparing MOE.

The following sections provide additional details on simulation model selection, data collection, model development, data analysis, development of optimal signal timing plans, and estimation of MOE.
5.1. Simulation Model Selection

In this study, the macroscopic simulation model Synchro was selected for the development of a special signal-timing plan optimal for rainy conditions. Next, the microscopic simulation model SimTraffic was used to evaluate the impact and benefits of these signals timings. The main features of both models are described in sections 3.5.1 and 3.5.2.

5.2. Data Collection for Model Development

Traffic Flow Data: Traffic flow data of interest include through and turning volumes at the intersections and the speeds of the moving vehicles. The through volumes and turning volumes for all movements at each of the nine intersections were collected for one day during peak periods (from 4:00 PM to 6:00 PM) using JAMAR manual counters.

Geometric Data: Geometric data includes number of lanes for each approach, their configuration, and the length of turning lanes. This data were collected from site visits. The lengths of the turning lanes were measured using a circular tape measure.

Traffic Control Data: Traffic control data refers to information about the type of traffic control. Signal timing data for each intersection were collected from field visits, and existing coordination plans were developed according to the field settings.
5.3. Simulation Model Development

The study site was located on Hwy 79 and consisted of nine intersections (from the Pine Hill intersection followed by Industrial Pkwy, 6th Avenue and Lawson Rd, Valley Crest Rd, Pawnee Village Rd, Wine Wood Rd, Meadow Craft Rd, Sun Hill Rd, and Carson Rd). Figure 15 shows the network of Highway 79 that was coded into Synchro.

5.4. Data Analysis

As described previously, Synchro was used to design a special rain-specific signal timing plan while SimTraffic was used to evaluate the likely benefits of implementing these signals timings, the model was developed in Synchro while simulations were performed using SimTraffic.
5.4.1. Model Development for Dry Conditions

For dry conditions, a model of the study site was developed based on existing field conditions, and simulations were run under the normal dry signal timing plan (scenario 1). Table 11 shows signal timings for all of the movements under the dry signal-timing plan.

5.4.2. Model Development for Wet Condition

The results shown in chapter 4 were used to obtain volumes and speeds for wet conditions. As volumes were decreased by 3 to 4% during rain, a 4% decrement was assumed for wet conditions along with a reduction in speeds by 7%. As noted earlier, past studies suggest that saturation flow rates decrease by 5%-15% for inclement weather conditions, so saturation flow rate was assumed to decrease by 6%, which reduced the base saturation flow rate from 1900 vehicles per lane per hour (vplph) to 1786 vplph. A model was developed in Synchro using reduced volumes, speeds, and saturation flows to represent “wet” conditions.

5.5. Developing Optimal Signal Timing Plans for Rainy Conditions

With the developed model, signal optimization was performed in Synchro using the wet condition parameters. For optimizing signal timings in Synchro, the following optimization steps were followed:

a. Optimization of network wide cycle length was performed.
b. Optimization of signal offsets was performed using Synchro’s quasi-exhaustive search optimization algorithm.

5.6. Estimation of MOE

Initially simulations were run in SimTraffic using existing field timings (dry signal timing plan) and then with optimized dry signal timing plan (scenario 2). The outputs from these runs (MOEs) provided the means for comparison between existing and optimized signal timing plans. The MOEs considered in this study included total delay, delay per vehicle, and total travel time.

*Total Delay* is equal to the total travel time minus the travel time for the vehicles, assuming free flow speeds and no traffic control devices. It is measured in vehicle-hours.

*Delay Per Vehicle* is calculated by dividing the total delay by the number of vehicles and measured in seconds/vehicle

*Total Travel Time* is the total of the time taken by all of the vehicles present in the system to traverse the corridor and measured in vehicle-hours.
Table 11. Signal timings under dry signal timing plan

<table>
<thead>
<tr>
<th>HWY 79 &amp; Pine Hill Road</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left/Right (sec)</td>
<td>Left (sec)</td>
<td>Through (sec)</td>
<td>Through/Right (sec)</td>
</tr>
<tr>
<td>Eastbound</td>
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<td>17.0 4.0 2.0</td>
<td>89.0 4.0 2.0</td>
<td>72.0 4.0 2.0</td>
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<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
</tr>
<tr>
<td>Southbound</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
</tr>
<tr>
<td>Total Split</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Yellow Time</td>
<td></td>
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</tr>
<tr>
<td>All-Red Time</td>
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<table>
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<th></th>
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<td>Through (sec)</td>
<td>Through/Right (sec)</td>
</tr>
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<td>101.0 4.0 2.0</td>
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<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
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<tr>
<td>Southbound</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
</tr>
<tr>
<td>Total Split</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Time</td>
<td></td>
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</tr>
<tr>
<td>All-Red Time</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
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<tr>
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<td>Left (sec)</td>
<td>Through/Right (sec)</td>
</tr>
<tr>
<td>Eastbound</td>
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<td>30.0 4.0 2.0</td>
<td>21.0 4.0 2.0</td>
<td>80.0 4.0 2.0</td>
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<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
</tr>
<tr>
<td>Northbound</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
</tr>
<tr>
<td>Southbound</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
</tr>
<tr>
<td>Total Split</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All-Red Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HWY 79 &amp; Valley Crest Road</th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Left/Through/Right (sec)</td>
<td>Left (sec)</td>
<td>Through/Right (sec)</td>
</tr>
<tr>
<td>Eastbound</td>
<td>23.0 4.0 2.0</td>
<td>23.0 4.0 2.0</td>
<td>21.0 4.0 2.0</td>
<td>81.0 4.0 2.0</td>
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<tr>
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<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
<td>4.0 2.0 2.0</td>
</tr>
<tr>
<td>Northbound</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
</tr>
<tr>
<td>Southbound</td>
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<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0</td>
</tr>
<tr>
<td>Total Split</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Time</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>All-Red Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All-Red Time</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>----------------</td>
<td>-----</td>
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**HWY 79 & Pawnee Village Road**

<table>
<thead>
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<th>Southbound</th>
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<td></td>
<td>Left/Right (sec)</td>
<td>Left (sec)</td>
<td>Through (sec)</td>
<td>Through/Right (sec)</td>
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<td>Total Split</td>
<td>17.0</td>
<td>16.0</td>
<td>108.0</td>
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<td>4.0</td>
<td>4.0</td>
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<tr>
<td>All-Red Time</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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**HWY 79 & Wine wood Road**

<table>
<thead>
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<th>Southbound</th>
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<tr>
<td></td>
<td>Left/Through/Right (sec)</td>
<td>Left/Through/Right (sec)</td>
<td>Left (sec)</td>
<td>Through/Right (sec)</td>
</tr>
<tr>
<td>Total Split</td>
<td>23.0</td>
<td>23.0</td>
<td>17.0</td>
<td>85.0</td>
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<td>Yellow Time</td>
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<td>4.0</td>
<td>4.0</td>
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<tr>
<td>All-Red Time</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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</table>

**HWY 79 & Meadow Craft Road**

<table>
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<th>Southbound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left/Right (sec)</td>
<td>Left (sec)</td>
<td>Through (sec)</td>
</tr>
<tr>
<td>Total Split</td>
<td>29.0</td>
<td>21.0</td>
<td>96.0</td>
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<td>Yellow Time</td>
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<td>4.0</td>
</tr>
<tr>
<td>All-Red Time</td>
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<td>2.0</td>
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</table>

**HWY 79 & Sun Hill Road**

<table>
<thead>
<tr>
<th></th>
<th>Westbound</th>
<th>Northbound</th>
<th>Southbound</th>
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<tr>
<td></td>
<td>Left/Right (sec)</td>
<td>Through/Right (sec)</td>
<td>Left/Through (sec)</td>
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<td>Total Split</td>
<td>80.0</td>
<td>17.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Yellow Time</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>All-Red Time</td>
<td>2.0</td>
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**HWY 79 & Carson Road**
<table>
<thead>
<tr>
<th></th>
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<th>Westbound</th>
<th>Northbound</th>
<th>Southbound</th>
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<tr>
<td></td>
<td>Left (sec)</td>
<td>Through/Right (sec)</td>
<td>Left (sec)</td>
<td>Through/Right (sec)</td>
</tr>
<tr>
<td>Total Split</td>
<td>19.0</td>
<td>30.0</td>
<td>19.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Yellow Time</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>All-Red Time</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
5.7. Results and Discussion

The MOE for dry and wet pavement conditions with existing and optimized signal timing plans are presented in Table 12.

The results from scenario 1 show no change in delay between dry and wet conditions under the existing dry signal-timing plan. As Table 11 shows, a minimal increase in delay per vehicle (1.6 sec) was observed under wet conditions. Note, however, that under such conditions a decrease in vehicle volumes was observed along with the decrease in vehicle speeds.

In Scenario 2, signal timings were optimized for dry and wet conditions and compared as shown in Table 11. The results demonstrate that the delay per vehicle under the optimized rain-specific timing plan was decreased by 17.3 sec/veh compared to the same rain scenario run under signal timings optimized for dry conditions. It is also worth noting that significant savings in delay per vehicle (approximately 30 sec/veh) can be obtained by optimizing signal timings under wet conditions rather than using the dry conditions signal timing plans that currently exist at the study site. The dry and wet optimized signal plans developed for Scenario 2 have been included in the Appendix to this report.
Table 12. MOE for each Scenario

<table>
<thead>
<tr>
<th>SCENARIO 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pavement Condition</strong></td>
<td><strong>Signal Timing Plan</strong></td>
<td><strong>Cycle Length (sec)</strong></td>
<td><strong>Volume (veh/hr)</strong></td>
<td><strong>Total Delay (hours)</strong></td>
<td><strong>Delay/Veh (sec/veh)</strong></td>
</tr>
<tr>
<td>Dry</td>
<td>Under Dry Signal Timing Plan</td>
<td>125</td>
<td>4756</td>
<td>499.70</td>
<td>378.10</td>
</tr>
<tr>
<td>Wet</td>
<td>Under Dry Signal Timing Plan</td>
<td>125</td>
<td>4595</td>
<td>484.90</td>
<td>379.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCENARIO 2</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pavement Condition</strong></td>
<td><strong>Signal Timing Plan</strong></td>
<td><strong>Cycle Length (sec)</strong></td>
<td><strong>Volume (veh/hr)</strong></td>
<td><strong>Total Delay (hours)</strong></td>
<td><strong>Delay/Veh (sec/veh)</strong></td>
</tr>
<tr>
<td>Dry</td>
<td>Under Optimal Signal Timing Plan</td>
<td>125</td>
<td>4563</td>
<td>457.30</td>
<td>365.50</td>
</tr>
<tr>
<td>Wet</td>
<td>Under Weather Specific Optimal Timing Plan</td>
<td>125</td>
<td>4570</td>
<td>435.80</td>
<td>348.20</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td>22</td>
<td>17.3</td>
<td>12.3</td>
<td></td>
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</tbody>
</table>
6. COST AND BENEFIT ANALYSIS

The cost and benefit analysis in this study aims at defining and formulating costs and benefits associated with the implementation of weather specific timing plan for rainy conditions.

The main assumptions made for calculating cost and benefits in this study are as follows.

1. Weather specific signal timings for study corridor can be implemented without purchase of new hardware, so cost associated with it is taken as zero.

2. The value of time and vehicle occupancy rates are unknown for Alabama. For the purposes of this study, the value of time and vehicle occupancy rates were used similar to those reported in a similar study in New Jersey (25, 26, 27).

3. Gas prices may vary from time to time; at the time of this study the unit price of gas was $3.50 per gallon, which was used for calculating the benefit.

4. Out of 117 rainy days per year we assumed that at least half have a rainfall that ranges between 1 to 4 hours during daytime.

6.1. Cost Model

In general, the costs considered in this study are classified into three major components: engineering services, hardware, and administrative, so the cost associated with signal optimization for intersection i is formulated as follows (25):
\[ CI_i = CE_i + CH_i + CA_i \] 
Where
\[ CI_i = \text{total cost (}$\) \]
\[ CE_i = \text{engineering services cost (}$\) \]
\[ CH_i = \text{hardware cost (}$\) \]
\[ CA_i = \text{administrative cost (}$\) \]

6.2. Benefit Model

The benefit model consists of three components, namely road user’s time, fuel consumption, and vehicle emissions (25). These components are determined based on traffic volume, vehicle composition, speed, travel time, value of time, and vehicle occupancy.

More specifically, the reduced road user’s time cost can be derived from the saved travel time multiplied by the value of user’s time. Travel time savings are based on the difference in delays experienced under optimal signal timing plans for dry and rain-specific signal timing plans.

The delay estimated from SimTraffic is vehicle based. Therefore, by introducing vehicle occupancy, the user cost can be converted into traveler-based cost savings. According to the Highway Economic Requirements Systems, the vehicle occupancy-weighting factor can be obtained using the following equation (25).

\[ VWF = (VOC \times (Vs/100))_{auto} + (VOC \times (Vs/100))_{truck} \] 

Where
\[ VWF = \text{vehicle occupancy weighting factor (persons per vehicle)} \]
\[ VOC = \text{average vehicle occupancy (persons per vehicle)} \]
\[ Vs = \text{vehicle split ratio (percentage)} \]

Therefore, the road user’s cost saving is calculated as:
TS_{RU} = V_T * V_{WF} * D_S \quad \cdots \cdots \cdots \cdots \quad (3)

Where

\begin{align*}
TS_{RU} & = \text{road user’s cost saving ($)} \\
V_T & = \text{value of time ($ per person-hour)} \\
D_S & = \text{travel time saving (vehicle-hour obtained from Sim Traffic)}
\end{align*}

*Reduced Fuel Consumption* (FC) Cost: Savings in FC are based on the reduced fuel consumption after implementation of a rain-specific signal timing plan multiplied by unit price of gasoline (25).

\[ F_S = \Delta FC \times P_f \quad \cdots \cdots \cdots \cdots \quad (4) \]

Where

\begin{align*}
F_S & = \text{reduced fuel consumption cost ($)} \\
\Delta FC & = \text{reduced fuel consumption (gallons)} \\
P_f & = \text{Unit price of gasoline ($ per gallon)}
\end{align*}

*Vehicle Emission*: The reduced vehicle emission cost is defined as the reduced fuel consumption multiplied by the emission production factor (25). Pollutants considered in this study include carbon monoxide (CO), oxides of nitrogen (NOX), and hydrocarbons (HC). The equation used to calculate vehicle emission related costs is as follows:

\[ E_m = \Delta FC \times P_m \quad \cdots \cdots \cdots \cdots \quad (5) \]

Where

\begin{align*}
E_m & = \text{emission rate (grams) of pollutant } m \\
m & = \text{index of CO, NOX} \\
P_m & = \text{emission production factor (grams per gallon) of pollutant } m
\end{align*}

6.3. Cost Estimation

Because the optimized signal timing plans considered in this study can be implemented without purchasing new hardware, the costs involved in the implementation of weather specific signal timings would consist only of engineering service costs, including collecting traffic volume data, processing data, developing Synchro models,
optimizing signal timing, and preparing new signal timing plans for rainy conditions and simulation. Administrative costs include agency technical oversight and field implementation. With the itemized cost assumptions made in Table 13 the total cost estimated for the implementation of new signal timing for rainy conditions for a nine-intersection study corridor is around $35,000.

Table 13. Total Cost for Different Components

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Total Costs</th>
<th>Cost ($)</th>
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<tbody>
<tr>
<td>Engineering Services</td>
<td>Data collection for all nine</td>
<td>9,000</td>
</tr>
<tr>
<td></td>
<td>intersections</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Network modeling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Signal timing optimization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preparing new signal timing plans</td>
<td>23,000</td>
</tr>
<tr>
<td></td>
<td>for rainy conditions</td>
<td></td>
</tr>
<tr>
<td>Administrative</td>
<td>Implementing new signal timing</td>
<td>3,000</td>
</tr>
<tr>
<td></td>
<td>plans for all nine intersections</td>
<td></td>
</tr>
<tr>
<td>Hardware</td>
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<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>35,000</td>
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</table>

6.4. Benefit Estimation

Table 14 shows the values of various variables used for estimating the benefit from signal timing optimization for rain conditions.

According to Sim Traffic results, the total intersection delay in the nine-intersection corridor dropped from 457.30 vehicle-hours to 435.80 vehicle-hours, and fuel consumed dropped from 494.9 gallons to 479.1 gallons under the rain-specific signal optimal timing plan when compared to the dry optimal signal timing plan, the total reduction in delay was 12.3 hours, which is equivalent to $250, and the total reduction in
fuel consumption was 16 gallons of fuel, which is equivalent to $56. With weather signal timings, vehicular emissions were also reduced; resulting in vehicular cost savings of $44 per hour. The total benefit from implementing the weather specific signal-timing plan for rainy conditions was $350 per hour. To estimate the annual benefits, this value (benefit/hour) should be multiplied by the number of rainy hours per year in Birmingham, AL.

Table 14. Cost of Various Variables Used to Estimate the Benefit (25)

<table>
<thead>
<tr>
<th>Benefit Model Decision Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Variable</td>
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<tr>
<td>Value of time $V_T$ (25,26)</td>
<td>$12.75 $21.25</td>
</tr>
<tr>
<td>Vehicle occupancy $V_{OC}$ (25,27)</td>
<td>1.59</td>
</tr>
<tr>
<td>Gas unit price (28)</td>
<td>$3.50</td>
</tr>
<tr>
<td>Pollutant Unit Price per Kilogram</td>
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</tr>
<tr>
<td>CO (25)</td>
<td>$0.0063</td>
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<tr>
<td>NO$_X$ (25)</td>
<td>$1.28</td>
</tr>
<tr>
<td>HC (25)</td>
<td>$1.28</td>
</tr>
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</table>

Local TV meteorological departments, as well as other national meteorological agencies, were contacted to obtain rainfall statistics for Birmingham, AL. However, no replies were received. Therefore, the exact number of hours of rain in a year for Birmingham, AL, is unknown, but the number of days of rainfall is known to be 117 days per year (29). To calculate the annual benefits we assumed that at least half of these rainy days in a year might have an hourly rainfall range between 1 to 4 hours during daytime. This correlates to 58, 117, 175, or 234 rainy hours per year (Figure 16).
The annual benefits may vary from $20,300 to $81,900 per year, but the actual benefits depends upon the duration and time of day of rainfall. Typically, signal timing remains in effect for a number of years. A general rule of thumb is that signal-retiming adjustments are reassessed every three years (33). If the weather specific signal timing plan is in effect for multiple years, and then greater benefits can be realized.

It should be noted, however, that the numbers presented above are indicative merely of potential benefits and that the cost benefit analysis presented here includes a number of assumptions that need to be considered carefully, should decisions be made on the basis of costs and benefits. For example, the numbers presented earlier are applicable to peak hours when traffic volumes are high. Benefits during off-peak times will likely be much less and probably non-existent during evening hours. As a result, actual benefits are expected to be lower than those calculated here, and additional data and analysis is needed in order to calculate costs and benefits with confidence.

![Figure 16. Graph Showing Annual Benefits with Weather - Specific Signal Timing Plan](image)
7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

This report aimed at assessing the impact of rain conditions on traffic flow parameters at signalized intersections along Highway 79 in Birmingham, AL and evaluating the likely operational benefits of implementing special timing plans for inclement weather conditions. The main conclusions of the study are as follows:

1. The results indicate that the rainy conditions have a significant impact on traffic volumes and speeds.

2. The implementation of special signal timing plans for rainy conditions brought measurable changes in delays per vehicle along the study corridor.

3. Based on the study assumptions, the benefits may vary from $20,300 to $81,900 annually with the implementation of weather specific signal timing plan.

4. Generally new signal timing plans take 10 minutes or more before traffic patterns normalize. Therefore, to work efficiently, weather specific timing plan should be implemented for rain events of longer duration. Coordination would be required between the operator of signal timing plans and the local meteorological agencies in order to determine if implementation of weather specific timing plans would be necessary.

7.2. Recommendations for Further Research

1. The current study primarily focused on the impact of rain on traffic flow parameters and the operational benefits of implementing special timing plans for rain conditions during the peak hours. Future research is therefore suggested to study the likely operational benefits during non-peak hours.
2. This study assumed a change to saturation flow rates based on findings of past research. Future studies could evaluate the changes in saturation flow rates and start-up lost time based on local conditions.

3. The duration of inclement weather event has a significant impact on the benefits obtained from inclement weather signal timing plans. A study is therefore needed to determine the threshold duration of the rain event based on which alteration of signal timings is justified in order to account for changes in traffic parameters due to rain.

4. Although rain sensors are not currently used in conjunction with traffic signal timing plans, rain sensors can be installed and used to measure rainfall amounts. Such data will be very valuable in determining threshold values for adjusting signal timing plans in response to rain conditions.

5. The findings from the case study are based on data analysis for one study corridor. It remains to be determined if such findings are transferable to other study sites. Extension of this study to include additional experimental sites is thus recommended and is expected to increase the confidence in the findings.
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APPENDIX - OPTIMIZED SIGNAL TIMING PLANS UNDER DRY AND WET CONDITIONS
Table 1. Signal Timings under Dry Optimal Signal Timing Plan

<table>
<thead>
<tr>
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<td>Through (sec)</td>
<td>Through/Right (sec)</td>
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<tr>
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Table 2. Signal Timings under Weather Specific Signal Timing Plan

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## HWY 79 & VALLEY CREST ROAD

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## HWY 79 & WINE WOOD ROAD

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## HWY 79 & MEADOW CRAFT ROAD

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BIOGRAPHY

Mr. Suman Reddy Surabhi is an Engineering Technician with David E. Wooster & Associates, Inc. He obtained his Bachelor of Engineering degree in Civil Engineering from Osmania University (OU), Andhra Pradesh, India, in May 2006. He is currently pursuing a Master’s degree in Civil Engineering with an emphasis in Transportation at the University of Alabama at Birmingham under the direction of Dr. Virginia P. Sisiopiku.