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16. Abstract

Manual traffic control is a common intersection control strategy in which trained personnel, typically police law enforcement officers, allocate intersection right-of-way to approaching vehicles. Manual intersection control is a key part of managing traffic during emergencies and planned special events. Despite the long history of manual traffic control throughout the world and its assumed effectiveness, there have been no quantitative, systematic studies of when, where, and how it should be used or compared to traditional traffic control devices.

The goal of this research was to quantify the effect of manual traffic control on intersection operations and to develop a quantitative model to describe the decision-making of police officers directing traffic for special events and emergencies. This was accomplished by collecting video data of police officers directing traffic at several special events in Baton Rouge, LA and Miami Gardens, FL. These data were used to develop a discrete choice model (logit model) capable of estimating police officer’s choice probabilities on a second-by-second basis. This model was able to be programmed into a microscopic traffic simulation software system to serve as the signal controller for the study intersections, effectively simulating the primary control decision activities of the police officer directing traffic. The research findings suggested police officers irrespective of their location, tended to direct traffic in a similar fashion; extending green time for high demand directions while avoiding gaps in the traffic stream.

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MANUAL TRAFFIC CONTROL FOR PLANNED SPECIAL EVENTS AND EMERGENCIES

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EXECUTIVE SUMMARY

Manual traffic control is a common intersection control strategy in which trained personnel, typically police law enforcement officers, allocate intersection right-of-way to approaching vehicles. Manual intersection control is a key part of managing traffic during emergencies and planned special events. It is widely assumed that the flow of traffic through intersections can be greatly improved by the direction given from police officers who can observe and respond to change conditions by allocating green time to the approaches that require it the most. Despite the long history of manual traffic control throughout the world and its assumed effectiveness, there have been no quantitative, systematic studies of when, where, and how it should be used or compared to more traditional traffic control devices.

The goal of this research was to quantify the effect of manual traffic control on intersection operations and to develop a quantitative model to describe the decision-making of police officers directing traffic for special events and emergencies. This was accomplished by collecting video data of police officers directing traffic at several special events in Baton Rouge, LA and Miami Gardens, FL. These data were used to develop a discrete choice model (logit model) capable of estimating police officer’s choice probabilities on a second-by-second basis. This model was able to be programmed into a microscopic traffic simulation software system to serve as the signal controller for the study intersections, effectively simulating the primary control decision activities of the police officer directing traffic. The research findings suggested police officers irrespective of their location, tended to direct traffic in a similar fashion; extending green time for high demand directions while attempting to avoid long gaps or waste in the traffic stream. This indicates that when officers are placed in similar situation they are likely to make the same primary control decisions.

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CHAPTER 1. INTRODUCTION

Manual traffic control is a common intersection control strategy in which trained personnel, typically police law enforcement officers, allocate intersection right-of-way to approaching vehicles. The need for manual control is often associated with abnormally high, unbalanced, or widely varying directional and intersecting traffic demand. Although such conditions can occur at any time, they are particularly common before and after special events and also associated with emergencies such as power outages and evacuations. Manual traffic control has been effective under these conditions because police can directly observe and adapt to the changing patterns of demand (Weston, 1996). In addition to being able to directly allocate right-of-way at intersections in response to changing demand, police-conducted manual control can also put "boots-on-the-ground" to observe conditions, respond to problems, and project the presence of authority during times of crisis (Carson and Bylsma, 2003).

Manual traffic control has most often been used at high volume intersections and for planned special events and emergencies at locations where traffic from one or more exit routes merges or conflicts with traffic with another (Weston, 1996). It has generally been used to minimize congestion, expedite emergency traffic, exclude unauthorized vehicle entries, and protect the public (MUTCD, 2009). Depending on the amount of traffic, number of lanes involved, and complexity of the location, as few as one and as many as several officers may be required at a single intersection.

Manual traffic control has typically been conducted using one of two methods; the traditional "officer in the intersection" approach and the more modern "clicker" method. The "officer in the intersection" positions uniformed personnel near the center of the intersection, directing vehicles and pedestrians using hand gestures. The advantages of this method are that it is easy to deploy and can be used at any intersection with little to no preparation. The major disadvantage is that it can be unsafe for the officer and is prone to inefficiencies in which vehicles inevitably slow down and oftentimes completely stop to ask the operator questions on a variety of subjects (Marsh, 1927; Weston, 1996). The "clicker" method enables a police officer to allocate right-of-way by changing the phase length from the traffic signal controller. Operators are able to change which approach directions will receive a green indication from the controller with the "click" of a button. The advantages of this method are improved safety for the officer and the elimination of the inefficiencies in flow caused by drivers slowing down to avoid the officer standing in the intersection. However, this method can only be used at intersections with properly equipped controller hardware and the operator must have a key to access the locked control panel.

1.1 Problem Statement

In addition to their enforcement responsibilities, police personnel play many important roles before, during, and after emergencies. These range from maintaining law and order; providing security in impacted areas; serving as first responders for health and safety emergencies; and conducting rescue operations (ESF#13, 2009). Despite its advantages during emergencies manual traffic control exposes officers to unacceptable safety risks, requires significant manpower, and may be a poor utilization of limited police resources during emergencies (Parr and Kasiar, 2011). It is further suggested that conventional signal control can provide a safer, more efficient, and more effective option for moving traffic. Based on these two conflicting views, a disagreement exists among those who believe manual traffic control is an essential element of special event and emergency traffic management and those who believe traffic would flow more efficiently using conventional signal control. The discussion of whether manual control is effective and when, where, and how it should be used, has not been systematically quantified or scientifically studied. A review of the current state-of-practice has shown that the administration, implementation and execution of manual traffic control have historically been based on expert judgment, local knowledge, past experience, and, in some cases, public perception. Furthermore, it is unknown whether manual traffic control is conducted in a uniform manner across the country or even within the same state, county or locale.

1.1.1 Police Implementation

There are four basic levels of police jurisdiction, including Federal, State, County, and City. It has been estimated that there are approximately 20,000 police agencies within the United States, each of which conduct manual traffic control for highways on a regular basis using their own set of policies and practices (USDOJ, 2008). It is particularly notable that none of these 20,000 police agencies have developed comprehensive guidelines or collected any best-practices on the administration of manual traffic control. This is in contrast to the transportation profession, where practices are more formalized and regulated through the publication of guidelines, manuals, and procedures for practice. The terminology between police and transportation officials also differs. Transportation professionals use the term “manual control” or “manual traffic controls”, as defined in the Manual on Uniform Traffic Control Devices (MUTCD, 2009). On the other hand, police literature typically uses “directing traffic” or “traffic direction” to describe manual signal control (Weston, 1996).

As a result, no single universally recognized authoritative source or sets of guidelines that govern manual traffic control currently exist. The manner in which an officer directs traffic and allocates right-of-way has been virtually unstudied within the transportation community. For example, no research has been conducted to date on the stimulus-response relationship between operational traffic stream characteristics and officer decision-making while directing traffic. Without an understanding of how and why police allocate green time, it is not possible to assess the performance of manual traffic control from a systematic engineering point-of-view.

The current state-of-the-practice in evaluating traffic operations and control employs traffic simulation modeling to assess conditions. However, due to the un-quantified nature of manual traffic control, it has not been possible to accurately represent or calibrate simulation models to fit empirical observations. As a result, current special event and emergency evacuation simulations have been unable to realistically model the essence of neither manual traffic control nor the results that are produced by it. Without this ability, the traffic management plans developed for these situations cannot be tested in advance via traffic simulation.

1.2 Research Need

Many event traffic management plans and emergency traffic management plans call for the use of manual traffic control in response to oversaturated traffic conditions. Expediting traffic flow is a particularly high priority during emergencies when the effective movement of traffic may be a matter of life and death. For example, the Nuclear Regulatory Commission (NRC) suggests the use of manual traffic control to facilitate the evacuation of areas surrounding nuclear power plants in the event of a disaster (NRC, 2011). However, during emergencies, police personnel are also in great demand for other non-traffic related duties. During non-emergency events, police presence can have a high economic cost because it often requires overtime or extra duty pay. It is therefore essential to identify the benefits and costs, as well as the trade-offs, advantages, and disadvantages associated with manual intersection traffic control.

There is also a need to quantify the operational effects of manual traffic control on intersection performance. Allowing the performance of manual traffic control to be compared to an actuated controller. This will enable the travel-time savings, if any from manual control to be weighed against the cost of deploying the police officer at the intersection. Without such comparisons, there can be no quantitative metric to evaluate manual control.

Under manual traffic control, police officers must make decisions of phase length and phase sequence while directing traffic. By definition, these decisions have an impact on traffic operations of the intersection. Thus, the actions taken by the officer have significant consequences (both positive and negative) for potentially hundreds of people approaching the intersection. It has been observed that the likelihood of inadequate green time allocation is greater if the officer is inexperienced or has not been properly trained (Marsh, 1927). If an officer provides inadequate green time to one phase of an intersection, the resulting queue can propagate upstream interfering with the operations of adjoining intersections. Traffic simulation is a relatively inexpensive tool used to evaluate proposed traffic management strategies for effectiveness and efficiency. However, no simulation software has the ability to simulate the effect that a police officer directing traffic has on roadway operations. It would be useful to develop a simulation tool capable of effectively representing manual traffic control for the purpose of evaluating traffic flow. Such a tool will help identify where, how and when manual traffic control should be implemented to better utilize officer resources and intersection right-of-way. With this tool, event planners would also be able to evaluate "what if" scenarios with quantifiable results to aid in their decision-making. Furthermore, emergency managers will have a better understanding of where to place police resources in the event of a catastrophe.

1.3 Research Goals and Objectives

The goal of this research was to quantify the effect of manual traffic control on intersection operations and to develop a quantitative model to describe the decision-making of police officers directing traffic for special events and emergencies. This was achieved by collecting video data of police officers directing traffic at several special events in Baton Rouge, LA and Miami Gardens, FL. The data was used to develop a discrete choice model (logit model) to quantify the independent variables likely to effect an officer's right-of-way allocation while directing traffic. This model was programmed into a microscopic traffic simulation program, VISSIM 5.3 to replace the signal controller logic for the study intersections. This had the effect of simulating manual traffic control, which was then compared to the video footage collected in the field for validation purposes. This model was used to compare the performance of the police officer to a fully actuated traffic controller. The research objectives were summarized in Table 1. A performance metric using proven quantifiable measures was created (when applicable).

Table 1: Research Objectives and Performance Metric

Order	***Objectives***	***Performance Metric***
1	Conduct a review of the existing body of literature on manual traffic control from both transportation and police research perspectives	A literature review encompassing the breadth and depth of knowledge in the field, both state-of-the-art and state-of-the-practice
2	Conduct a quantitative analysis of the stimulus-response relationship between the traffic stream and officers' right-of-way decisions while directing traffic	Traffic stream variables with strong and weak correlation to observed officer actions were measured using a p-value of 0.05 and 0.1, respectively
3	Simulate manual traffic control for the intersections in the study	The performance of the simulation model was compared to recorded videos using regression analysis with R^2-values no less than 0.80 and comparison T-test/ANOVA
4	Evaluate the cost-benefit relationship between manual traffic control and automated traffic control	The traffic control measures are compared using a two sample T-test analysis at ±5% at 95% confidence

The next chapter starts by reviewing and synthesizing relevant research, facts, and opinions from the perspective of the police and transportation professions. The following chapter describes the research methodology developed to address the problem statement and the existing gaps in the literature. Chapter 4 and Chapter 5, discuss the discrete choice model results and the application of the discrete choice model as a means of simulating manual traffic control, respectively. The final chapter summarizes and concludes the research effort as well as providing opportunities for future work.

CHAPTER 2. BACKGROUND

The design, implementation, and maintenance of traffic control devices in the United States has been an evolutionary process. Police officers were the first true traffic control devices. Over time, however, police officers were replaced by simple traffic signals which were improved, later by the introducing advanced traffic control systems. For the development of this research, several areas of literature were reviewed including the history of traffic control, police traffic control training, manuals and handbooks, manual of uniform traffic control devices (MUTCD), special event and emergency planning, and empirical studies on manual traffic control.

2.1 History of Traffic Control

Traffic control began to emerge in London, England in the early 18th century. As early as 1722, traffic control measures were taken to ensure swift movement of horse drawn carriages, buggies, carts, and pedestrians across the London Bridge. At the time, crossing the bridge was seen as an inconvenience due to the disorderly nature of the traffic movements. The Lord Mayor organized a coalition of three men and appointed them as public servants to monitor and regulate individuals crossing on the bridge. Their job was to keep traffic on the left side of the road and to keep the traffic moving at all times (Paxton, 1969).

Traffic control in the United States dates back to the 1860's when New York City's Police Department was assigned to manage the reckless driving of horse-drawn buses within the city. This was in response to public outcry over the deaths of several pedestrians trampled by the horse-drawn buses. The New York City Police Department assigned the tallest officers on the force to the new squad to ensure that the officers could see over carriages and pedestrians. The officers were known to point, wave, and shout to move traffic on the busy streets (Paxton, 1969).

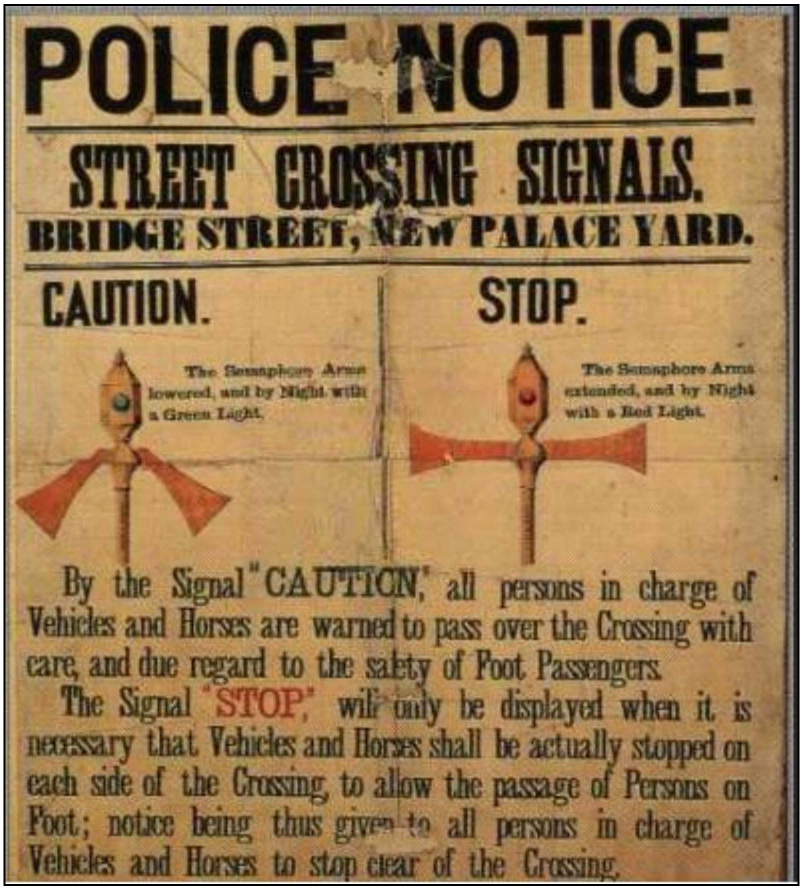
The first traffic control device was introduced in London, England in 1868 at the intersection opposite Palace Yard, near the House of Parliament. The device was a composite semaphore signal with color coded gas lanterns for lights (green for go and red for stop). It was built by railway signal engineers Saxby and Farmer of the London Brighton and South Coast railway company. The semaphore consisted of three arm leavers, each facing one of the three intersecting streets: Bridge Street, Great George Street, and Parliament Street.

To alert the traveling public of the new traffic control measure, the Metropolitan Police printed 10,000 copies of a police notice seen in Figure 1. The police notice informed travelers when the semaphore arms were lowered so by night, when the lantern was green, they could proceed into the intersection with caution; meanwhile when the arms were raised or the lantern burned red to stop.

> By the Signal “CAUTION,” all persons in charge of Vehicles and Horses are warned to pass over the Crossing with Care, and due regard to the safety of Foot Passengers. The Signal “STOP,” will only be displayed when it is necessary that Vehicles and Horses shall be actually stopped on each side of the Crossing to allow the passage of Persons on Foot; notice being thus given to all persons in charge of Vehicles and Horses to stop clear of the Crossing (University of London, 2013).

The semaphore was operated by a police constable and was considered a success. However, the semaphore was soon removed due to safety concerns after a series of explosions caused by an underground gas leak led to the death of the constable on duty in 1869 (Wolkomir, 1986).

After the invention of the automobile, the police officer-controlled semaphore became the default traffic control measured used in the United States, starting in Toledo, OH in 1908 and spreading around the country. With the automobile boom of the early 20th century, large cities soon needed more sophisticated ways of controlling mixed, horse-carriage, and automobile traffic. In 1914, the Cleveland, OH Police Department installed the world’s first permanent Red-Green traffic signal on the corner of 105th Street and Euclid Avenue. The traffic signal was electronic and operated by a police officer pushing buttons from a controller booth near the sidewalk. The light only controlled the main street traffic while officers on opposite corners of the intersection controlled the side street traffic (McShane, 1999).



POLICE NOTICE.

STREET CROSSING SIGNALS.

BRIDGE STREET, NEW PALACE YARD.

CAUTION.

The Semaphore Arms lowered, and by Night with a Green Light.

STOP.

The Semaphore Arms extended, and by Night with a Red Light.

By the Signal "CAUTION," all persons in charge of Vehicles and Horses are warned to pass over the Crossing with care, and due regard to the safety of Foot Passengers.

The Signal "STOP," will only be displayed when it is necessary that Vehicles and Horses shall be actually stopped on each side of the Crossing, to allow the passage of Persons on Foot; notice being thus given to all persons in charge of Vehicles and Horses to stop clear of the Crossing.

Figure 1: Semaphore Police Notice (Copyright University of London)

With the problem of officer visibility and communication being addressed by semaphores and manual controlled traffic lights, the next pressing issue of traffic control was coordination. Police officers only had a limited ability to coordinate their traffic movements with officers at neighboring intersections. Take the example of a busy urban grid network: one officer would have to coordinate his movements with traffic coming from four directions. Meanwhile, the officer at the upstream intersection would have to coordinate his actions to match another three directions. The complexity was magnified by larger networks and busy roadways (Marsh, 1927). This scenario was best illustrated in a cartoon from the time depicting two police officers trying to coordinate their traffic movements amid the chaos of an urban grid network, Figure 2.

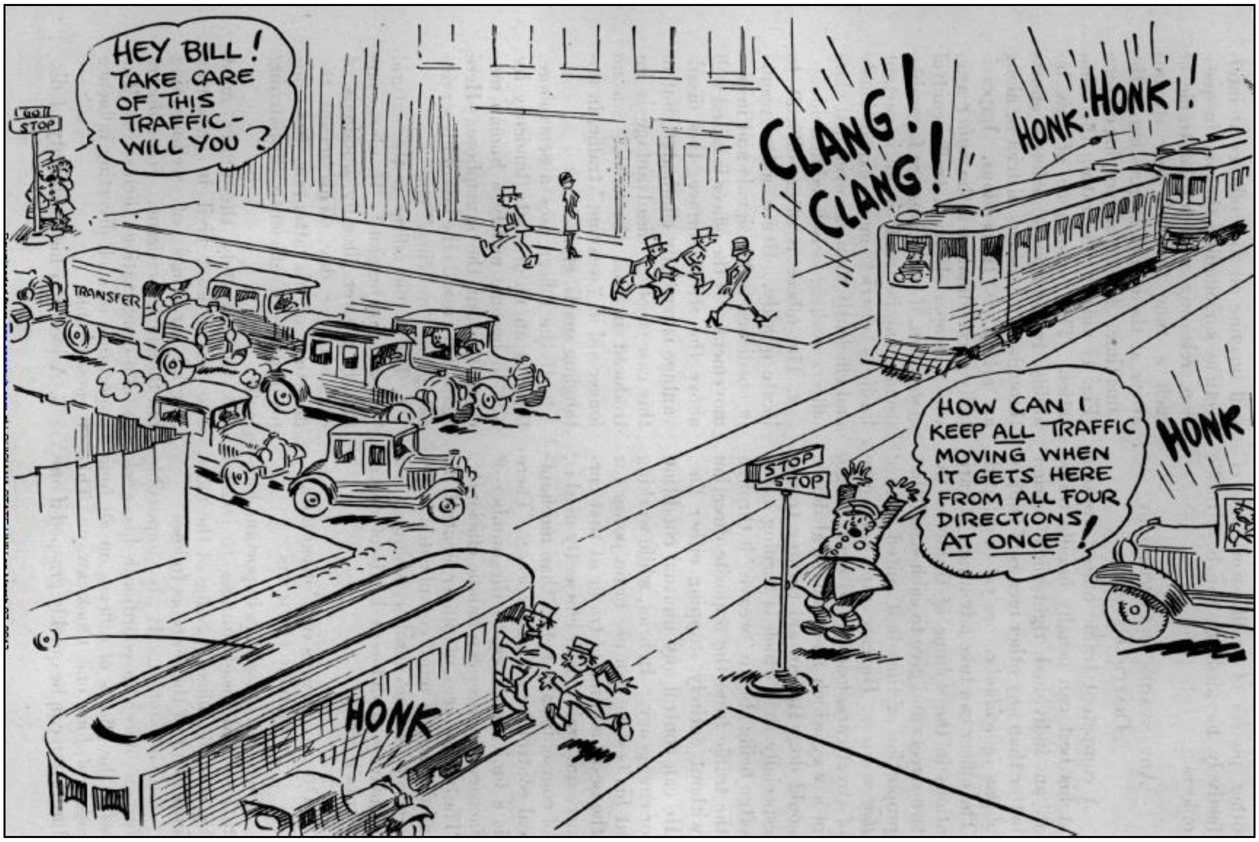


Figure 2: Police Signal Coordination Cartoon (Marsh, 1927)

The need for a better means of officer communication for operational coordination between intersections led to the development of coordinated flag systems (Schad, 1935). In 1914, 5th Avenue in New York City, NY was coordinated using a series of flagman, communicating traffic orders between intersections. This system was partially successful in that it worked over a short distance. The shortcomings of the flagman system led to the innovation of the Traffic Crowsnest (i.e., Traffic Tower), a raised and covered platform located in the middle of an intersection. Above and below the platform were two pairs of electric powered semaphore arms (color coded), Figure 3.

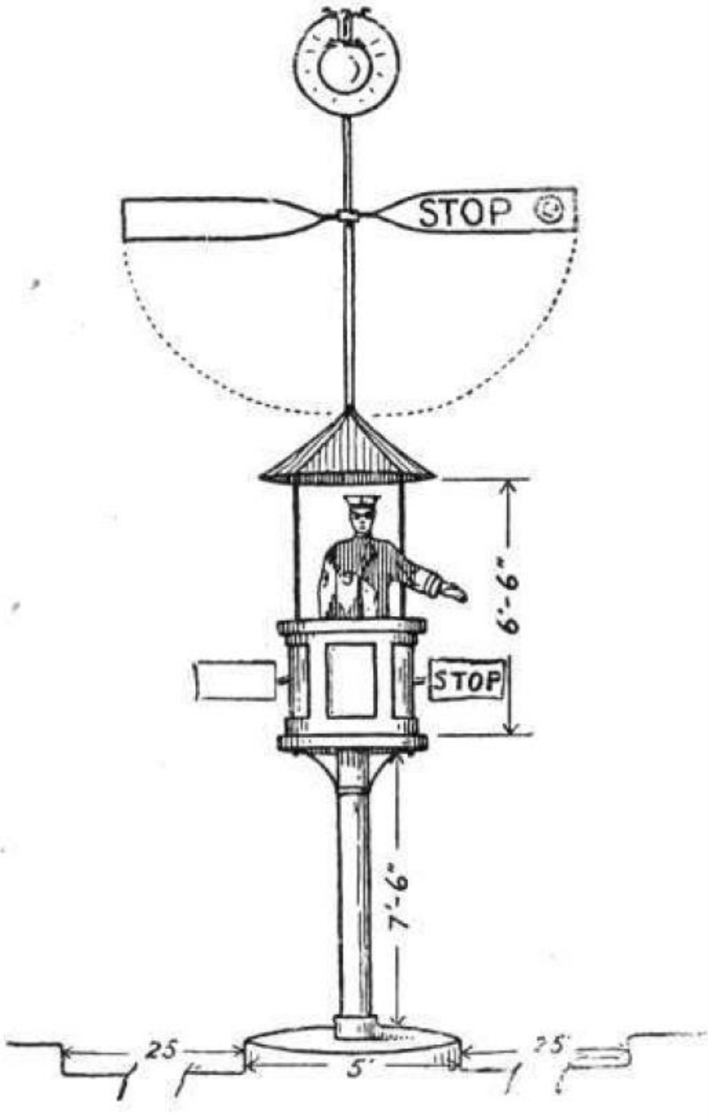


Figure 3: Traffic Crowsnest Schematic (Eno, 1920)

Within the Traffic Crowsnest was a telephone whereby direct communication was made with the operating officer when the intersection needed to remain clear for an approaching fire brigade. From the Crowsnest, the officer could see over vehicles and pedestrians and could be easily seen by commuters, increasing efficiency. The major advantage of the Crowsnest was that officers at neighboring intersections could synchronize their movements more efficiently as the Crowsnest was more visible. The first Traffic Crowsnest was employed at the intersection of Woodward and Michigan Ave. in Detroit, MI in 1917 and received approval by police officials and the public, (Figure 4). The success of the Traffic Crowsnest quickly spread and replaced the flagman system used on 5th Avenue in New York City, NY by 1919 (Schad, 1935).

The benefit of the Traffic Crowsnest in synchronizing the movements between neighboring intersections was furthered in the early 1920's. By 1922, communication between towers on New York's 5th Avenue was conducted using flashing lights, push-button-signals, and telephone communication. During this time, Atlanta, GA developed a system where signals were suspended over roadway intersections and operated by a single Crowsnest in conjunction with the main intersection (Schad, 1935).

Figure 4: Detroit Traffic Crowsnest (Eno, 1920)

Another major advancement in traffic control was the addition of the yellow caution light. In 1917, Detroit police officer William Potts added a yellow caution light to a manually controlled traffic signal to assist pedestrians and allow time for vehicles to clear the intersection. The addition was a success and spread to Chicago and New York where they were adopted into their manual control signals by 1918. Officer William Potts went on to invent the first four-direction manually controlled traffic light in 1920, (Figure 5). His traffic light consisted of only three bulbs, requiring the location (top and bottom) of the red and green light to switch for each approach. This light was state-of-the-art until the invention of the 12-bulb signal in 1928 (Lay, 1992).

Figure 5: Four Direction Three Bulb Traffic Light (Henry Ford Museum)

In 1922, the railroad signal company Crouse-Hinds developed the first automated timed traffic signal (Halvorson, 1925). This signal controller was demonstrated on a nine-intersection corridor in Houston, TX. The traffic signals were linked together and synchronized from a central point. In 1923, Chicago deployed a similar system on Michigan Avenue spanning a distance of 2.5 miles (Schad, 1935). By 1924, New York and Los Angeles had begun to adopt the automated traffic signal controller. This system then spread rapidly through North America and by the end of 1925, it was present in most major U.S. cities (Hoyt, 1927). By 1924, it was estimated that one-thousand intersections in the U.S. were controlled by automated signal controllers. This number grew to around 4000 by 1925 and 8000 by 1926, Figure 6.

Prior to the invention of the automated traffic signal, police had been the only intersection traffic control measure used. With the widespread implementation of traffic control systems, a debate emerged as to whether a police officer or an automated signal controller could allocate intersection right-of-way more effectively. Burton Marsh, a traffic engineer for the Pittsburgh Department of Public Safety summarized the advantages and disadvantages of police control compared to automated timed control of intersections (Marsh, 1927). Marsh stated that for a single isolated intersection, there was no better means of control then a police officer. He contended that during an individual minute, an officer could outperform an automated signal controller. He also stated that an officer had the ability to give priority to emergency and public transportation vehicles, as well as allocate appropriate left turn movements (protected left turns were not common circa 1927). Marsh summarized the advantages of manual traffic control as "brain power efficiently used is, of course, usually better than mechanical control for a single corner (intersection)". Marsh also presented the disadvantages of manual control of isolated intersection. His primary concern was that an officer had no way to coordinate his actions with officers directing traffic at nearby intersections. He further contended that an officer at an intersection was difficult to see by approaching vehicles and that, over time, an officer could become complacent and distracted. Furthermore, the public sought to asked questions of the officers, distracting them from their duties. Police officers, as one of their basic duties, must write tickets and make arrests, which may take away from their traffic control responsibilities.

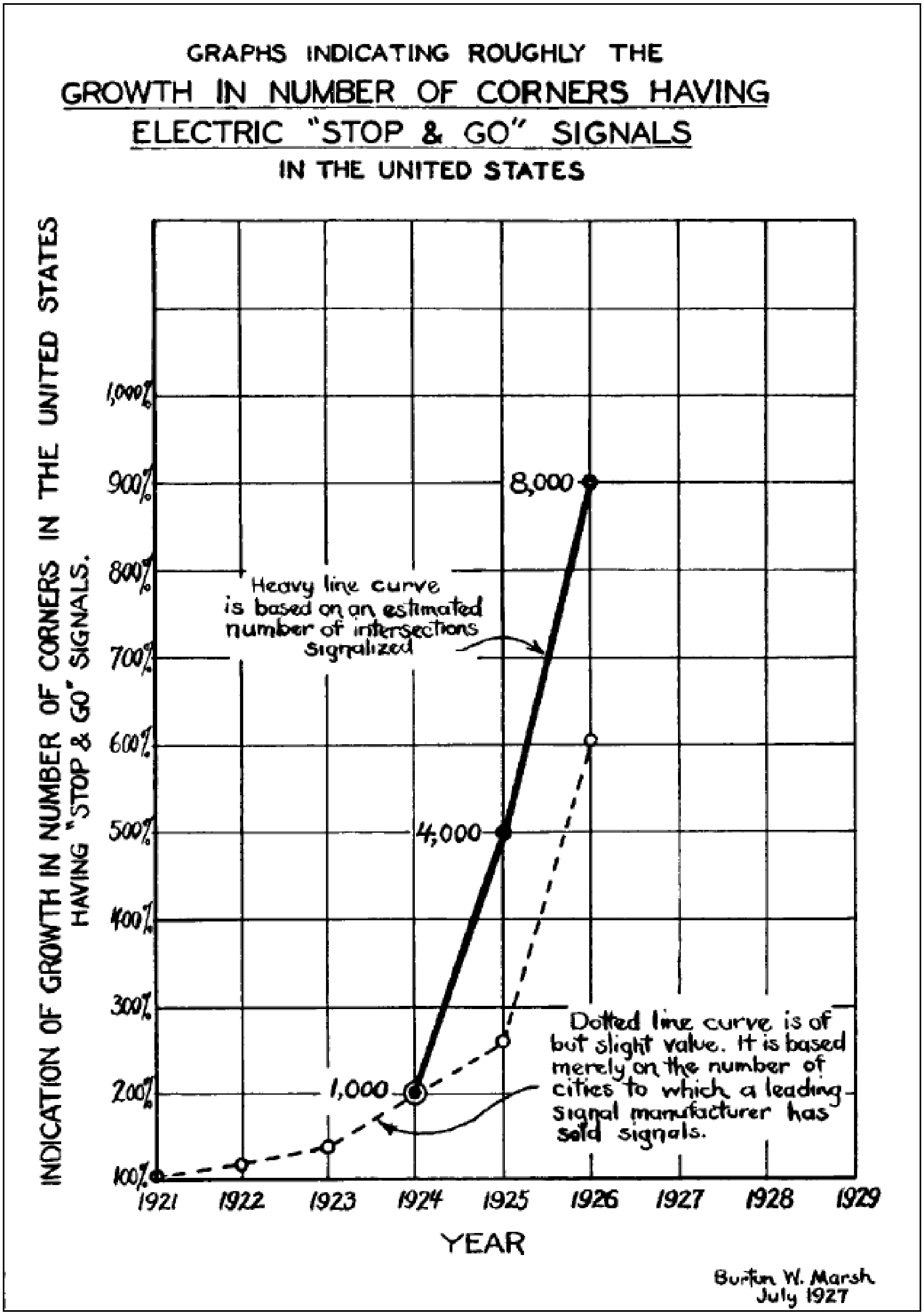


Figure 6: Estimate of Automated Traffic Signal Controllers in the U.S. (Marsh, 1927)

Another disadvantage of manual traffic control was the tendency toward human error. An officer must be trained and experienced in directing traffic to become proficient; even veteran officers can have bad days. The last and most pressing issue was the financial implication of manual traffic control versus automated control. Marsh compared the operating cost of both control strategies, stating that over the course of five years, an officer would operate an intersection for eight hours a day at a cost of $9,200 (in 1927) as compared to an automated signal controller which will cost $3,000 for 24 hour service, Table 2.

Table 2: Advantages and Disadvantages for Manual Traffic Control (Marsh, 1927)

Police Control of Isolated intersections	
Advantages:	**Disadvantages:**
An officer can control of an individual corner better than any other means	An officer cannot coordinate his actions with officers at neighboring intersections
An officer is best at allocating time appropriately at any given instance	It can be difficult to see an officer standing a the corner of the intersection
An officer can give priority to emergency and public transportation vehicles	An officer can become complacent over time
An officer can handle varying left hand turn volumes better than any other signal control system	An officer is subject to being asked questions by the public
An officer can use common since judgments at a moment notice	An officer can be distracted easily
	An officer must perform police duties
	A rookie officer is subject to a learning curve
	A veteran officer will have bad days on occasion
	An officer is much more expensive than an automated signal controller

In addition to presenting the advantages and disadvantages of manual control, the article presented the advantages and disadvantages of automated signal control. The article stated that automated signal control was less expensive, easier to locate in an intersection, and could operate 24 hours a day independent of weather conditions. Additionally, automated signal control reduced traffic accidents in the vicinity of an intersection, provided pedestrians a clear and defined time to cross safely, and was more efficient at allocating green time at large or otherwise complicated intersections. The disadvantages of automated signal control generally originated from the fact a signal could not adjust to the current traffic volume. An automated signal controller did not efficiently handle unbalance or widely-varying traffic volumes; the signal allocated green time to movements which did not have demand and the signal was inefficient if placed at intersections at which volume did not warrant them. Furthermore, automated signal controllers were limited in the number of lights that could be used. Too many lights could confuse drivers and the signal would require more frequent mechanical maintenance. The advantages and disadvantages of automated traffic control are shown in Table 3.

Table 3: Advantages and Disadvantages for Automated Signal Control (Marsh, 1927)

Automated Signal Control of Isolated intersections

Advantages:	**Disadvantages:**
A signal is less expensive than an officer	A signal is limited in the number of lights it can display
A signal is easier to locate and understand	The time allotted each movement remains constant throughout the day
Signals generally reduce traffic accidents in the vicinity of an intersection	Signals have a hard time dealing with unbalanced or widely varying traffic volumes
A signal gives pedestrian a clear and defined time to cross	A signal requires regular mechanical maintenance
A signal provides service 24 hours a day, 7 days a week	A signal at times will hold up traffic to allow movements from the side streets, when there is no demand for such movements
A signal is more efficient at allocating intersection right-of-way for large or otherwise complicated intersections	A signal will at times be placed at intersections where traffic volumes do not justify its placement.

The unmistakable advantage of automated traffic control was the cost over manual traffic control. In 1928 New York City had an estimated 2,243 automated signal controllers (Hoyt, 1927). From the time period of 1925-1928 the New York City Police Department reduced its traffic squad from 6,000 officers to 500 as a direct result of the added automated signal controllers. This reduction in manpower resulted in a savings of $12,500,000 annually (Kane and Finestone, 1928). This magnitude of savings was not restricted to New York City and municipalities across the U.S. found they too could save millions by switching to automated traffic signals. Traffic officials in Syracuse, NY claim that in addition to increasing travel times in the central business district, the entire cost of implementing the new automated signal control system was recovered in the first year by the savings made in officer salary (Walrath, 1925).

Additionally, automated traffic signals excelled were manual traffic control struggled; in coordinating movements between neighboring intersections. Automated signals allowed intersections within a corridor to be timed so that a driver could receive a green signal over the entire span of the corridor. The coordinated signal control system was found to be more effective than officers coordinating from traffic towers (Hoyt, 1927; Marsh, 1927). However, the additional coordination was not without its drawbacks. It was found that drivers would race down a coordinated corridor, attempting to keep up with the traffic signals (McShane, 1999). In a traffic survey of Philadelphia (PA) in 1929, 341 automatically timed signal intersections under coordinated control were evaluated for safety. The study found that collisions increased by 40 percent (Marsh, 1930). Marsh attributed the increase in accidents to poor implementation of the traffic signals and not coordination.

The controversy over automated signal control was immediate with the spread of the new systems implementation. Outspoken traffic research expert Miller McClintock believed that the new signals would never replace police officers (McClintock, 1923). E. P. Goodrich, a consultant engineer for the Borough of Manhattan dismissed automated signal control as a “fad” that would pass and suggested the city not waste the money for their implementation (Goodrich, 1927). William Philp Eno, considered to be the father of highway safety stated “students of traffic are beginning to realize the false economy of mechanically controlled traffic, and hand work by trained officers will again prevail” (Eno, 1927). The State of New Jersey required manual traffic control for all state highways because officials believed automated signal control to be inefficient for their truck-line highways (Marsh, 1927). Underlining these concerns was the belief that without an officer present to enforce traffic laws at an intersection, drivers and pedestrians would do as they please (McShane, 1999).

The push to overcome the obstacles faced by automated signal control came from the engineering field. Based on the work done by early traffic engineers it was undeniable that automated traffic control, as a means of general practice in urban environments was more effective as a result of coordinated systems and more efficient financially, if by no other measure. However, it was left to the engineering field to convince the commuting public. To do this, engineering organizations collaborated with public and private representatives of the motoring community. Furthermore, police agencies provided support to the movement to automated signals by enforcing the first installments of the new system. The success of these efforts is self-evident today. By 1930, semaphores, traffic towers and manual traffic control in urban areas for routine traffic conditions was a thing of the past (Sessions, 1971). From this point on automated traffic control was the dominate traffic control measure used in developed countries.

After the 1920's manual traffic control was reserved for directing special event and emergency traffic. Conditions where routine traffic control plans do not adequately provide the capacity needed for rare events. The previous research comparing manual traffic control to automated traffic control only evaluates these strategies for routine conditions and not their common practice today. The evaluation techniques used during this time (cura 1925) to compare manual and automated signal control were qualitative in nature, not presenting any data on traffic speed, travel time, volume, etc. Furthermore, advancements in both fields over the last 90 years warrant a fresh comparison between the traffic control measures. There exists a gap in the research that mandates a quantitative analysis between manual traffic control and modern signal controllers for use during planned special events and emergencies.

2.2 Manual of Uniform Traffic Control Devices (MUTCD)

The Manual of Uniform Traffic Control Devices (MUTCD) is the document that sets the national standards for all traffic control devices governing streets, highways, bikeways and roadways otherwise open to public travel in the United States. The MUTCD designates a traffic control device as any signs, signal, markings or any other devise used to regulate, warn or guide motor vehicles, bicyclist or pedestrians (MUTCD, 2009). Prior to the publication of the first MUTCD in 1935, two previous manuals governed traffic control devices in the U.S. (Hawkins, 1992). The first published in 1927 then revised in 1929 was the Manual and Specifications for the Manufacture, Display and Erection of U.S. Standard Road Markers and Signs. This document was sponsored by the American Association of State Highway Officials (AASHO) in conjunction with the National Conference on Street and Highways Safety (NCSHS). AASHO is now known as the American Association of State Highway Transportation Officials (AASHTO). This manual provided standards for rural roads and did not include standards for traffic signals; manual, automatic or otherwise (AASHO, 1929). The other predecessor to the MUTCD was the Manual on Street Traffic Signs, Signal and Markings, also sponsored by the National Conference on Street and Highway Safety (NCSHS). This manual, in contrast to the Manual and Specifications for the Manufacture, Display and Erection of U.S. Standard Road Markers and

Signs, was designed to accommodate urban traffic signs, markings and was the first national standard for traffic signal regulation in the U.S. However, having two set of national regulations governing roadway sign, signals and markings was undesirable. Therefore, the MUTCD was created to bring uniformity and establish a single source for regulating the design of road sign, signals and markings (MUTCD, 2009).

The National Conference on Street and Highway Safety was responsible for the Manual on Street Traffic Signs, Signal and Markings. This document makes no mention of manual traffic control but does note “Traffic officers stationed in roadways shall be illuminated at night, by flood lights if necessary, in the interest of safety” (NCSHS, 1930a). However the NCSHS, in an attempt to bring uniformity to city traffic laws published a model set of municipal traffic ordinances. In this document, the authors recognize the role of police and the need for their authority in directing traffic.

> It shall be the duty of the Police Department of this city to enforce the provisions of this ordinance. Officers of the Police Department are hereby authorized to direct all traffic either in person or by means of visible or audible signal in conformance with the provisions of this Ordinance, provided that in the event of a fire or other emergency or to expedite traffic or safeguard pedestrians, officers of the Police or Fire Department may direct traffic, as conditions may require, notwithstanding the provision of this Ordinance (NCSHS, 1930b).

The most recent MUTCD published in 2009 makes little mention of manual traffic control of intersections. The document discusses traffic incidents and states, “if manual traffic control is needed it should be provided by qualified flaggers or uniformed law enforcement” (MUTCD, 2009). The manual does however specify that officers directing traffic are subject to the same high-visibility safety apparel as flagmen when operating near the roadway. Furthermore, the MUTCD developed a Traffic Control Point Sign (EM-3) to be used at locations where manual traffic control is used on a regular basis (MUTCD, 2009). Other than these three instances, the 862 page document publishing the national standards for all traffic control makes no mention of manual traffic control despite its frequent use during planned special events and emergencies.

2.3 Police Training For Traffic Control

The effectiveness of a police officer at directing traffic is a function of training and experience. Prior to formal regulations, officer training was conducted entirely within each department. Specialized training for law enforcement officers first emerged in 1935 with the founding of the FBI National Academy (Hoover, 1947). Between the years of 1935 and 1944 the FBI National Academy sent instructors to 1,513 local, county and state police agencies. In 1946 alone the academy instructed 1,785 schools attended by almost 90,000 law enforcement officials. Due to the size and scope of the traffic problem the FBI national Academy included traffic training from its founding in 1935 (Hoover, 1950). As director of the Federal Bureau of Investigations (FBI), J. Edgar Hoover institutionalized uniform training programs and training templates for police traffic control. Hoover believed that “the development of police executives and instructors cannot be accomplished without adequate training in traffic law enforcement” (Hoover, 1950). The FBI made police traffic control training available to local law enforcement in urban and rural areas. In 1949 over 150 police training schools were held specializing in traffic control. Small stations which did not have an adequate number of officers to justify holding an entire course at their department could go to “Zone Schools” which allowed officers from many neighboring communities to attend (Hoover, 1947; Hoover, 1950).

2.3.1 Northwestern University Traffic Institute

Private traffic control training for law enforcement officers began in 1936 with the founding of the Traffic Safety Institute at Northwestern University (Bradford, 2013). The Traffic Safety Institute, later known as the Traffic Institute, trained officers in crash prevention, traffic supervision and police management. Traffic supervision had three direct functions, accident investigation, traffic law enforcement and traffic direction (Woods, 1952). Since the founding of the Traffic Institute it has published several documents on manual traffic control.

Police traffic direction is defined by the Northwestern University Traffic Institute (NUTI) as “telling drivers and pedestrians how and where they may or may not move or stand at a particular place, especially during periods of congestion or in emergencies” (Woods, 1952). Published in 1952 the article Directing Traffic, what it is and what it does, was the first of its kind in providing a cross-jurisdictional standard for manual traffic control. While manual control had become more-or-less standardized in practice, this article was the first to publish and disseminate the procedure. The article states that officers while directing traffic must answer inquiries, tell drivers and pedestrians what to do and what not to do and in the cases of emergency traffic control, make rules for the flow of traffic when usual rules are inadequate. The article tells officers to act as a traffic light operating in coordination with neighboring signals, never allowing more vehicles through the intersection which the downstream intersection cannot handle (Woods, 1952). However, the article does not provide guidance on how to effectively and efficiently direct traffic in practice.

In 1960, the NUTI put out the first edition of Signals and Gestures for Directing Traffic. This publication was revised five times; the most recent version was released in 1986. The article explained, through illustration, how a police officer should communicate with vehicles and pedestrians while directing traffic. First, it explained different postures and then went on to illustrate how each hand gesture corresponded to a vehicle movement or action. The article then moved on to controlling traffic using the “clicker” method, however, the article implied that the “officer in the intersection” approach was more effective at directing traffic. Finally, the article concluded by explaining the role of the baton and whistle, as well as how to cope with directing traffic at night (NUTI, 1986). The article may be a good instructional guide for communications while directing traffic, but does not lend any insight on how to effectively or efficiently direct traffic.

The follow-up publication of NUTI to Signals and Gestures for Directing Traffic was Directing Vehicle Movements, published in 1961. This article was unique in that it employed traffic engineering concepts to assist in the effectiveness of manual traffic control. The guide stated that manual control is only necessary when an intersection is oversaturated for its current control technique (e.g., signal control, stop controlled, priority controlled), citing that motorists will exercise undue caution when entering an intersection governed by a police officer in the same fashion that drivers will hesitate to overtake a police patrol vehicle while driving on the highway. The presence of an officer inevitably led to a loss of efficiency and, thus, an officer should only direct traffic in situations where manual traffic control will offset the initial loss in efficiency. Therefore, an officer was only able to direct traffic when needed in oversaturated conditions. The article instructed officers to equitably distribute delay time between movements based on volume. Delaying one car for 30-seconds is equivalent to delaying 30 cars for one second, as such low volume movements should be delayed for longer periods. To maximize saturation flow rate, officers were instructed to hold a movement’s initial arrival until a group of vehicles formed, and then switch to that direction and keep them there so long as vehicles depart one right after the next. It stated officers should not keep vehicles waiting for longer than a minute in the hope of collecting a group and officers should not prolong green time for a single vehicle. The article stresses the importance of preventing queues from propagating into neighboring intersections. It instructed officers to force vehicles to detour if the queue is threating the upstream intersection. At an intersection where cross-street traffic and main-street traffic were equal, the officers were told to increase cycle length to reduce start-up lost-time and increase effective green time. Also, it stated officers should never waste green time; if an exit lane was blocked, officers were told to immediately switch to a free-flowing movement until adequate room was provide to allow the previously-blocked movement to continue. When switching between movements, officers were informed to wait until a natural gap in the traffic stream appeared. If no gap existed, officers were instructed to stop the flow of vehicles after a heavy truck. By letting the heavy truck pass the intersection, the start-up lost-time of having to halt and restart the large vehicle was reduced. In addition to informing officers on how to increase efficiency, officers were instructed on how to improve safety. Officers are told where to stand in the intersection, how to cope with wet and icy environments, and how to remain safe in intersections with irregular geometries (NUTI, 1961). The article assumed that the “officer in the intersection” approach was more efficient then the “clicker” method, which may not be true today given the advancements in traffic signal controllers.

2.3.2 Modern Police Training for Traffic Control

In 1973 the International Association of Chiefs of Police (IACP) collaborated with the National Highway Traffic Safety Administration (NHTSA) to develop a comprehensive collection of police traffic service polices for best practice. This partnership developed the Police Traffic Service Basic Training Program (Hale and Hamilton, 1973). The goal of this program was to improve the effectiveness of the National Highway Safety Program by establishing national standards on jurisdictional law enforcement training to provide police officers with basic, uniform training in police traffic services. This national training program was targeted at six major areas; 1) policy and traffic service, 2) traffic law, 3) traffic direction and control, 4) traffic law enforcement, 5) traffic management, and 6) traffic court. The traffic direction and control section of the training program stated that an officer had three goals when directing traffic: safe movement of vehicles and pedestrians, the mitigation of traffic congestion, and ensuring driver comply with traffic laws. The training program also discussed instances where police traffic control should be used, areas of periodic congestion (e.g., rush hour choke points), special events, and around hazardous scenes. However, the training program did not include guidance in determining when it may be more beneficial to use police in lieu of signalized control, when it should be used, where it can best be implemented, or how to evaluate its effect on the overall movement of traffic during emergencies, events, or routine traffic conditions.

By 1977, the IACP and NHTSA partnership had developed a system for evaluating police traffic services for the nation. This guide was intended to assist police agencies in determining the quantity and quality of services provided by their traffic control division. The manual was designed to evaluate an individual police officer’s performance. It was possible to measure and evaluate the performance of traffic control for a department if aggregated for the entire police force. The manual evaluated an officer based on several factors related to traffic control. An officer’s performance while directing traffic was based on the traffic flow through the intersection and eye witness reports of the officer’s actions (NHTSA, 1977).

In 1986, the IACP and NHTSA published the Manual of Model Police Traffic Services Policies and Procedures. This document consolidated, revised, and updated the work done in the previous decade. This effort was motivated by the need for police officials to remain compliant with traffic-related standards set by the Commission on Accreditation for Law Enforcement Agencies. The document detailed traffic control functions, such as staff and administrative service, traffic law enforcement, accident management, traffic direction and control, traffic engineering and ancillary motorist services. Under traffic direction and control, the document provided guidance on general policy and procedure, as well as identifying locations for traffic control, implementing temporary traffic control devices and traffic direction for special events, fire scenes, and adverse road conditions (NHTSA, 1986). An important note here was that only the *policy* differs with regard to directing traffic for regular operations, special events, and fire scene—not the *procedure*. The procedure for directing traffic remained the same regardless of the application.

Over the years, numerous other manuals were developed to describe the proper functioning of police traffic control (Leonard, 1973; Weston, 1996). However, these documents focus primarily on the role of police in accident reduction, selective traffic law enforcement, and the development of a traffic-orientated police force. They also provided guidelines for officer safety by identifying where and how to move within a congested intersection. The book by Weston (1996) provided a comprehensive reference for ensuring safety while directing traffic, but it did not specify when it may be more beneficial to use police in lieu of signalized control, when it should be used, where it can best be implemented, or how to evaluate its effect on the overall movement of traffic during emergencies, events, or routine traffic conditions.

2.4 Technical Manuals, Handbooks and Published Guidelines

An extensive amount of unpublished or otherwise not widely-disseminated practitioner training references exist for manual traffic control. These manuals have generally addressed the "nuts and bolts" of traffic direction. In general, they are designed to be a quick reference for an individual new to manual traffic control. These documents were usually developed by individual police departments and used as a jurisdictional guideline for new police officers. Most of these manuals were not made to be cited references and as such many do not list an author or date of publication. These documents were for "in-house" use, authored by senior officers on the force with years of manual traffic control experience.

Despite being developed to meet local traffic control needs, these manuals showed consistency with references to several key points. All of the reviewed documents shared the following:

- The use of reflective vest at all times
- The use of lighting for directing traffic in adverse weather
- The need for additional lighting at night from the police vehicle or additional flood lights
- Where to stand within the intersection
- How the officer should position his/her body to command vehicles
- Uniform hand signals to start and stop the flow of traffic
- Safety when directing conflicting turn movements
- The use of traffic control tools such as flashlights, whistle, illuminated batons and flares

While consistent, these documents have been inadequate in providing guidance on how to effectively distribute intersection right-of-way. These documents provided a "how to" for directing traffic; after reading one of these manuals an officer would know "how to" start and stop the flow of vehicles but would not know when or why. Without a basic understanding of traffic engineering concepts behind intersection control, which police officers developed with experience, new officers would certainly perform poorly. (Florida Highway Patrol, 1996;

Houston Police Department, 2004; Shults, 2005; Epperson, 2006; Jones, 2008; Anne Arundel County Police Department, 2009; Lincoln Police Department, 2011; Lundborn, 2011; Burlington Police Department, xxxx; City of Los Angeles Personnel Department, xxxx; Johnson, xxxx).

2.5 Special Event and Emergency Planning

Nearly every major planned special event has had a traffic management plan. Furthermore, most municipalities have had an emergency operations or emergency evacuation plan on some level (Region, State, County, City, etc.). Traffic management plans for special events and emergencies have been developed based on a set of common guidelines. For an emergency evacuation plan, the guidelines consisted of government regulations that typically required planning action. For planned special events, the guidelines were more of a collection of best practices aimed at assisting municipalities in event planning and management. Instead of looking at individual publications of traffic management plans, this sections looked at the guidelines by which authorities developing these plans use for guidance.

2.5.1 Special Event Planning

The National Cooperative Highway Research Program (NCHRP) had a mission to collect, evaluate and disseminate information on common highway problems faced by highway administrators, engineers and researchers. The synthesis series presented the state-of-the-practice in how these everyday problems were solved around the nation. One such problem, transportation planning and management for special events was addressed by NCHRP Synthesis 309. The document presented the ways by which agencies plan, coordinate, and manage the transportation system for planned special events. This document was a compendium of the best knowledge available on the practice of special event traffic management planning. When developing a traffic management plan for a special event, the “go to” document is the NCHRP 309.

The NCHRP synthesis 309 addressed all aspects of highway management for planned special events. This document made frequent reference to the use of police officers for manned traffic control points. “The advantage of using staffed traffic posts over signalized control is the presence of authority and the ability to make dynamic changes to the traffic flow”. Based on the survey conducted in NCHRP 309, manual traffic control of intersections for special events was a common traffic management technique used around the country. Therefore, any agency looking to develop a special event traffic management plan was encouraged to use manual traffic control.

Furthermore, these agencies were encouraged to use traffic simulation in the development of management plans. However, any event utilizing manual traffic control currently would have no reliable way of simulating the process for a comparative analysis.

2.5.2 Emergency Planning

Emergency planning has been governed by the Federal Emergency Response Agency (FEMA) and the Department of Homeland Security (DHS). These two departments, in a joint effort, developed the National Response Framework (NRF). The NRF was designed to assist personnel, governmental, commercial, and non-governmental organization officials in the response and recovery needed from a major disaster. The NRF developed various documents to assist state and local governments to create emergency traffic management plans for an all-hazards emergency (FEMA, 2009). One such set of documents, the Emergency Support Function (ESF), provided the structure for coordinating the interagency support needed to obtain federal resources to assist in the response to an emergency incident. The roles and responsibilities of relevant stakeholders are defined in a series of 15 documents known as the ESF Annexes. In order to obtain federal support in response to a disaster, the state and local government must comply with NRF and the ESF Annexes (FEMA, 2013).

The Emergency Support Function #13, Public Safety and Security Annex, provides federal assistance to local and state governments in order to maintain safety and security. Within this annex, the federal government may provide assistance to the local agencies for traffic control operations, namely traffic direction and control for vehicles and large crowds (ESF#13, 2009). The Mass Evacuation Incident Annex provides the criteria needed for federal support to assist in a mass evacuation. This annex stated that local police should be used to control the flow of vehicles on federal and state routes. This document referenced ESF #13 for the administration of traffic direction and control.

While FEMA and DHS have been the authoritative sources for the development of emergency traffic management plans for natural and man-made disasters, the traffic management plans for evacuations from nuclear power plant failures has been governed by the United States Nuclear Regulatory Commission (NRC). The NRC mandates, through governmental regulation, evacuation time estimates be developed for the population within the area surrounding a nuclear power plant (NRC, 1980). An evacuation time estimate (ETE) has been the calculated time required to evacuate an evacuation planning zone located within a ten mile radius of a nuclear power plant. The ETE has been primarily used by decision-makers to assist in choosing the correct protective action in the event of an incident at a nuclear power plant. However, it may also be used in the development of traffic management plans to support an evacuation (NRC, 2011).

The criteria for developing an ETE were given by NUREG/CR-7002 Criteria for Development of Evacuation Times Estimate Studies. This document highlighted manual traffic control stating, “In general, it may be assumed that manned traffic controlled intersections operate most efficiently” when compared to un-signalized, fixed-time signals and actuated signals. This document also supported the use of traffic simulation in the development of ETEs. It mandated that if manual traffic control is proposed as a part of a traffic management plan, then the simulation model must simulate the effects of manual traffic control. The document proposed modeling manual traffic control as an actuated signal with a signal timing plan which reflected more efficient operations (NRC, 2011). However, without full knowledge of manual traffic control operations, simulating manual traffic control as an actuated signal may not be realistic. Furthermore, no guidance was given on how to make the simulated actuated signal more efficient or how to simulate the actuated signal to produce results similar to that of manual traffic control.

2.6 Manual Traffic Control and Empirical Studies

Since the first studies to evaluate the effectiveness of manual traffic control in the 1920’s relatively little work has been conducted on this form of control. Since the 1920’s, manual traffic control under routine conditions in urban intersections was no longer commonplace (Sessions, 1971). After this time, manual traffic control has been primarily used for special events and emergency situations. However, in rare situations, manual traffic control is still used to supplement automated traffic controllers during peak hour periods in urban and rural areas. This was the case in Fort Belvoir, Virginia in 1953. At that time, a traffic study of ten intersections with narrow-width approaches (total width of two-way streets is less than thirty feet) was conducted to determine if the approach widths needed to be expanded (Sutermeister, 1956). Of the ten intersections studied, six were manually controlled by police officers (some using the “stand in the intersection” method and others using the “clicker” method), two were controlled under fixed time settings, one was an actuated controller, and the final one was all-way stop controlled. The highest capacities were observed using manual traffic control strategies. This was accomplished by officers extending the green time to the priority approach at the cost of the cross-street traffic. The report stated that during the 15-minute peak period, 31 approaches where found to be overloaded, however only two were recommended for widening. The study suggested that this was due to the added capacity of manual traffic control at the intersection and thus widening of the approach lanes was not necessary. Unfortunately, the study did not discriminate between manual traffic control conducted by the “officer in the intersection” approach or the “clicker” approach. This would have allowed more insight into the operational advantages of manual traffic control.

A study conducted in Brisbane, Australia evaluated manual traffic control to supplement congested at an un-signalized priority-controlled intersection during peak periods. As a part of this research a priority-controlled intersection was analyzed under manual traffic control during the evening peak period. From the rooftop of a nearby building, researchers used stopwatches to observe and time an officer directing traffic. The researchers recorded parameters such as phase length, number of vehicles and type, maximum queue length and the time to clear each queue. These values were then used to compare the officer’s performance to a hypothetical pre-timed and actuated traffic controller. The study found that saturation flow rate was not effected by manual control but average approach delay was slightly lower than expected when compared to a pre-timed isolated intersection. The paper concluded that it was unable to prove that an officer was superior to a traffic signal (Pretty, 1973). However, this conclusion is not generalizable based on the evidence that the study only considered one intersection under police control and observed this intersection for only one hour. Furthermore, the article states that the intersection was under-saturated. One of the primary applications for manual traffic control is for special events and emergency traffic, almost certainly operating in oversaturated conditions.

In some developing countries with high levels of congestion, manual traffic control during peak periods remains common for critical intersections. May and Montgomery (1988) evaluated pre-timed signal control settings as an alternative to manual traffic control for isolated and linked intersections in Bangkok, Thailand. An isolated intersection was studied for six days during evening peak periods. On days one, three, and five of the study pre-timed signalized control was used at the intersection. On days two, four, and six manual “clicker” control was used. Over the course of the experiment, the pre-timed signal control cycle and phase length settings were adjusted to increase their effectiveness. The results showed that at isolated intersections with over-saturated conditions, police out-performed pre-timed signal control on the basis of delay, queue length, and total throughput. The authors noted that saturation flow rate decreased over time, which represented inefficiencies in manual control as a result of long phase lengths.

This research also applied the same experimental methodology to evaluate the performance of pre-timed signal control at four linked intersections as a replacement to manual control. The study evaluated the four pre-timed signal settings over five consecutive days and compared the results of manual control to the following four days (excluding Saturday and Sunday). The results showed that a 21 percent decrease in travel time and a 29 percent increase in travel speed were possible using pre-timed coordinated signals as opposed to manual traffic control. However, it was necessary to have manual intervention when the corridor capacity was effected by major traffic incidents. The conclusions of this research were also backed by a quantitative analysis but, based on the high variation of the traffic demand between observation-days, the small sample size was not sufficient to draw statistically confident conclusion.

Another comparison of manual traffic control and automated control was conducted in Israel (Mahalel, Gur and Shiftan, 1991). This research compared manual traffic control of two isolated intersections to control by an actuated signal in oversaturated conditions. The first intersection was observed for two days under actuated signal control and four days under manual control. The second intersection was observed for one day of each. It was found that in over-saturated conditions, the actuated control performed similar to a pre-timed setting due to the recall of the maximum green. The research used total throughput and degree of saturation as measures of effectiveness. The study results showed that manual control was correlated to a decrease in lost-time by as much as 60 percent and an effective green time increase of 15%. This reduction in lost-time was attributed to the use of the longer cycles associated with manual control, resulting in fewer cycles per hour.

Confirming the findings found by May and Montgomery (1988), the Israeli research study also identified a decrease in saturation flow rate as phase length increased, despite the persistence of long queues. The authors quantified this phenomenon showing that 55 seconds into the phase, saturation flow rate decreased rapidly. This observation suggested that a trade-off exists between long phase length (increases in effective green time) and efficient use of green time (decreasing saturation flow rate). Further analyses of intersection throughput found that manual traffic control increased intersection capacity by as much as 9 percent, confirming the result found by Sutermeister (1956). A comparison of the degree of saturation suggested that manual control could increase capacity to such an extent that it could surpass demand. This conclusion is based on a comparison assuming constant cycle length and green splits for manual control. Research conducted by Marsh (1927) found that officers directing traffic do not operate in this manner. Furthermore, many of the advantages of manual traffic control can be hindered by such assumptions (see Table **2**). Therefore, conclusion suggested by Mahalel, Gur and Shiftan, (1991) are confirmed by previous research but due to the stated assumptions the magnitude of the capacity increase caused by manual traffic control may be larger. With a simulation tool for manual control these assumptions would not have been necessary.

During peak hours, roundabout intersections may also be supplemented with police control if demand warrants. A comparison of a police controlled roundabout to a traditional four-leg intersection evaluated intersection performance with regard to dynamic delay (i.e., delay from the end of a moving queue) was undertaken by Al-Madani (2002). Selecting two intersections (one roundabout and one traditional signalized four-leg) with similar traffic and geometric characteristics, video detection was used to produce vehicle trajectories. From these trajectories, vehicle delay was plotted against queue length for both intersections. The results showed that at distances less than 262ft (80m), the police controlled roundabout significantly out preformed the four-leg signalized intersection. However, when queue length surpassed this threshold, the four-leg signalized intersection reduced delay considerably when compared to the police controlled roundabout. It is uncertain whether the cause of this phenomenon could be attributed to the police control or the effect of an over-congested roundabout. Given the small sample size, the conclusions of this paper may not be widely generalizable to other locations and sets of conditions.

Manual traffic control has also been used frequently at all-way-stop controlled intersections before and after special events. Traffic volume at these intersections typically does not justify installing a traffic signal but during these instances of high, non-recurring congestion, manual traffic control is used to assist intersection operations. Using traffic simulation modeling, a comparison of manual traffic control and pre-timed signal control of an all-way-stop controlled intersection during a special event was undertaken by Ye, Veneziano and Lassacher (2008). This research determined the saturation flow rate from a one and half hour video recording of manual control operations. The saturation flow rate at this location was estimated to be 1,300 vehicles per hour. This is considerably less than the results of an earlier study by Pretty (1973) where the saturation flow rate was found to be nearly 1,700 vehicles per hour per lane.

During the observation period Ye, Veneziano and Lassacher (2008) observed the saturation flow rate decrease overtime; confirming the findings of Mahalel, Gur and Shiftan (1991) and May and Montgomery (1988) though not to the same extent. The manually controlled intersection was simulated as a pre-timed signal control using average cycle and phase lengths observed during the peak period of the special event traffic. These results were then compared to an optimized pre-timed signal plan within a traffic simulation environment. The results of the simulation showed that the optimized signal plan reduced vehicle delay by over half when compared to manual control. However, to simulate manual traffic control, this research assumed constant cycle lengths and phase splits in the same fashion as Mahalel, Gur and Shiftan, (1991) and contradicting Marsh (1927).

2.7 Summary of Literature Review Findings

Previous research on manual traffic control has shown that in oversaturated conditions, it outperforms automated control for isolated intersections (Sutermeister, 1953; May and Montongomery, 1988; Mahalel, Gur and Shiftan, 1991). However, in the case of under-saturated intersections, automated control prevails (Petty, 1974; Ye, Venexiano and Lassacher, 2008).

Research conducted before the 1930’s found that automated signal control outperformed manual control for coordinated systems (Marsh, 1927; Hoyt, 1927; Marsh 1930). Similar results were shown using a quantitative approach in more recent research (May and Montgomery, 1988). They also showed previous research agrees that under manual control, saturation flow rate decreases overtime as phase lengths increase (May and Montogomery, 1988; Mahalel, Gur and Shiftan, 1991; Ye, Venexiano and Lassacher, 2008). However, research on manual traffic control has been generally based on small sample sizes leading to questionable conclusions based on implied statistical significance. Furthermore, the previous research has only investigated the officer’s effect on the traffic stream and not what events in the traffic stream effect the officer’s decision making. Studies attempting to simulate manual traffic control have done so by assuming officers act like traffic lights, with constant cycle lengths and phase splits (Pretty, 1973; Mahalel, Gur and Shiftan, 1991; Ye, Venexiano and Lassacher, 2008). However, the emerpical observations show this is not the casue. Furthermore, Marsh (1927) suggested that many of the advantages of manual traffic control come from not having constant cycle length and phase splits. A comparison of Table 2 and Table 3 showed that the advantages of manual traffic control have been in an officer's ability to extend green time when needed, cut short phase, and accommodate unbalanced and uneven traffic volumes (Marsh, 1927; Eno, 1927; Schad, 1935). Oversimplifying manual traffic in simulation models by assuming constant cycle length and phase splits could lead to an unfair comparison between manual traffic control and automated control.

The most important conclusion of the review of past research studies and other documents showed that there is a gap in the base of knowledge, in there have been no studies using a statistically significant sample size to evaluated manual traffic control for planned special event and emergencies. At present, no research has been conducted on the stimulus-response relationship between the traffic stream and officer decision making while directing traffic. Also no research to date has ever programmed the traffic light to act as an officer, having phase length dictated by stimuli in the traffic stream. The research proposed in this report seeks to fill the gaps in knowledge by developing a discrete choice model able to replicate the actions taken by a police officer while directing traffic. The discrete choice model will then be programed into a traffic simulation model to replicate the police officer's logic while directing traffic. By incorporating the discrete choice model into the simulation model, the oversimplification and broad assumption made by Pretty (1973), Mahalel, Gur and Shiftan (1991) and Ye, Venexiano and Lassacher (2008) are not required, allowing for an "apples to apples" comparison of manual traffic control and automated control. The methodology used to undertake the work necessary to achieve these objectives is described in the following chapter.

CHAPTER 3. METHODOLOGY

The research methodology was developed to analyze and model manual traffic control. The methodology addresses the gaps in literature described in the second chapter. Broadly, the research methodology consisted of four primary tasks. The first task was the collection and processing of video footage of police officers directing traffic. The second task was the development of a discrete choice model capable of explaining right-of-way allocation decisions made by the police officers. The third task was programing the discrete choice model into the microscopic traffic simulator, VISSIM 5.3, to simulate the police officer directing traffic by “replacing” the intersection signal controller logic. The final task was to use this model to compare simulated manual traffic control model to a fully actuated signal controller.

Figure 7 provides a flowchart that graphically represents this methodology. The following sections of this chapter describe the primary research task: Data Collection and Reduction, Discrete Choice Modeling, and Simulation Model Development.

3.1 Data Collection and Reduction

The data requirements for discrete choice modeling dictated an extensive collection effort. Data was collected from nine intersections for eight special events in Baton Rouge, LA and Miami Gardens, FL. The data collection effort spanned over four months starting in the Fall 2012. In total, video data from over 320 hours of special event traffic was collected, viewed and cataloged. This was necessary because the location and timing of where and when police officers would direct traffic was unknown. From this video footage collected a total of 26 hours and 27 minutes (less than 10% of the total footage collected) was of police officers actively directing traffic.

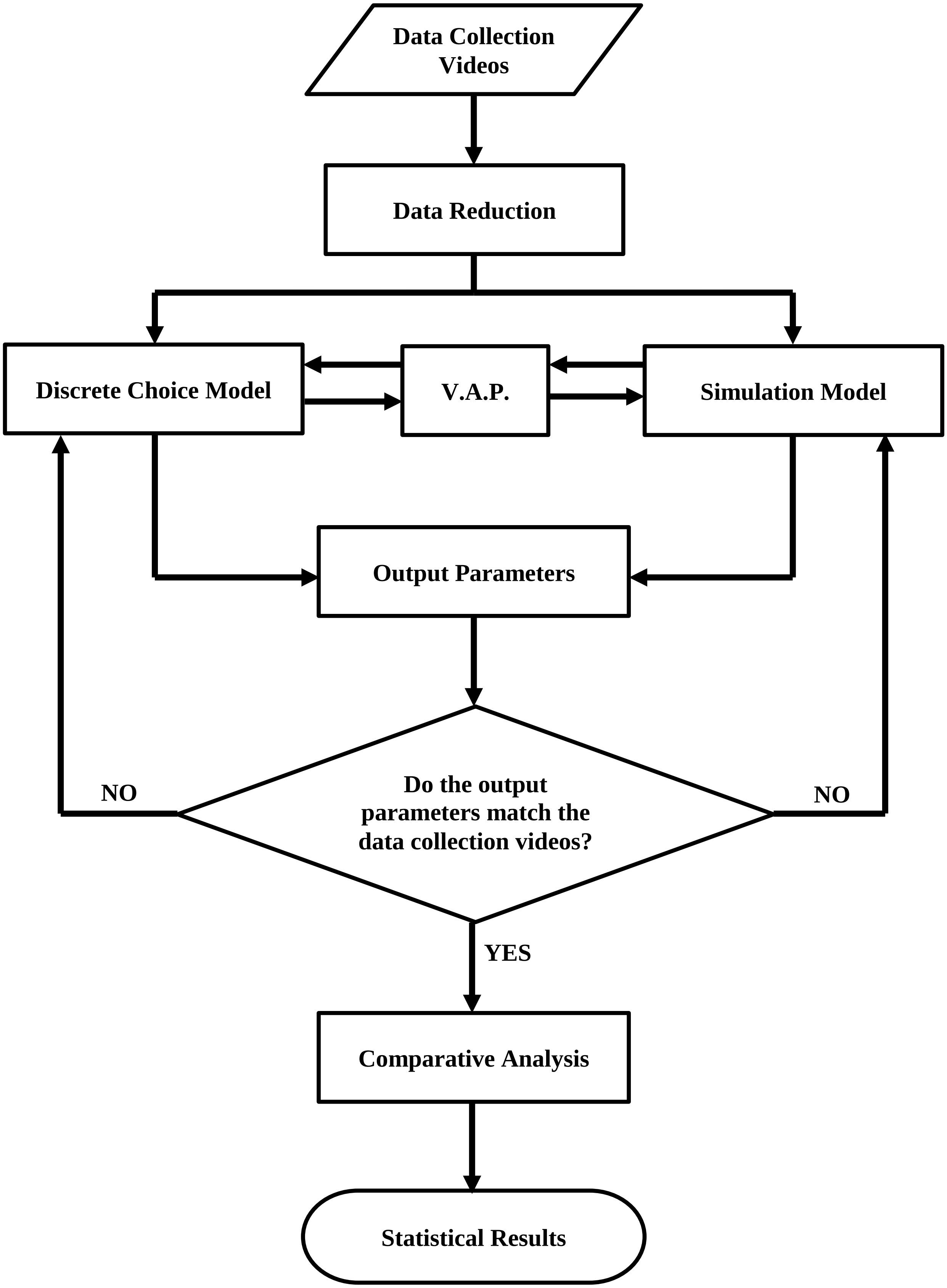


Figure 7: Methodology Flow Chart

In Baton Rouge, LA five intersections were selected for data collection during four special events. These intersections were selected from the LSU Game Day Traffic Management Plan provided by the Baton Rouge Department of Public Works. Of the five intersections selected in Baton Rouge, only three were observed to have police officers direct traffic in the video database. These intersections were Stanford and Perkins, Nicholson and Roosevelt and Nicholson and Lee. Their location in reference to Tiger Stadium at the LSU campus can be seen in Figure 8. The intersection of Nicholson and Lee is in close proximity (within 30 ft.) of a railroad crossing which, is not shown in the figure. The geometric configuration of the study intersection is provided in Appendix A.

In Miami Gardens, FL cameras were placed at four major intersection surrounding Sun Life Stadium for four special events. These intersections were chosen because of their proximity to the stadium and their location on critical routes. Of these four intersections one was observed to be under police control in the video database and for only three of the four events (one of the events did not use manual traffic control at any intersection). The study intersection located in Miami Gardens, FL was NW 183 St. and NW 27 Ave. Its location in reference to Sun Life Stadium is shown in Figure 9. The geometric design of this intersection is also provided in Appendix A.

Data for this study was collected from special event traffic only. While it would have been preferable to collect data from a mix of both special event and emergency situations, it was not practical with the scope and time schedule of the research. This research makes a broad assumption that manual traffic control is likely to be conducted similarly for special events and emergencies. The literature review provided justification for this assumption in modern police training (NHTSA, 1986) even though this research did not independently verify this.

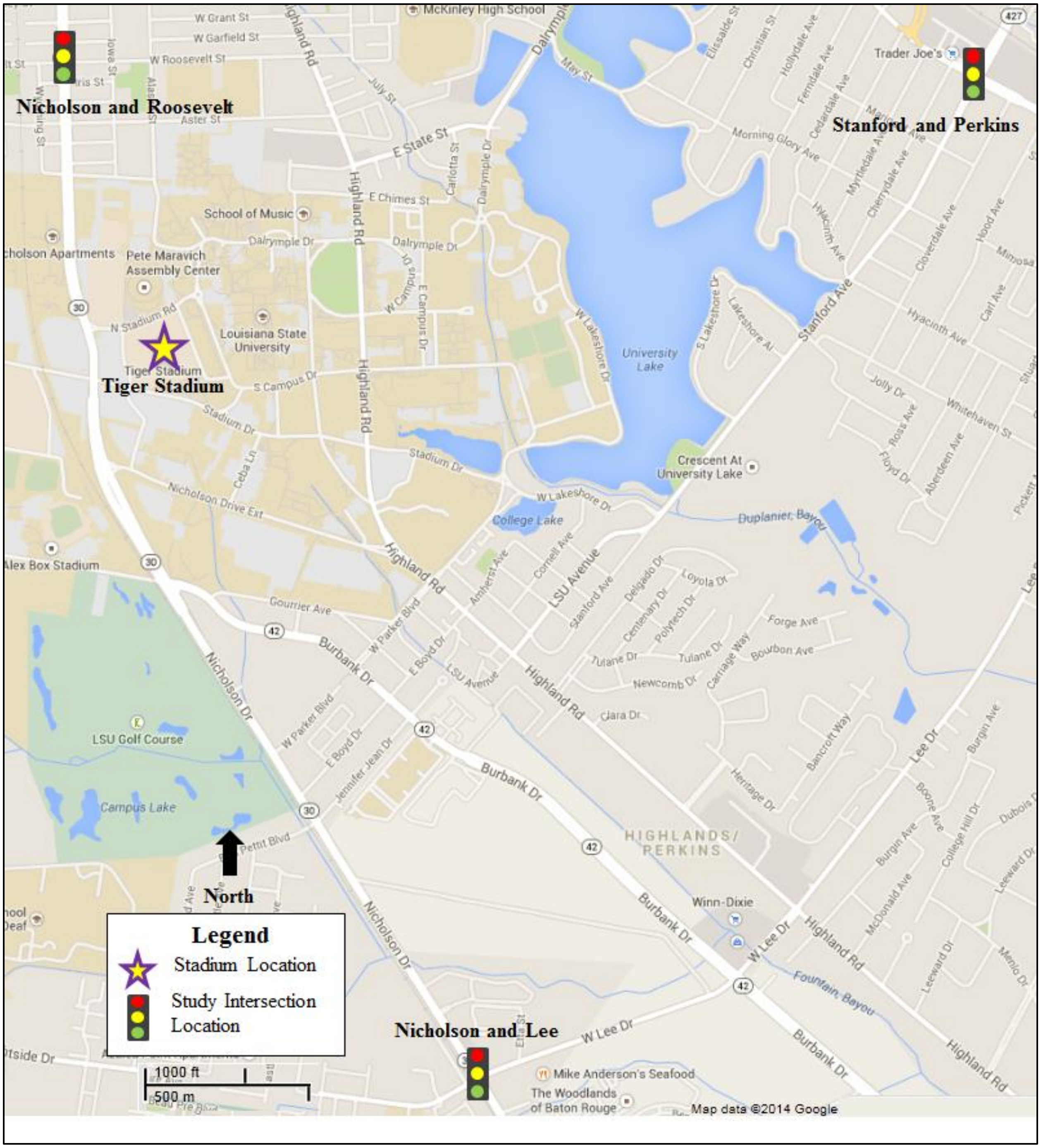


Figure 8: Baton Rouge, LA Study Area

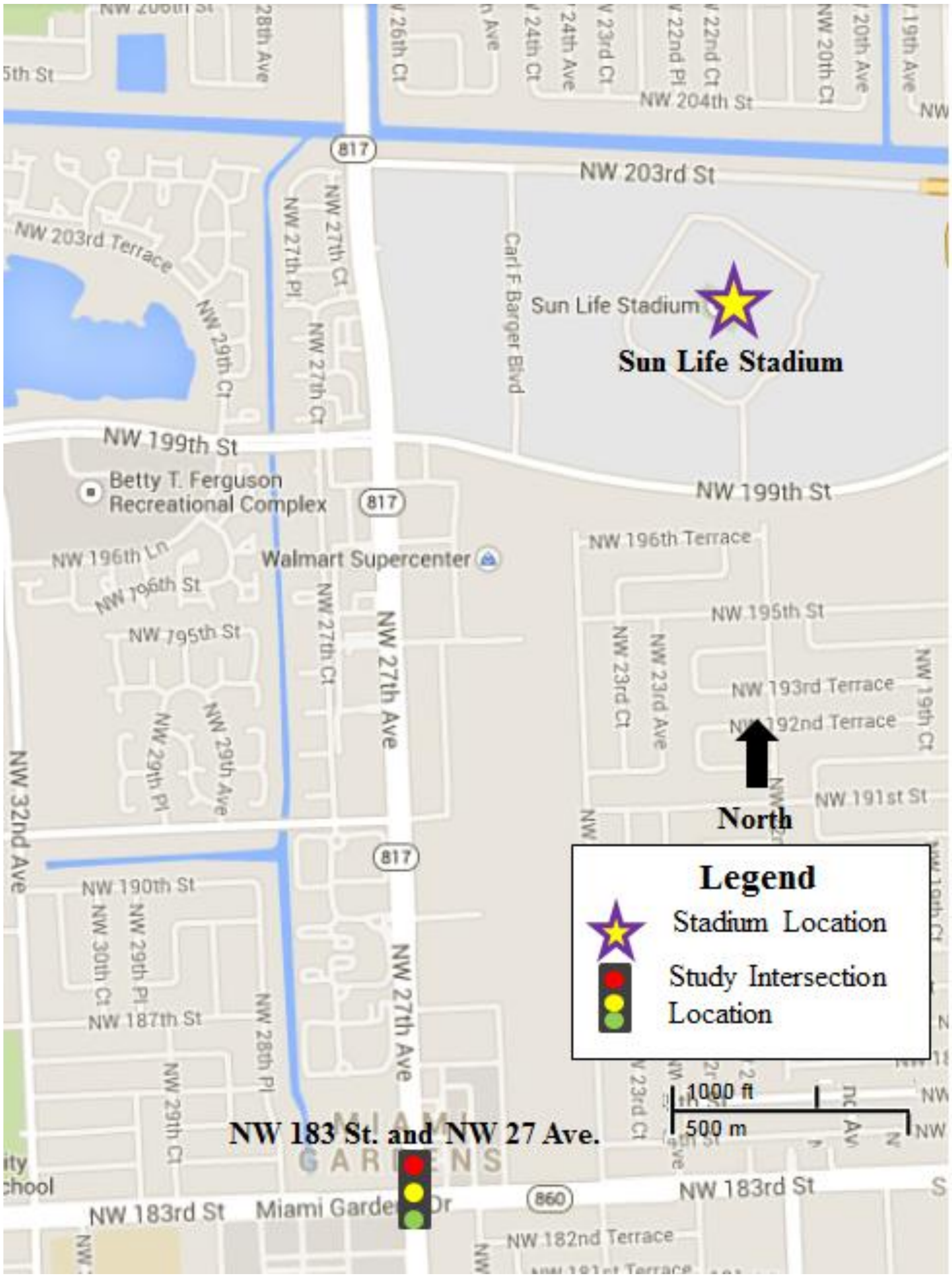


Figure 9: Miami Gardens, FL Study Area

Video recording was the preferred method to collect data because it was relatively inexpensive when compared to the labor cost associated with alternative methods. The video recording also allowed for a permanent record of the events and was the preferred data collection method in previous research (Al-Madani, 2002; Ye, Veneziano and Lassacher, 2008).

The data used in this research is summarized in Table 4. The remainder of this section describes how the video data was collected and processed for the development of the discrete choice and simulation models. The study events, collection equipment, pricing, and camera positioning within the intersection are also detailed. This section concludes with a description of the qualitative observations made during the video processing.

Table 4: Data Collection

Event Time	*Location*	*Num. Events*	*Num. Intersections*	*Num. Obs.*	*Time of Manual Control (Hours: Minutes)*
Fall 2012	Baton Rouge	4	3	12	21:49
Winter 2012	Miami Gardens	3	1	3	4:38
Total		7	4	15	26:27

3.1.1 Data Collection Device

The initial task required to collect the data was to identify a camera that satisfied the data collection requirements. The camera needed to record for at least four hours, provide high definition video quality and be waterproof. Also, it was desirable to have a camera that was securable and inexpensive. Based on these requirements the GoPro HD HERO™ was selected as the data collection camera.

The GoPro HD HERO™ is designed to be mounted on sporting equipment (helmets, dirt bikes, surfboards, etc.). It also records in HD and is waterproof. With an upgraded battery add-on and additional hard drive the camera can record for over five hours. While the camera is not securable, its small size made it easy to deploy and collect in the same day. Furthermore, the camera’s discrete profile made it go unnoticed among the existing intersection equipment (pedestrian call box, signal cables, detecting equipment, etc.). Figure 10 shows the entire video data collection assembly including GoPro HD HERO™, the Battery BacPac™, GoPro LCD Touch™ viewing screen, the waterproof case, plastic mounting platform, and 32 GB memory card used in each camera. The major advantage of the GoPro when compared to other camera alternatives was that the camera, power source and hard drive were self-contained in a small waterproof case. In wide angle mode the camera was capable of capturing a nearly 180° field of vision. This meant that only two cameras were required at each intersection to capture the approach queue length.

Ten sets of this camera assembly were purchased for a total cost of approximately $2,230 plus tax and shipping. Table 5 details these expenses.

Table 5: Data Collection Equipment Cost (US Dollars)

Description:	***Price:***	***Quantity:***	***Cost:***
GoPro HD HERO Camera	$129.99	10	$1,299.90
Battery BacPac	$49.99	10	$499.90
SanDisk 32GB SD Class 4 Card	$34.99	10	$349.90
GoPro LCD Touch BacPac	$79.99	1	$79.99
Tax			$89.19
Total			$2,318.88

The cameras were mounted to the traffic signal strain poles of each intersection. A camera was placed on the pole diagonally across from the traffic control box of each intersection while another camera was placed on the strain pole above the traffic control box, Figure 11. These locations were selected to ensure that the arrival and departure of the police officer at the controller box was also recorded. The cameras were placed at heights of 15 to 18 feet. This ensured that the cameras could capture the entire intersection unobstructed and that the cameras were out of sight of drivers and pedestrians, reducing the likelihood of theft or vandalism.

The waterproof camera case shown in Figure 10, detached from the four inch by four inch black, plastic platform. The platform was mounted to the strain pole using zip ties through small holes drilled into the platform corners as shown in Figure 12. The location of the mounting

Figure 10: Data Collection Camera

was critical. Improper mounting would have resulted in an inability to capture approach queue length. Test data collected prior to the events was used to make adjustments to the mounting position to ensure the approach queue lengths were properly recorded. Once positioned, the platforms remained in the field while the cameras were removed after each data collection event for downloading the data and recharging.

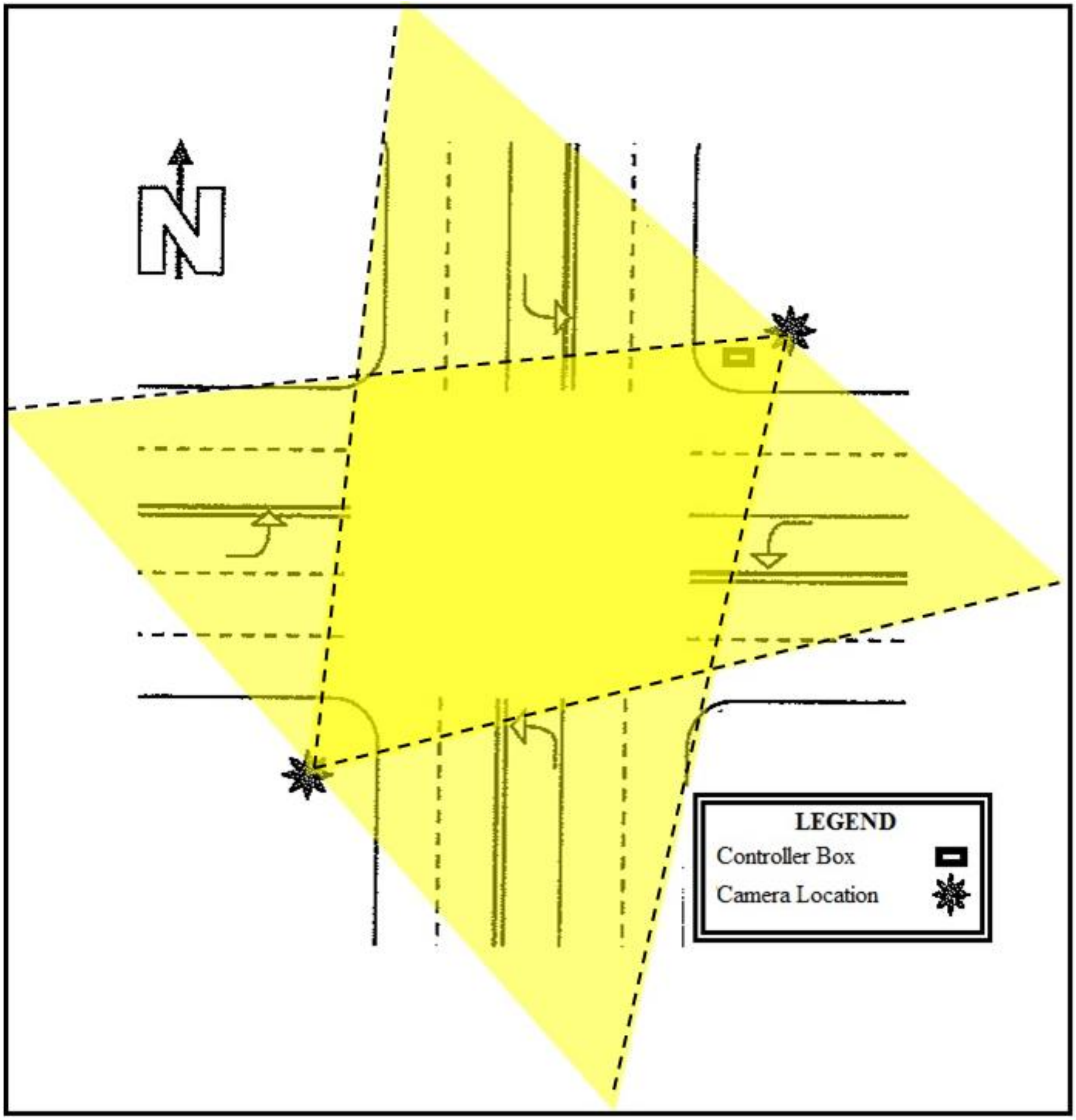


Figure 11: Relative Camera Locations and Coverage Areas

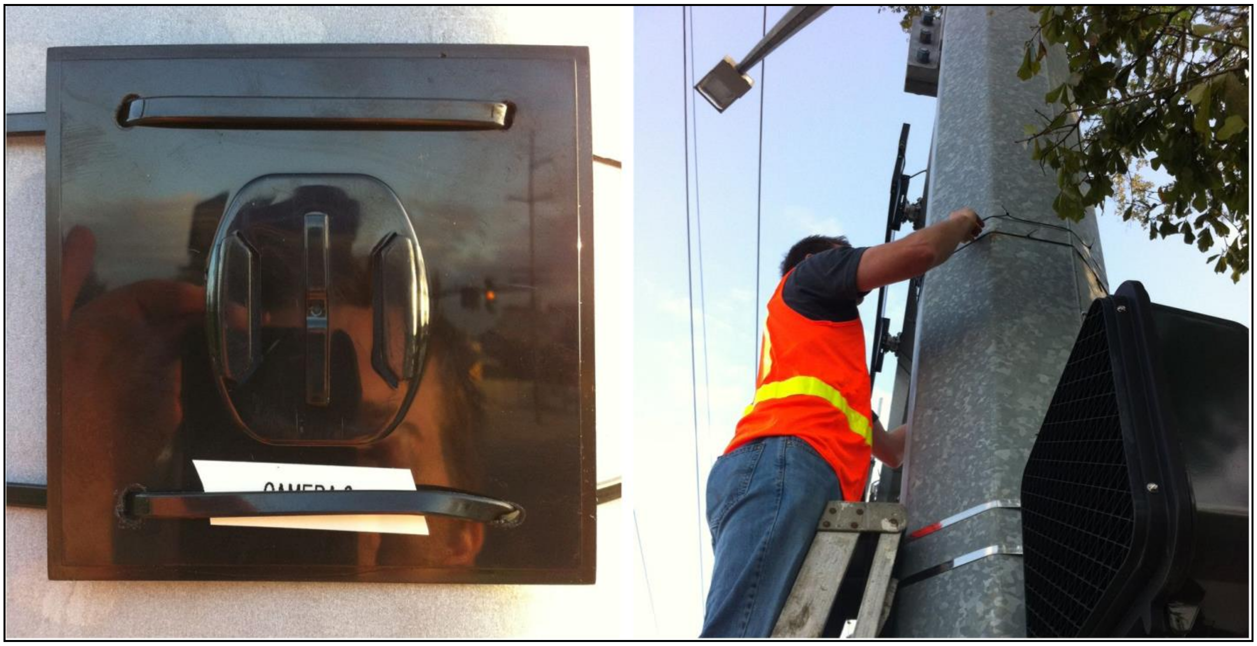


Figure 12: Camera Platform Mounting

The optimal setting for the cameras was determined based on the study requirements. The “wide-angle” setting was used to capture the approach queue length. The GoPro HD HERO™ was capable of recording in 720p, 960p, 1080p and analog (non-high definition). A setting of 720p was selected as it had the best tradeoff between resolution and memory requirements. It was determined early on that the analog mode did not provide the image resolution needed in the study. The frames captured per second (FPS) were set at thirty (FPS), to limit the memory storage space required to record a five hour event. Moreover, the cameras operated in low lighting conditions because many of the events took place at night.

Approximately two hours prior to the peak traffic demand period of the event, cameras were deployed at the intersections. Because of the battery constraints of the cameras, only five hours of recording was possible per camera per event. It was therefore necessary to deploy the cameras at a time that was as close to the estimated peak period as possible. When in place, the cameras recorded until the battery was exhausted. Once the event had ended, the cameras were removed from the strain poles, batteries recharged and memory cards downloaded to a desktop computer and then erased to make room for recording the next event. This process was repeated for each event.

3.1.2 Data Reduction

Through the data reduction process, the recorded video footage was systematically categorized it into numeric observations. The end product of the data reduction process was a time-line capturing the events (phase changes, phase length, lane groups, vehicle departures, etc.) that took place within the intersection. This process was completed in two-steps. The first step required manually recording lane groups, phase length and phase sequence for the periods immediately before, during, and immediately after the officer was directing traffic. Because access to the controller box during the special event was not permitted, this task could not be automated. During this time, observations of red-light running, emergency vehicle movements, and other abnormal road user behavior were made.

The next step was to time-stamp individual vehicle departures. Vehicle departures were time-stamped manually using the “Bookmark” function of VLC Media Player™. Initially it was thought this process could be automated using an Autoscope TrackVision Terra™. However, to capture the traffic signal faces the camera had to be tilted upward. The camera tilt meant it was not possible to use the Autoscope TrackVision Terra™ due to the angle requirements of the video processing software. Each movement at the intersection was observed separately, requiring the video to be watched numerous times. A “Bookmark” was created each time a vehicle crossed a predetermined line on the video screen for each movement. These “Bookmarks” were then transferred to a spreadsheet and converted into time-stamps using the synchronized internal clock of the Go-Pro HERO HD™ camera. In addition to the departures, the time period when the intersection was blocked by vehicles due to congestion was captured. Also, temporary gaps in the traffic stream were recorded. These gaps typically occur when vehicle platoons break-up due to poor coordination, lack of demand or long distances between intersections.

There were several limitations of manual data reduction. The accuracy of the process was subjective. Two individuals recording vehicle departures for the same movement would result in slightly different time-stamps. These inconsistences were usually in the range of one second but in some instances it was larger. The manually reported data was verified for accuracy using random spot-checks.

Manual data reduction for one hour of video for a four-legged intersection required about 9-10 man-hours. One hour for watching lane groups, phase length, and phase sequence; three hours for lane movement departures; two hours for intersection blockages, two hours to record vehicle gaps and one hour to convert the "Bookmarks" into time-stamps. This process could be made faster if the video was played at faster-than-real-time speed, however, this may have effected reporting accuracy.

Using the manually-coded data, a second-by-second timeline was created incorporating departures for all intersection movements, lane groups, phase length and phase sequence, and intersection blockages and gaps (periods where no vehicles traversed the intersection). Table 6 shows a representative 14-second period of manual traffic control. The first column of the table was the actual time of day, which has been converted to match the internal clock of the camera. The next 12 columns represent departure movements. For example, three vehicles departed the northbound through movement from 1:28:16 a.m. thru 1:28:18 a.m. The next column is a binary variable with a value of 1 if there was a significant gap (time-headway longer than 4 seconds) in the vehicle platoon and 0 otherwise. The final column was also a binary variable, which was 1 if a vehicle was stopped in the intersection and 0 otherwise. The shaded green columns highlight movements that received a green indication. It is noteworthy that at 1:28:23 a.m. a vehicle ran a red-light by making an illegal left; most likely due to the blockage of the intersection. The time-line was later used to create the variable pool for the development of the discrete choice model and also the required input for the traffic simulation model

Table 6: Sample Intersection Event Time-Line

TIME	***WL***	***W***	***WR***	***NL***	***N***	***NR***	***EL***	***E***	***ER***	***SL***	***S***	***SR***	***G***	***B***
1:28:16					1						1		0	0
1:28:17					1								0	0
1:28:18					1						1		0	0
1:28:19													0	0
1:28:20					1						1		0	0
1:28:21													0	1
1:28:22					1	1							0	1
1:28:23				1									0	1
1:28:24													0	1
1:28:25					1								0	1
1:28:26													0	1
1:28:27					1	1							0	1
1:28:28													0	0
1:28:29					1								0	0

Once the time-lines were created, they were examined for errors and inconsistences. This led to the conclusion that not all of the *hours of manual control* reported in Table 4 were usable.

The intersection of Nicholson and Lee experienced two incidents that resulted in the removal of data collected on 10/13/2012 and on 11/17/2012. On the first date, a traffic accident occurred at the intersection and the officer stopped directing traffic to assist the motorist involved. On the second date, a train superseded the officer's ability to change phases. Additionally, the intersection of Stanford and Perkins on 11/03/2012 was removed. On this date the officer directing traffic frequently changed phase sequence, constituting an additional discrete choice not considered at other intersections. While the addition of this discrete choice warrants investigation, as it may have led to improved intersection performance, adding an additional choice to the model formulation was considered outside the scope of this research. The use of irregular phase sequencing was also observed at the intersection of NW 183 St. and NW 27 Ave. when the police officer was directing traffic by hand ("officer in the intersection approach"). These observations were also removed from consideration to not introduce additional variability in the data. Also at this intersection, the observations taken on data 01/01/2013 were removed. During this time the intersection was under-saturated and as concluded in the literature review, this has a significant effect on manual traffic control (Pretty, 1973; May and Montgomery, 1988; Mahalel, Gur and Shiftan, 1991). Also, the intersection of Stanford and Perkins on the data of 10/13/12 was used as a pilot study and therefore could not be used as a part of the main study effort. Table 7 showed the data collection date and location along with its dataset classification.

Table 7: Data Partition

Intersection:	***10/13/12***	***11/3/12***	***11/10/12***	***11/17/12***	***12/23/12***	***1/1/13***	***1/7/13***
Stanford & Perkins	PS	R	S	S	n/a	n/a	n/a
Nicholson & Roosevelt	S	S	S	S	n/a	n/a	n/a
Nicholson & Lee	R	S	S	R	n/a	n/a	n/a
183 & 27	n/a	n/a	n/a	n/a	R	R	S

R = removed from study; S = Satisfactory; PS = pilot study dataset

3.1.3 General Observations

This section describes the general observations from a qualitative perspective that were made by watching the videos. These observations provided researchers an idea of the concepts and principles that may (or may not) contribute to the way in which officers' direct traffic. These observations, along with the literature review, led to all subsequent analysis.

While viewing the video it was not clear what prompted the police officer to start directing traffic. Some officers started immediately while others did not. In general it may have a relationship with phase failure (the inability of a phase to discharge its queue). Likewise, the criterion for ending manual traffic control was unclear. In general the officers stopped when traffic was light or when the required cycle length needed to service all approach queues was low but not always. Furthermore, the police officers tended to have a building up effect, where cycle length increased to a peak and then tapered off. This was likely due to the peaking nature of traffic arrivals but it was not present at every observed intersection. There were a number of instances where the phase length between cycles jumped drastically but in general, phase length was increased and decreased incrementally over the period of a few cycles. It was also observed that emergency vehicles (police cars, ambulances, and fire trucks) did have an impact on the officer. Some instances resulted in a green-extension or red truncation while others resulted in no effect on the officer at all. Interestingly, many times after an emergency vehicle would leave the intersection, the officer would immediately change phases, irrespective of what phase or how long it had been green.

Watching the video it became obvious that the police officers do not like to waste any green time. Gaps in the traffic stream, generally from the breaking up of vehicle platoons, promptly resulted in a phase change. Also, the officers had inherent priorities for certain directions. For some directions the officer was willing to tolerate more frequent and longer gaps when compared to other directions. Inevitable at every oversaturated intersection, the downstream queue would propagate and block the study intersection. Each officer addressed this in different ways and there was not a consistent approach to remedy this situation. Also, it did not appear that pedestrians had any effect on the officer. Moreover, it seemed evident that the officer did not have any effect on the pedestrians, as jaywalking was prevalent. Furthermore, red light running occurred at all study intersection but seemed more prevalent in Baton Rouge as compared to Miami Gardens (this effect could be due to the number of observations in the sample). And despite having the ability to change phase sequence, most of the officers did not use this ability to their advantage, preferring instead to keep to the same phase sequence pattern for the event duration.

3.2 Discrete Choice Modeling

Discrete choice modeling defines a class of models aimed at predicting choice outcomes from a set of known alternatives. In this research, discrete choice modeling was used to model the police officer’s actions while directing traffic. Discrete choice modeling was important because it allowed the decisions made by police officers in the field to be described mathematically. For example, when using the “clicker” method, an officer had to decide when to push the button to end the current phase and start the next. These actions are considered discrete choices in which an officer has a “choice” to end the current phase or let it continue. Once the button is pressed, the controller initiates the yellow and all-red time before continuing on to the next phase. Using discrete choice modeling, the goal was to statistically model officer’s actions with quantifiable accuracy.

In the following section a brief background on the principles of discrete choice models is given. This is followed by the selection of an appropriate discrete choice model to represent police officers for this research. Then a discussion on the discrete choice model parameters is followed by a review of the goodness-of-fit measures of effectiveness used to evaluate the discrete choice models in this research.

3.2.1 Discrete Choice

The goal of any discrete choice model is to understand the process that leads to a decision maker’s selection of an alternative from a set of alternatives (Wilson, 2009). For discrete choice modeling to be applied, all alternatives must be mutually exclusive, all possible alternatives must be known, and the number of alternatives must be finite. Historically, most discrete choice models have been based on the concept of utility-maximization. Under this idea a decision maker is required to choose an option, which provides the highest available utility at the time of the decision. All discrete choice models which assume random utility are comprised of the parameterized utility function consisting of observed independent variables x and an unobserved parameter ε. These values can be estimated from a sample of observed choices made by decision makers. Therefore, there exists a set of factors that collectively lead to an individual’s selection of an alternative.

Of course, it is impossible to successfully predict all chosen alternatives made by all individuals. Therefore, it is necessary to view the utility of each alternative as a random variable. In the random utility approach to discrete choice analysis, the true utility value of an alternative is unknown and must be considered a random variable. Utilities are deemed random due to the presence of unobserved attributes, unobserved taste variants, measurement errors and the use of proxy variables. Despite not knowing the true utility, under the assumption of utility-maximization, the probability that an alternative will be selected is equal to the probability that the alternative has the highest utility (Ben-Akiva and Lerman, 1985).

The random utility model states that the probability of any alternative *i* being selected by person *n* from choice set C_n is equal to the probability that the utility of *i* as seen by *n* is larger than the utility of all other alternatives, as seen in Equation 1 (Ben-Akiva and Lerman, 1985). However, this model ignores the probability that $U_{in} = U_{jn}$ will occur for any *i* and j pair.

$$P(i|C_n) = \Pr(U_{in} \geq U_{jn}, \forall j \in C_n) \qquad (1)$$

Applying this formulation to police officers directing traffic, it can be assumed an officer that chooses to change phases sees a higher utility in ending the current phase and starting a new one. Under the assumption that the officer is attempting to maximize the utility, it must be true that the officer sees a higher utility in the new phase or else the officer would not make the change. Therefore, despite not knowing the absolute value of the utilities for either phase, it can be assumed that the new phase has a higher utility than the current one.

This can be seen in Equation (**1**), where only the relative value of U_{in} as compared to $U_{jn}, \forall\, j$ distinguishes between the selection of alternative *i* for all alternatives within j. Therefore, the random utility model is ordinal in nature and thus the specification of the absolute levels of their utility is irrelevant; only the relative values of two utilities matter (Ben-Akiva and Lerman, 1985). This attribute of the random utility models signifies that the utility function can be scaled up or down by multiplying a constant and shifted left or right by adding or subtracting values to each alternative utility without effecting the model results.

The utility of alternative *i* for individual *n* is U_{in} and is divided into the observed aspect of the utility V_{in} and the unobserved parameters ε_{in}. The observed independent variables along with the attributes, if any, of the decision maker are presented in a vector form as x_{in}. Therefore, the utility of alternative *i* for individual *n* can be represented as Equation 2 (Ben-Akiva and Lerman, 1985):

$$U_{in} = V(x_{in}) + \varepsilon_{in} \qquad (2)$$

The term ε_{in} in Equation (2) represents the collective effect of the unobserved attributes or taste, error in observations and collection or processing and any effect for proxy variables. In the equation, ε_{in} is a single term but it represents the contribution of all un-captured attributes to the utility function. This term also represents the cumulative effect of all error within the model.

3.2.2 Discrete Choice Model Selection

The most important aspect in the selection of a specific discrete choice model in this research was the ability to accurately represent the actions taken by the police officers directing traffic. The nature of the discrete choices faced by officers directing traffic, to push a button and change phases, dictated that the discrete choice model have a binary dependent variable. Second to this, the discrete choice model had to evaluate probabilities in real-time so that it could be programmed into a microscopic traffic simulation software. This was needed because the majority of traffic simulation models operate on a time-step basis, and thus the choice probabilities must be calculated every time-step. Therefore, the more complex the calculation of the choice probabilities, the more computational time would be required for the simulation model. It was therefore preferable to have a “simple” or straightforward calculation of the choice probabilities.

The binary dependent variable criteria of the discrete choice model application changed the formulation of the random utility model. This is a special case when the solution set C_n contains exactly two alternatives i and j, i.e. $C_n = \{i, j\}$, the probability of choosing alternative i is provided in Equation 3 (Ben-Akiva and Lerman, 1985):

$$P_n(i) = \Pr(U_{in} \geq U_{jn}) \qquad (3)$$

Likewise, the probability of choosing alternative j is provided in Equation 4 (Ben-Akiva and Lerman, 1985):

$$P_n(j) = 1 - P_n(i) \qquad (4)$$

The appropriate form of the discrete choice model in this study was based on the research needs and the assumptions made about the distribution of the unobserved parameters ε_{in} and ε_{jn} and the distribution of their difference $\varepsilon_n = \varepsilon_{jn} - \varepsilon_{in}$ because only the relative utility can effect alternative selection.

In prior studies, the three most common binary discrete choice models have been the linear probability model, probit model, and logit model. The linear probability model assumes that the difference between the alternatives ε term, ε_n ($\varepsilon_n = \varepsilon_i - \varepsilon_j$), is uniformly distributed between two fixed values. This assumption is not based on any observation; it is made to minimize the error of assuming the wrong distribution. These types of models are typically characterized by forecasting unrealistic probabilities near the fixed values of the uniform distribution. For this reason, the linear probability model was excluded from consideration in this research.

Probit models assume that ε_n can be viewed as a cumulative effect of a large number of unobserved independent components. Therefore, by the central limit theory, the distribution of the ε_n term would tend toward the normal distribution. However, the probit model choice function has an “open form”, meaning that it can never predict any alternative with 100 percent certainty. The “open form” of the probit model would make the calculation of the choice probability more complex resulting in added computation time during the simulation process. Therefore, the probit model was not suitable for this research.

Based on these reasons, the binary logit model was ultimately selected as the discrete choice model for this research. The features that make the binary logit model unique from other discrete choice models is the assumption that the unobserved parameters ε_i and ε_j are Gumbel distributed; or more importantly, that the distribution of the difference between two unobserved parameters is logistically distributed. Logistic distribution is an approximation of the standard normal distribution (but with “fatter” tails or extremes), which was assumed to be the case for officer actions while directing traffic. The advantage of the logit model over the probit model, which makes a similar assumption, was that the choice probability of the logit model was less computationally extensive to calculate, making it better for a microscopic traffic simulation model where choice probabilities needed to be estimated for each time-step.

The logit model choice probability that an individual *n* will choose alternative *i* given the measurable portion of the utility function V_{in} is shown in Equation (5) (Ben-Akiva and Lerman, 1985):

$$P_n(i) = \frac{e^{uV_{in}}}{e^{uV_{in}} + e^{uV_{jn}}} \tag{5}$$

Applying this formulation to a police officer directing traffic, Equation (5) calculates the probability that an officer will change phase based on attributes (V_{in}) observed in the traffic stream.

3.2.3 Utility Function

The utility function of logit models for representing discrete choices is linear. However, linearity in the parameters do not necessitate the observed attributes must be linear. Functions of the attributes may take the form of any polynomial, piecewise, linear, logarithmic, exponential or any other real transformation of the attributes (Ben-Akiva and Lerman, 1985). To represent this in modeling police officer's actions, the independent variable vector x_{in} is modified by the parameter coefficient vector β_k. This vector represents the preferences of the decision maker, signifying that the observed independent variable *x* contributed to the utility of alternative *i* by a factor of β_k. By combining the parameter coefficient vector β_k for *k* parameters and the vector of the independent variables, the utility function took the form of Equation 6 (Ben-Akiva and Lerman, 1985):

$$U_{in} = \beta_o + \beta_1 x_{in1} + \beta_2 x_{in2} + \cdots + \beta_k x_{ink} + \varepsilon_{in} \tag{6}$$

The parameter coefficient vector β_k adjusts the independent variable vector x_{in} so that the utility function U_{in} can accurately represent the observed choice behavior. For example, if x_1 is a variable that is determined to affect the officer's decision-making, then x_1 effects the officer's choice by a factor of β_1. The parameter coefficient vector β_k, is econometrically inferred from a sample of *N* observations. This is done using the maximum likelihood estimation procedure that estimates parameter coefficients that predict the highest choice probabilities to match the observed choice behavior within the sample. This procedure is described in Equations 7 (Ben-Akiva and Lerman, 1985).

$$\ell'(\beta_1, \beta_2, \dots \beta_k) = \prod_{n=1}^{N} P_n(i)^{y_{in}} P_n(j)^{y_{jn}} \tag{7}$$

Where,

y_{in} is equal to one if individual *n* choses alternative *i,* and is zero otherwise

y_{jn} is equal to one if individual *n* choses alternative *j,* and is zero otherwise

Because the likelihood function is exponential in form, it is often more convenient to maximize the log likelihood function. This function has been known to be globally concave and by differentiating the function with respect to the parameter coefficients and setting the partial derivatives equal to zero, the optimum coefficient values are determined as shown in Equation 8 and 9 (Ben-Akiva and Lerman, 1985).

$$\ell'(\beta_1, \beta_2, \dots \beta_k) = \sum_{n=1}^{N} y_{in} Log P_n(i) + y_{jn} Log P_n(j) \tag{8}$$

Subject to,

$$\frac{\partial \ell}{\partial \widehat{\beta_k}} = \sum_{n=1}^{N} \left\{ y_{in} \frac{\partial P_n(i)/\partial \widehat{\beta_k}}{P_n(i)} + y_{jn} \frac{\partial P_n(j)/\partial \widehat{\beta_k}}{P_n(j)} \right\} = 0 \; \forall k \tag{9}$$

This process estimated the β values used in Equation 6, enabling the choice probabilities to accurately represent empirical observations. Therefore, using this procedure it is possible to estimate the probability an officer will decide to change phases based on observations made in the field.

3.2.4 Model Goodness-of-Fit

Goodness-of-fit for logit models refers to how well the predicted model estimates the observed choice outcomes. For this research three goodness-of-fit measures were used to evaluate the effectiveness of the binary choice model in predicting intersection phase changes. These goodness-of-fit test include the pseudo R-squared (ρ^2), the Hosmer-Lemeshow Test and the area under the Receiver Operator Curve. The following section describes these tests in further detail.

3.2.3.1 Pseudo R-squared (ρ^2)

The most common goodness-of-fit measure for logit models is the pseudo R-squared (ρ^2) value. This goodness-of-fit technique compared the performance of the parameter coefficients estimated using only market shares (observed percentages in the sample population) and the final coefficients estimated by maximum likelihood procedure as seen in Equation 10 (Ben-Akiva and Lerman, 1985).

$$\rho^2 = 1 - \frac{\ell(\widehat{\beta})}{\ell(c)} \tag{10}$$

Where,

ℓ(c) is the log likelihood corresponding to market shares

$\ell(\hat{\beta})$ is the log likelihood corresponding to estimated parameter coefficients

The value of ρ^2 ranges between zero and one, where the later value implies that the model predicts the observed choice behavior perfectly. As a general rule, a ρ^2 value less than 0.1 indicates “poor” model performance, a value between 0.1 and 0.2 indicates “acceptable” performance, a value between 0.2 and 0.3 indicates “good” model performance, and anything 0.3 or higher is “excellent” model performance (Hosmer and lemeshow, 1980).

3.2.3.2 The Hosmer-Lemeshow Test

The Hosmer-Lemeshow Test was developed as a goodness-of-fit measure for binary logistic regression (Hosmer and lemeshow, 1980). The estimated number of choice probabilities of the model is divided into *g* groups (usually 10). The first group n_1 contained *n/g* observations and corresponded to the smallest estimated probability, with each group's choice probability range increasing thereafter. A 2 x *g* table is constructed with column one representing *y* = 1 and the other representing *y* = 0. Column one estimates the number of successful predictions by summing the choice probabilities of the logit model for all observations within group g. Likewise, the value of the *y* = 0 column was calculated by summing the complementary probabilities of the model. The Hosmer-Lemeshow goodness-of-fit statistic $\hat{C}$ is calculated by taking the Pearson chi-squared statistic for the 2 x g table and comparing it to the observed and model predicted frequencies (Hosmer and lemeshow, 1980).

$$\hat{C} = \sum_{k=1}^{g} \frac{(o_{lk} - n'_k\overline{\pi_k})^2}{n'_k\overline{\pi_k}(1 - \overline{\pi_k})}$$

Where,

c_k is the number of covariate patterns in the k^{th} , (11)

$\bar{\pi}_k$ is the average estimated probability in the k^{th} group and,

$$\overline{\pi_k} = \frac{1}{n'_k}\sum_{j=1}^{c_k} m_j\bar{\pi}_j \qquad (12)$$

Hosermer and Lemeshow (1980) showed that $\hat{C}$ statistic can be approximated by the chi-squared distribution with g – 2 degrees of freedom, $\chi^2(g-2)$.When the p-value is less than 0.05, the null hypothesis is rejected; indicating that observed and predicted values were significantly different (i.e., the model does not fit). If the p-value is larger than 0.05, the test fails to reject the null hypothesis and therefore the predicted and observed choices are statistically similar (i.e., good model fit).

3.2.3.3 The Area Under the Receiver Operator Curve (ROC)

The receiver operator curve utilizes two parameters (sensitivity and specificity) to estimate model fit. Sensitivity is the proportion of the sample that was correctly predicted positive and specificity was the proportion of the sample that was correctly predicted negative. The Receiver Operator Curve plotted the complementary probability of the specificity; the probability of a false positive on the x-axis and the sensitivity on the y-axis. The figure is a graphical representation of the probability of distinguishing between a true-false pair. The area under the curve is used to discriminate between correctly predicted true-false pairs as a proportion of the sample population. This value ranges between zero and one, with 0.5 representing a model which predicts no better than a coin flip. As a general rule for the area under the curve, values between 0.7 and 0.8 are considered good, values between 0.8 and 0.9 are excellent and anything above 0.9 is considered outstanding (Hosmer and lemeshow, 1980).

3.3 Simulation Modeling

Traffic simulation modeling for this research used discrete choice modeling (logit models) to quantitatively represent the primary control decision activities of the police officers that were observed in the field. This was done by "replacing" the traffic signal controller logic in the simulation model with a binary logit model developed from the observed actions. This was made possible with the use of Vehicle Actuated Programming (V.A.P.) that allowed the simulated intersection controller to be governed by an external program file that contained the logit model. Once the simulation model was calibrated and validated, it was used to compare the performance of manual traffic control with an actuated signal controller. The development and application of the simulation model was described in the following sections of this chapter. The results of the simulation model development, calibration and validation as well as the comparison to the actuated controller are described in the Chapter 5: Simulation Model Analysis Chapter.

3.3.1 Simulation Model Building

The research required micro-level traffic simulation to permit the logit model to be programmed into the signal controller function. Based on this requirement, the traffic simulation package VISSIM 5.3 was selected because it supports time-step behavior-based modeling in urban traffic environments (PTV, 2009). This makes it ideal for the simulation of manual traffic control.

3.3.1.1. Logit Model Programming

The police control logit model was programmed into the simulation using the V.A.P. (Vehicle Actuated Programming) interface of VISSIM 5.3. The V.A.P. allowed for real-time detector information within the simulation to be written into the V.A.P. program file (PTV, 2007). The V.A.P. file used the detector information to create the logit model independent variables. These variables were then used by the logit model to produce a choice probability for phase change by the officer in each successive time-step. These probabilities were evaluated against the officer's threshold value or cut-point. If the probability of changing phases was higher than or equal to the officer's threshold probability value, the V.A.P. notified the signal controller inside the VISSIM model to change phases and proceed to the next time step. If the cut-point was not reached, the V.A.P. allowed VISSIM to proceed with the next time-step without a phase change. Figure 13 provides an example of a cut-point at 40%. In the figure choice probabilities calculated by the logit model are plotted on the y-axis for a five second interval. A cut-point of 40% has been shown with a solid black line. In this example, the signal changed phase after the four second mark, because this was the only choice proabablity to be greater than or equal to the cut point value of 40%.

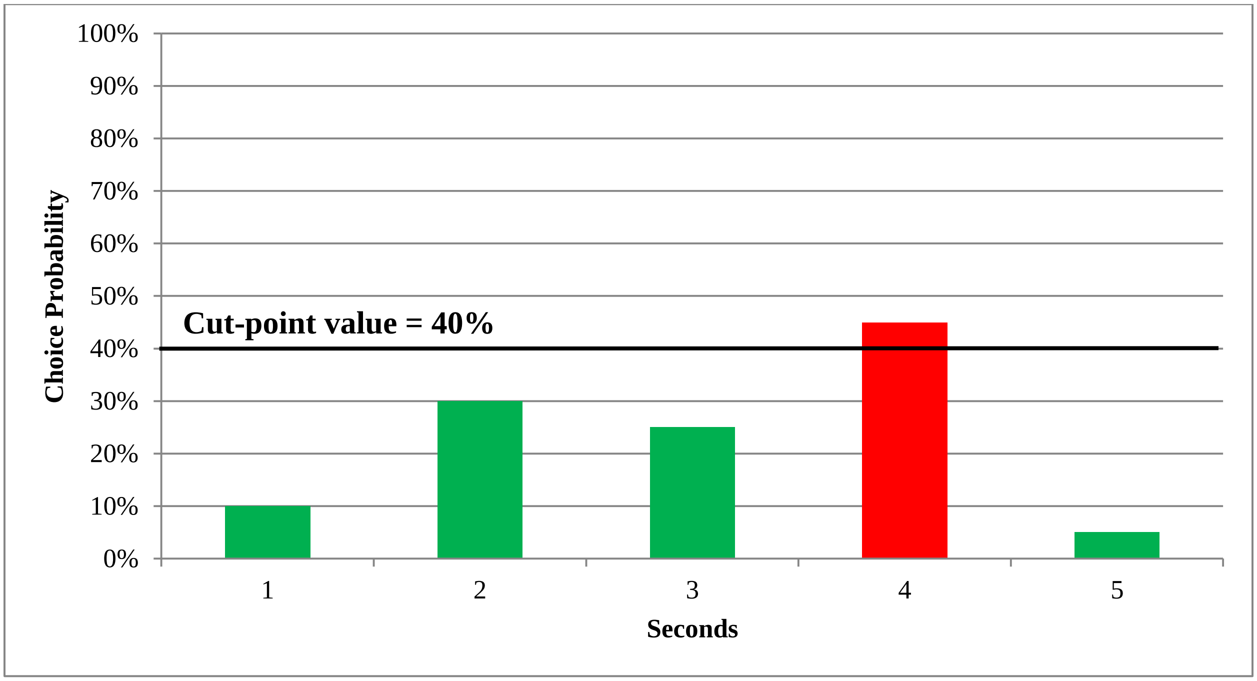


Figure 13: Cut-Point Example

3.3.1.2 Cut-point Estimation

After running the initial simulations it was discovered that the simulated phase length did not vary by more than a few seconds. This was in contrast to the observations made in the field, which found much larger variations in phase length. This phenomenon indicated that the officers directing traffic did not have constant cut-points. It is more likely that when confronted with similar situations the officers were likely to vary when they changed phases. From a choice modeling perspective this was the effect of unobserved parameters i.e. some portion of the ε term. To account for this in the simulation model, the cut-point was assumed to be a random variable from a uniform distribution. By randomly changing the cut-point, phase to phase, it was possible to more accurately represent this behavior in the simulation model.

At the end of each phase, the cut-point for the next phase was calculated using Equation 13. The cut-point value (k_p) of phase p, was computed by adding and subtracting a pseudo-random number to a static cut-point (S_p). The value of the static cut-point was chosen to be a cut-point, which resulted in the correct number of phase changes. For example, if 30 phase changes were observed in the video, the static cut-point (S_p) was set to the value of the 31st highest choice probability. This ensured that on average, 30 phase changes would likely occur permitting the modeled and observed intersections to have approximately the same number of phase changes.

The upper and lower bound of the random number was confined by the calibration variable α_p. This allowed the degree to which the cut-point varied to be calibrated to match the observations in the field. This was done by adjusting this variable up or down until the standard-deviation for the simulated phase lengths was equal to the standard deviation observed in the videos. The calibration variable α_p was multiplied by a pseudo-random number, which was calculated using a linear congruential random number generator (Wilson, 2009). This formulation of the pseudo-random number generated also required a seed value to calculate the initial random variable. The value of the seed number varied for each simulation.

$$k_p = S_p \pm \alpha_p * \frac{(aX_n + c) \bmod m}{m} \tag{13}$$

Where,

k_p cut-point value for phase p

s_p is the static cut-point value

$\alpha_p$is calibration parameter

X_n is a random number generated in the initial time step

a is1,597,

c is 51,749,

m is 244,944.

3.3.1.3 Demand Modeling and Geometric Design

The simulation model also required the geometric design of the intersections and the vehicle demand as model inputs. The geometric design of the four study intersections was programmed into VISSIM 5.3 using open source high-resolution satellite images provided by Google™. The accuracy of these measurements was verified during site visits. Using the traffic count and turning movement information in the intersection event time-lines, the intersection discharge flow rate observed in the videos was aggregated into 15-minute flow rates and programed into the simulation. Due to the nature of the data collection, only the intersection discharge flow was able to be determined from the video data. Therefore, the observed demand had to be estimated in the simulation model through an iterative calibration process. The 15-minute traffic flow rates in the simulation were adjusted to match the discharge flow rates from the videos. Details of the calibration and validation of the simulation model are presented in Chapter 5: Simulation Model Analysis.

CHAPTER 4.0 LOGIT MODEL ANALYSIS

A binary logit model was used to model the intersection control decisions made by police officers directing traffic. The development of the binary logit model involved three steps. The first step was selection of the independent variables. The second step was the estimation of the logit model coefficients and the third step was evaluating the models through a) assessment of goodness-of-fit for the model and b) assessment of *model transferability*.

4.1 Variable Selection

To develop the binary logit models dependent and independent variables were quantified from the video footage. The data collection and reduction process resulted in a second-by-second time-line of events which took place in the traffic stream (See Chapter 3). This time-line was used to develop the variables for the logit model analysis. The time interval used in this research was one second. Therefore, the discrete choice represented by the logit model was between an officer changing phases over a one second interval (dependent variable y=1) and the officer not changing phases during this second (y=0).

Prior to the generation of the independent variables the intersection clearance time (the yellow and all red time which transitions between signal phases) was removed from the timeline. This was done because the clearance time could only occur after a phase change decision was already made by the officer, making any observations during the period unable to be used as an independent variable. Inclusion of this interval would bias the model because when this interval occurred was dependent upon the officer's decision. Once the clearance time was removed, the time-line served as the basis for the development of the independent variables used by the logit model.

An initial pool of independent variables was tested for the statistical significance of their relationship with the dependent variable. This pool consisted of phase variables, which identified the phase that was green, phase length, presence of "gaps" in the traffic stream (time-headways between vehicles greater than 4-seconds) intersection blockages (stopped vehicles in the intersection), approach headway (sec/veh), flow rate (veh/hr) and cumulative count of vehicle served during the existing phase?. Additionally, interactions between these variables were included in the model. A Pearson Correlation Analysis found that many of the independent variables were correlated with each other. While the inclusion of these variables does not affect the logit model's predictive capability, it does however, make it difficult to estimate the variables significance level. Therefore, if two variables had a correlation coefficient with a magnitude higher than 0.8, one of the two variables had to be removed from the variable pool. For example, *Gap* and *Headway* were found to be highly correlated (0.9), therefore the variable with the stronger relationship to the dependent variable (*Gap*) remained in the variable pool, while the other (*Headway*) was removed. This process resulted in the removal of flow, cumulative count and headway.

The updated variable pool was then used to estimate a logistic regression model with backward selection procedure. This assumed that the model included all variables in the variable pool first and then, systematically removed variables to estimate the model performance. The inclusion criteria for a variable to remain in the model was selected to be a p-value of 0.05 and the exclusion criteria was set to a p-value of 0.1. From this process it was determined that intersection blockages were not significantly related to the dependent variable. The remaining variables are listed in Table 8.

There are three primary independent variables used in this research: *Time, Gap,* and *Phase.* The *Time* variable was the phase length duration, or how long the current phase has received a green indication. The *Gap* variable accounted for periods of time where no vehicles traversed an intersection approach despite having a green indication (time-headways greater than 4-seconds). These "gaps" were generally the result of the breaking down of vehicle platoons. The *Gap* variable took a value of one, if one of the intersection approaches had a "gap"; two, if two of the approaches had a "gap" during the same time interval and zero if no gap was present. The *Phase* variable was a set of four binary variables that indicated which phase was receiving the green indication. Each of these four variables represented a phase (northbound/southbound thru, northbound/southbound left, etc.). The four *Phase* variables were labeled according to the priority they received from the police officers. These are *Primary, Secondary, Tertiary* and *Quaternary.*

The *Primary* variable represented the phase that received the largest proportion of the green time allocated by the officer. For example, if the northbound/southbound thru phase received more green time than any other phase, this phase would be labeled as the *Primary* phase. This was done to compare *Primary* phases between intersections regardless of the intersections' geometric characteristics. As such, *Secondary, Tertiary* and *Quaternary* represent the phases with the ensuing green time proportions. Also, it was hypothesized the impact that time and the presence of gaps had on the officer's decision making varied for each direction. Therefore, these variables were tested for their interaction as shown in Table 8. It was found that these interaction variables were significant, indicating the contribution to the decision making process made by the *Time* and *Gap* variables varied depending on which phase was green.

Table 8: Variable Description

Variable	***Description***	***Value***
Phase Change	Did the officer change phases this time interval? (Dependent)	0 = No 1 = Yes
Time	How many seconds has the current phase been green?	(1, ∞)
Gap	Number of approaches without a stream vehicle traversing the intersection.	[0,1,2]
Prim.	Is the phase with the highest priority green?	0 = No 1 = Yes
Sec.	Is the phase with the second highest priority green?	0 = No 1 = Yes
Tert.	Is the phase with the third highest priority green?	0 = No 1 = Yes
Quat.	Is the phase with the fourth highest priority green?	0 = No 1 = Yes
PTime	The interaction between Primary and Time (Primary x Time)	(0, ∞)
STime	The interaction between Secondary and Time (Secondary x Time)	(0, ∞)
TTime	The interaction between Tertiary and Time (Tertiary x Time)	(0, ∞)
QTime	The interaction between Quaternary and Time (Quaternary x Time)	(0, ∞)
PGap	The interaction between Primary and Gap (Primary x Gap)	[0,1]
SGap	The interaction between Secondary and Gap (Secondary x Gap)	[0,1]
TGap	The interaction between Tertiary and Gap (Tertiary x Gap)	[0,1]
QGap	The interaction between Quaternary and Gap (Quaternary x Gap)	[0,1]

Table 9 provides an example of five coded observations. Each observation represents one second of video footage. In total 60,999 observations were used in estimation of the logit models for this research. Each observation was coded in the same fashion as the example. In the example, the *Ph.Ch.* column is the dependent variable and show that a phase changed occurred during the third observation. *Time* and *Gap* are shown in the next two columns. The *Phase Variables* are abbreviated as *Prim, Sec, Tert, and Quat*, in the next four columns. The ensuing four columns represent the interactions between *Time* and the *Phase Variables* and the final four columns are the interactions between the *Gap* and *Phase Variables.*

Table 9: Data Coding Example

			Phase Variables				***Time Interaction***				***Gap Interaction***			
Ph.Ch	**Time**	**Gap**	**Prim**	**Sec**	**Tert**	**Quat**	**PT**	**ST**	**TT**	**QT**	**PG**	**SG**	**TG**	**QG**
0	146	2	1	0	0	0	146	0	0	0	2	0	0	0
0	147	2	1	0	0	0	147	0	0	0	2	0	0	0
1	148	2	1	0	0	0	148	0	0	0	2	0	0	0
0	1	0	0	0	1	0	0	0	1	0	0	0	0	0
0	2	0	0	0	1	0	0	0	2	0	0	0	0	0

4.2 Logit Model Estimation

A total of nine logit models were estimated for this research, one from each observation event, not including the pilot study data. These events were referenced in the tables by their intersection initials followed by the data collection date. For example, the model estimated for the intersection of Nicholson and Roosevelt in Baton Rouge, collected on 10/13/12 was labeled as “N & R 10/13”..

The logit model results are divided into 5 tables, one for each of the four phase priority variables (Primary, Secondary, Tertiary, and Quaternary) and one for the constant variable. This allowed for an “apples to apples” comparison of the coefficient values by showing the results based on their perceived importance by the officer instead of their geometric layout (northbound, southbound, eastbound, and westbound). Each of the five tables showed a *Coef.*, *St.D.*, *P>|z|*, and *Obs*. column. The *Coef.* column represented the variable coefficient value estimated for the utility function in equation 6 and the *St.D.* value was the standard deviation of the coefficient value. The *P>|z|* column displayed the p-value result of a single sample T-test comparing the coefficient value to zero. P-values less than 0.05 indicated that the coefficient value was not equal to zero at a 95% confidence interval and therefore had a significant impact on the dependent variable. P>|z| values less than 0.001 are rounded to 0.00 within the table. The *Obs*. column was the number of observations from which these parameters were estimated. Each table was followed by a statistical analysis of coefficient values, testing if these values were consistent between the models estimated.

The coefficient values are then compared between observation events. This was done to determine if the coefficient values estimated by the logit models from different locations and days were statically equivalent. If so, this may suggest that police officers were directing traffic in a similar fashion between observations.

4.2.1 The Constant Variable

Table 10 shows the constant variable for each of the logit models estimated. This coefficient value represents the cumulative effect of all error within the model. The negative coefficient values indicate the officer prefers not to change phases i.e. all things being equal the officer would not change phases. The p-value suggests that the cumulative error had a significant impact on the decision making process (all p-values are less than or equal to 0.05).

Table 10: Constant Variable

	Constant Variable			
Intersection:	**Coef**	**St.D**	**P>|z|**	**Obs**
N & R 10/13	-3.79	65.3	0.00	7534
N & R 11/03	-5.61	163.4	0.01	6385
N & R 11/10	-3.75	65	0.00	3141
N & R 11/17	-3.86	64.8	0.00	3134
N & L 11/03	-4.76	41.2	0.00	6898
N & L 11/10	-7.31	95.7	0.00	4581
S & P 11/10	-3.39	35.6	0.00	3486
S & P 11/17	-7.56	104.4	0.00	3987
183 & 27 01/07	-3.29	22	0.00	6541

These values of the constant variables were compared using a two-tailed, two sample student T-test or a one-way ANOVA test, where applicable. The constant variable estimated from data collected at intersection of Nicholson and Roosevelt (models *N & R 10/13, N & R 11/03, N & R 11/10* and *N & R 11/17*) are compared in

Table 11 and labeled *N & R*. Likewise, a T-test was conducted on the observation collected from Nicholson and Lee and Stanford and Perkins, these are labeled *N & L* and *S & P*, respectively. Additionally, an evaluation was conducted on all three-phase intersections (intersection which had a three phase sequence) and four phase intersections, these are labeled *Three Phase* and *Four Phase*, respectively. The three phase intersections in the study were Nicholson and Roosevelt and Nicholson and Lee. The four phase intersections were Stanford and Perkins and NW 183 St. and NW 27 Ave. Finally, an ANOVA test was completed which included all of the constant variables estimated from the logit models. This comparison was labeled *All* in Table 11.

Table 11: Statistical Testing for the Constant Variable

Comparison	***Test***	***Statistic***	**P>|z|**
N & R	ANOVA	0.658	0.58
N & L	T-Test	1.962	0.05
S & P	T-Test	2.246	0.02
Three Phase	ANOVA	1.049	0.39
Four Phase	ANOVA	7.016	0.00
All	ANOVA	1.173	0.31

The statistical analysis was unable to reject the null hypothesis that the constant variable terms generated from the different intersection were statically different. This indicates that the value estimated for the constant variable could be equal across all intersection in the study. In other words, the constant term estimated from one intersection was not statistically different (within the statistical boundary) when compared to most other intersections. This suggest that the models were capturing (or not capturing) the same decision making characteristics at all of the study intersections

4.2.2 Primary

The coefficients the *Primary* variable as well as the interactions between the primary variable and *Time* and *Gap* variable are discussed in this section. Table **12** showed the coefficient values, standard deviation and statistical significance for each to these variables estimated by the nine logit models developed for each data collection event. In this table, as in all remaining tables in this chapter, P>|z| values less than 0.001 are rounded to 0.00 for ease of display. Looking at the table horizontally, showed the result of the single model estimate on the given day. Looking vertically, the table showed how the coefficient values varied for data collection events.

Table 12: Primary Direction

	Primary			***PTime***			***PGap***			
Intersection:	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Obs**
N & R 10/13	-5.34	83.7	0.00	0.01	0.115	0.00	2.81	44.9	0.00	5712
N & R 11/03	-2.23	152.6	0.30	0.01	0.153	0.00	1.03	31.5	0.02	5004
N & R 11/10	-7.56	79.7	0.00	0.02	0.239	0.00	3.28	28.6	0.00	2389
N & R 11/17	-4.35	90.6	0.02	0.02	0.205	0.00	1.05	60.9	0.39	2461
N & L 11/03	-2.45	45.1	0.00	0.02	0.194	0.00	0.47	21.3	0.16	4162
N & L 11/10	0.34	93.5	0.83	0.01	0.174	0.00	-0.18	23.8	0.67	3326
S & P 11/10	-8.06	90.9	0.00	0.01	0.200	0.00	2.66	41.1	0.00	2319
S & P 11/17	-3.91	111.7	0.10	0.02	0.269	0.00	2.04	30.6	0.00	2249
183 & 27 01/07	-5.56	50.7	0.00	0.03	0.291	0.00	1.48	20.2	0.00	3975

From the p-values it is apparent that all three variables are statistically significant in explaining the phase change decision.. The negative coefficient of the *Primary* variable suggests that when the primary direction was green, the officer preferred not to change phases, as compared to other directions. This was to be expected for all phase variables that receive some degree of priority. That is to say all phase variables except *Tertiary* for three phase intersections and *Quaternary* for four phase intersections, as these receive no preferential treatment from the police officer. The positive coefficients observed for *PTime* and *PGap* suggest when these two values increased, so too did the likelihood the office would change phases. This too was expected; as phase length increases and the traffic stream thins, the officer was more likely to change phases.

The variables were compared in Table 13 using a two-tailed, two sample student's t-test or a one-way ANOVA test, as was done in the previous section. The table indicates that coefficient values collected from Nicholson and Roosevelt are statistically indistinguishable in providing priority to the *Primary* phase but handle time and gaps for this phase differently. The intersection for Nicholson and Lee and Stanford and Perkins, showed that the model coefficient values remained consistent across data collection days. In other words, the officers directing traffic at these intersections treated the primary phase similarly for every event. The Four Phase evaluation found that data collected from the intersection of Stanford and Perkins in Baton Rouge and data collected from the intersection of NW 183 St. and NW 27 Ave. in Miami Gardens was were not statistically different, i.e. the officers directing traffic were likely treating the priority direction similarly in both cities.

Table 13: Statistical Testing for the Primary Direction

		Primary		*PTime*		*PGap*	
Comparison	**Test**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**
N & R	ANOVA	1.414	0.24	7.006	0.00	2.761	0.041
N & L	T-Test	1.696	0.09	1.766	0.08	1.233	0.218
S & P	T-Test	1.378	0.17	1.058	0.29	0.576	0.564
Three Phase	ANOVA	2.453	0.03	5.420	0.00	4.817	0.000
Four Phase	ANOVA	1.492	0.23	2.097	0.12	1.168	0.311
All	ANOVA	2.434	0.01	4.552	0.00	3.697	0.000

4.2.3 Secondary

This section provides a similar discussion for the Secondary direction and the coefficients are provided in Table 14. The Secondary direction was the direction which received the second largest proportion of green time allocated by the police officer. The negative coefficient signs for the *Secondary* variables indicate again that the officer preferred not to change phases when the secondary direction was green. The table also shows that in general officers put less emphasis on time and more emphasis on the presence of gaps (based on relative significance of the coefficients shown in Table 12 and Table 14), when compared to the primary direction. This makes sense because the *Secondary* phase was shorter in duration than the *Primary*, suggesting less of a reliance on time.

Table 14: Secondary Direction

	Secondary			*STime*			*SGap*			
Intersection:	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Obs**
N & R 10/13	-2.01	36.7	0.02	0.02	0.261	0.01	1.23	13.5	0.00	5712
N & R 11/03	0.41	71.6	0.84	0.00	0.196	0.68	2.12	13.0	0.00	5004
N & R 11/10	-2.42	37.4	0.09	0.04	0.429	0.03	1.61	18.4	0.02	2389
N & R 11/17	-1.32	32.4	0.31	0.03	0.300	0.03	1.41	10.0	0.00	2461
N & L 11/03	-0.42	29.3	0.51	0.01	0.210	0.00	0.31	18.7	0.44	4162
N & L 11/10	2.82	47.9	0.06	0.01	0.205	0.20	-0.24	11.8	0.51	3326
S & P 11/10	-3.10	28.8	0.01	0.03	0.311	0.04	1.51	10.8	0.00	2319
S & P 11/17	1.08	58.4	0.59	-0.01	0.427	0.39	3.25	19.2	0.00	2249
183 & 27 01/07	-2.44	20.8	0.00	-0.02	0.398	0.21	2.21	11.1	0.00	3975

Again, a statistical analysis was conducted to test if the officers were directed traffic in a similar fashion across the data collection events. The results were provided in Table 15. The statistical analysis of the officers directing traffic at the intersection of Nicholson and Roosevelt was unable to reject the null hypothesis that these officers were providing the same consideration toward the secondary direction with respect to time and the presence of gaps. This suggests that the values estimated by the logit models from the various data collection days are statistically similar. This was also true for the intersection of Stanford and Perkins. Furthermore, the statistical analysis conducted on all three-phase intersections was unable to distinguish between data collection days or location. Suggesting the police officers treated the secondary direction statistically similar across time and space. This was also shown to be true for four phase intersections. However, the statistical analysis comparing the officers directing traffic at three phase intersections and four phase intersections rejected the null hypothesis that these values were the same. This suggested that police officers treated the secondary direction differently for three-phase and four-phase intersections and implies that an officer's approach to directing traffic at a four phase intersection was not a "three phase plus one" approach but an entire reallocation of priority.

Table 15: Statistical Testing for Secondary Direction

		Secondary		***STime***		***SGap***	
Comparison	**Test**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**
N & R	ANOVA	0.725	0.54	2.180	0.09	0.968	0.41
N & L	T-Test	2.365	0.02	0.623	0.53	0.868	0.39
S & P	T-Test	1.555	0.12	1.871	0.06	1.925	0.05
Three Phase	ANOVA	2.023	0.07	1.869	0.10	3.931	0.00
Four Phase	ANOVA	2.514	0.08	2.369	0.09	2.586	0.08
All	ANOVA	1.965	0.05	2.905	0.00	5.293	0.00

4.2.4 Tertiary

The tertiary direction received the third largest proportion of the green time allocation. For three phase intersections this was the lowest possible priority, i.e. no priority. Because of this the value of the *Tertiary* variable for three phase intersections must be equal to zero. In

Table 16, the *Tertiary* variable for S & P 11/17 was estimated to be -30.99 and the *TGap* variable was estimated at 17.46, two relatively extreme values. This occurred because every observation of a phase change occurred when *TGap* was equal to two, i.e. the phase changed only when gaps on both approaches of the phase were present. Furthermore, the coefficient and p-values indicate a heavier reliance on *Time* and *Gap* variables when compared to other directions.

Table 16: Tertiary Direction

	Tertiary			*TTime*			*TGap*			
Intersection:	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Obs**
N & R 10/13	0.00	0.0	1.00	0.07	0.565	0.17	2.02	4.7	0.00	5712
N & R 11/03	0.00	0.0	1.00	-0.04	0.227	0.01	2.20	15.4	0.04	5004
N & R 11/10	0.00	0.0	1.00	0.49	1.680	0.03	1.05	4.7	0.09	2389
N & R 11/17	0.00	0.0	1.00	1.19	3.272	0.02	0.01	4.4	0.98	2461
N & L 11/03	0.00	0.0	1.00	0.04	0.392	0.03	1.32	7.0	0.00	4162
N & L 11/10	0.00	0.0	1.00	0.28	1.194	0.00	1.35	5.6	0.00	3326
S & P 11/10	-1.61	18.7	0.11	-0.03	0.481	0.30	2.40	18.7	0.02	2319
S & P 11/17	-30.99	0.0	0.00	0.03	0.394	0.07	17.46	11.3	0.00	2249
183 & 27 01/07	-1.52	16.4	0.01	-0.02	0.582	0.29	1.70	10.1	0.00	3975

The statistical testing results of the *Tertiary* direction are presented in Table 17. The p-values indicate that the *Tertiary* direction was relatively unique to the data collection day when compared to the other directions, only *TTime* for the four phase analysis and the *TGap* for the three phase analysis were consistent between observations. This may indicate that the officers did not allocate much attention to these directions given the lower demand that led to lower priority. This may also reflect a desire by the officer to move past this phase quickly to service the demand on the competing approaches.

Table 17: Statistical Testing for Tertiary Direction

		Tertiary		*TTime*		*TGap*	
Comparison	**Test**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**
N & R	ANOVA	0.000	1.00	14.143	0.00	0.592	0.62
N & L	T-Test	0.000	1.00	4.299	0.00	0.050	0.96
S & P	T-Test	37.343	0.00	1.940	0.05	15.164	0.00
Three Phase	ANOVA	0.000	1.00	17.271	0.00	0.751	0.59
Four Phase	ANOVA	833.541	0.00	2.045	0.13	291.661	0.00
All	ANOVA	439.358	0.00	22.244	0.00	113.892	0.00

4.2.5 Quaternary

The *Quaternary* direction was only present for four phase intersections. Therefore, the three phase intersections have been excluded from this analysis. The *Quaternary* direction had the lowest priority for the four phase intersections and as such the coefficient for the *Quaternary* variable must be equal to zero as seen in Table 18. The p-value for the *QTime* variable was not statistically different for any of the four phase intersection. This indicated a stronger reliance on the presences of gaps in the decision making process for the police officers.

Table 18: Quaternary Direction

	Quaternary			*QTime*			*QGap*			
Intersection:	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Coef**	**St.D**	**P>|z|**	**Obs**
S & P 11/10	0.00	0.0	1.00	0.11	1.158	0.13	0.95	12.7	0.25	2319
S & P 11/17	0.00	0.0	1.00	0.06	1.035	0.26	1.93	15.5	0.02	2249
183 & 27 01/07	0.00	0.0	1.00	-0.05	0.610	0.07	1.90	7.7	0.00	3975

The statistical results from the Quaternary direction analysis are provided in Table 19. The officers directing traffic at the intersection of Stanford and Perkins statistically treated the quaternary statistically indistinguishable at a 95% confidence interval. When compared with the intersection of NW 183 St. and NW 27 Ave., the officers treated the gaps for this phase similar but not time.

Table 19: Statistical Testing for the Quaternary Direction

		QTime		*QGap*	
Comparison	**Test**	**Statistic**	**P>|z|**	**Statistic**	**P>|z|**
S & P	**T-Test**	0.566	0.57	0.805	0.42
Four Phase	**ANOVA**	3.168	0.04	0.615	0.54

Generally it was observed that direction coefficients were negative in value and the coefficients for time and the presence of gaps were positive. This suggests that officers show priority to certain directions as compared to others and as phase length grows or if gaps were present, the officer was more likely to change phase. These observations were made in almost all instances and show that the models were intuitively correct in predicting phase changes. The models developed from multiple observation days at the same intersection generally produced coefficient values that were statistically indistinguishable. However, logit models generated from three phase intersection and four phase intersection did not produce statistically similar values. This suggests that an officer’s approach to directing traffic at a four phase intersection was not a “three phase plus one” approach but an entire reallocation of priority. The only exception to this was seen with the constant variable, which was statistically indistinguishable for all intersections within a 95% confidence interval. This suggest that the cumulative effect of the error was consistent between all models and was an indication the models were capturing (or not capturing) the same decision making characteristics. The most significant finding was the statistical similarities between intersections despite being collected at separate intersections in different cities. The statistical analysis was usable to determine that the officers directing traffic in Baton Rouge, LA were doing anything different than the officers in Miami Gardens, FL. This may suggests that police directing traffic in Baton Rouge and Miami Gardens may in fact use a similar approach.

4.3 Goodness-Of-Fit

Goodness-of-fit for logit models is a measure of how well the predicted choice outcomes match the observed data. Goodness-of-fit for this research was quantified using three metrics: the pseudo R-squared (ρ^2) value, the Hosmer-Lemeshow chi-squared statistic ($\hat{C}$) and the area under the receiver operator curve (ROC). These measures of goodness-of-fit were provided in Table 20. Also shown in this table was the p-value corresponding to the chi-squared statistic with eight degrees of freedom for the Hosmer-Lemeshow Test. In general, the model fit was in the "good" to "outstanding" range. However, the models estimated for intersection of the Nicholson and Lee did dip into the "acceptable" range (Hosmer and Lemeshow, 1980). The p-value indicated the estimated probabilities made by the logit model were statistically similar to those observed in the data with 95% confidence.

Table 20: Goodness-of-Fit

Intersection:	ρ^2	$\hat{C}$	**P>|z|**	***ROC***
N & R 10/13	0.277	7.47	0.49	0.864
N & R 11/03	0.223	4.53	0.81	0.855
N & R 11/10	0.338	4.81	0.45	0.935
N & R 11/17	0.287	7.59	0.47	0.886
N & L 11/03	0.145	13.13	0.11	0.828
N & L 11/10	0.190	10.46	0.23	0.817
S & P 11/10	0.224	5.71	0.68	0.891
S & P 11/17	0.366	1.92	0.98	0.958
183 & 27 01/07	0.221	5.05	0.75	0.874

4.4 Model Transfer and Validation

The goal of the model validation was to show that the parameters estimated by the models (the officer's decision making) were consistent temporally and spatially. This was done by using *model transfer*. For each intersection, the coefficient values from one or more data collection days were projected onto the data collected from a different day. The pseudo R-squared *(ρ^2)* value was then used as a measure of model validation. If the officer's decision making was consistent between observation days, then the pseudo R-squared value estimated from the validation data should fall into the acceptable range (greater than 0.1).

For the purposes of validation, the intersections were broken up into two datasets: calibration and validation. The calibration dataset represents the models that were transferred. The validation dataset represents the data on which the calibration parameters were being transferred to. This was shown in Table 21. The validation of the simulation model, discussed in the next chapter was conducted in a similar fashion using the calibration and validation pairing shown in Table 21.

Table 21: Validation Partition

Intersection:	***10/13/12***	***11/3/12***	***11/10/12***	***11/17/12***	***12/23/12***	***1/1/13***	***1/7/13***
Stanford & Perkins	n/a	n/a	C	V	n/a	n/a	n/a
Nicholson & Roosevelt	C	C	C	V	n/a	n/a	n/a
Nicholson & Lee	n/a	C	V	n/a	n/a	n/a	n/a
183 & 27	n/a	n/a	n/a	n/a	n/a	n/a	C

C = calibration dataset; V = validation dataset;

The intersection of Nicholson and Lee was validated by transfer the coefficients estimated on 11/03/12 to the data collected on 11/10/12. Likewise, the validation of Stanford and Perkins was conducted by transferring coefficients estimated by the model for 11/10/12 onto the data collected on 11/17/12. Since, only one data collection day was available for the intersection of NW 183 St. and NW 27 Ave. this intersection was validated using the model estimated for Stanford and Perkins on 11/10/12.

The only intersection which required having more than one intersection data collection day combined into one model was Nicholson and Roosevelt. This was because Nicholson and Roosevelt was the only intersection with more than two observation events. The other intersections only required one set of coefficients to be used to estimate pseudo R-squared ***(ρ^2)*** on the validation dataset. The combined Nicholson and Roosevelt model was estimated by combining the data collected from three of the data collection day's (10/13/12, 11/013/12 and 11/10/12) into a single dataset and estimating a new logit model. These coefficients were then used to estimate a pseudo R-squared value for the fourth data collection day (11/17/12). The Bayesian Updating approach to model transfer was considered but, since the original dataset was available from the estimated models, Bayesian Updating was not needed and would likely lead to less accurate results (Atherton and Ben-Akiva, 1976).

Table 22 shows the model coefficients estimated by the combined Nicholson and Roosevelt dataset. The number of observations used to estimate the model was 17,060 and the pseudo R-squared ***(ρ^2)*** was 0.235, suggesting good model fit. The p-value indicated that all of the model variables were statistically significant at a 95% confidence interval. The sign value for each of the variables appeared to be intuitively correct with the exception of *TTime*. This may have resulted from the relatively small number of observations when the *Tertiary* direction was green. To validate the Nicholson and Roosevelt model, these values were used on data collected on 11/17/12 to estimate the pseudo R-squared.

Table 22: Nicholson and Roosevelt Combined Logit Model

Variable	***Coef***	***St.D***	***P>|z|***
Primary	-5.423	83.33	0.00
Secondary	-2.429	67.08	0.00
PTime	0.007	0.13	0.00
STime	0.009	0.51	0.02
TTime	-0.052	1.78	0.00
PGap	2.143	46.53	0.00
SGap	1.567	28.98	0.00
TGap	1.199	32.00	0.00
Constant	-2.977	56.05	0.00

4.4.1 Validation Results

Table 23 shows the logit model validation results. The *Model* column indicated which log likelihood value was being compared. $L^*(0)$ referred to the log likelihood when only the constant term was estimated. This value was used as the basis of comparing the pseudo R-squared value for the validation process, the value for the denominator in equation 10 (In Chapter 3). The $L^*(\theta_0)$ referred to the model estimated using the data from which it was collected. This was the goodness-of-fit measure provided in Table 20. The values in Table 20 are the upper bound for the validation goodness of fit (no model would fit better on the validation dataset than calibration data). The $L^*(\theta)$ represented log likelihood value estimated by completely transferring the calibration model onto the validation dataset and the $L^*(\theta')$ was the result of updating the transferred model's constant term. This resulted in the $L^*(\theta')$ model always producing better results than the $L^*(\theta)$. The *LL* column was the log likelihood value estimated and the *C* value was the constant term used for each calculation.

Table 23: Logit Model Validation Results

	Nicholson & Roosevelt			***Nicholson & Lee***			***Stanford & Perkins***			***183 & 27***		
Model	**LL**	**ρ^2**	**C**	**LL**	**ρ^2**	**C**	**LL**	**ρ^2**	**C**	**LL**	**ρ^2**	**C**
L*(0)	-235		-4.2	-248.		-4.6	-223		-4.5	-725		-3.7
L*(θ_0)	-168	0.287	-3.8	-201	0.190	-7.3	-141	0.366	-7.5	-565	0.221	-3.2
L*(θ)	-185	0.212	-2.9	-375	-0.514	-4.76	-182	0.185	-3.6	-647	0.108	-3.3
L*(θ')	-178	0.242	-2.3	-255	-0.028	-6.6	-169	0.241	-4.3	-646	0.109	-3.5

From Table 23 it was observed that in general the model transfer results were in the “acceptable” to “good” range, with the exception of Nicholson and Lee (Hosmer-Lemenshow, 1980). Nicholson and Roosevelt showed the most successful model transfer. This was likely due to the larger dataset which was used to estimate the transfer model. The intersection of Stanford and Perkins also showed good transferability. This too was not surprising given that the original model had the highest goodness-of-fit measure. The intersection of NW 183 St. and NW 27 Ave. showed results that were on the lower end of the “acceptable” range. This was to be expected given that this was the only model transferred to a different location from which it was estimated. Nicholson and Lee started with the lowest ρ^2 value and therefore, was not expected to transfer well (Atherton and Ben-Akiva, 1976).

4.5 Summary of Logit Model Findings

The logit models estimated from the signal operation data were able to reasonably capture the choice behavior of the police officers directing traffic. This was evident in the goodness-of-fit statistics provided in Table 20. In general, the variables which were determined to affect when the officer changed direction were both intuitive and statistically significant. Generally, logit models estimated statistically similar coefficient values, indicating that officers placed in similar situations will likely direct traffic in a similar fashion. This was consistent both spatially and temporally. However, stronger correlations were observed for officers directing traffic at the same intersection but on different days as compared to officers directing traffic at different intersections. The statistical analysis also indicated that officers directing traffic at a three phase intersection allocate green time differently than those at four phase intersection. It was also apparent that officers directing traffic in Baton Rouge, LA and Miami Gardens, FL did so in a similar fashion. These results were verified by validating the logit models through *model transfer*. This showed that choice behavior estimated from one observation (in the case of Nicholson and Roosevelt, three), were statistically indistinguishable when evaluated on data from another observation, provided they had the same number of phases (three phases or four phases).

CHAPTER 5. SIMULATION MODEL ANALYSIS

After completing the logit model development and validation process, the research turned to the integration of the logit model into a microscopic simulation model. Broadly, the logit models quantified the control decisions of the police officers that were observed in the field. However, to observe the effects of these control decisions under a variety of traffic conditions, it was necessary to incorporate the police decision models into a conventional traffic simulation system. In this research, the microscopic traffic simulation software, VISSIM 5.3 was used. The integration of the logit models into VISSIM was accomplished using Vehicle Actuated Programming (VAP) that allowed the simulated intersection controller to be governed by an external program file, which contained the information from the logit models. The following sections of this chapter discuss the calibration and validation of the simulation models. Also discussed in this chapter was the application of the simulation model to compare manual traffic control with the existing actuated controllers.

5.1 Simulation Model Calibration

The goal of the calibration process was to have the simulation model statistically match the quantifiable measures observed in the video data. The calibration process was important because data that could not be observed in the video footage but was necessary for the simulation model to produce the correct results was inferred from making incremental changes to the input parameters. There were three parameters that needed to be estimated through the calibration process that were unique to each simulated intersection, the logit model coefficients (β_k), the variance of the cut-point (α_p), and the approach demand.

The calibration of these three parameters was conducted in parallel because each of these parameters was interdependent. For example, by adjusting the logit model coefficients, the signal timing would change, altering the intersection throughput. An added complexity to this was the stochastic nature of the simulation runs. As a result, multiple simulation runs were required to estimate if the changes observed in the simulation model were a result of calibrating the relevant parameters or the stochastic nature of the simulation model.

Once calibrated, an analysis was conducted to determine the number of simulation runs required to estimate reliable results. This analysis used the average cycle length to estimate the number of simulation runs required. It was determined that anywhere between three and nine simulation runs were required for each model to ensure that the average cycle length was consistent between runs. Therefore, each event was simulated ten times and the results averaged.

5.1.1 Vehicle Demand Calibration

The vehicle counts collected in the video footage were those of intersection discharge flow. This outflow represents a combination of the approach demand and signal timing. The input required in VISSIM was the approach demand. This demand value was estimated through an iterative calibration process. The 15-minute traffic flow rates in the simulation were adjusted to match the discharge flow rates from the videos. The intersection throughput, as observed in the video data was entered as the initial value for calibration.

The simulated results were evaluated using a chi-squared test and a regression analysis. The chi-squared test compared the average 15-minute counts of the simulated runs to the expected count frequencies in the video footage. The results of this test are presented as the p-value shown in g the data collection periods.

Table 24 under the $P > |z|$ column. P-values greater than 0.05 indicated that the simulated counts are statistically indistinguishable from the observed traffic counts at a 95% confidence interval. The regression analysis plotted the average simulated vehicle counts and the observed counts for every 15-minute observation pair. The R^2 column of g the data collection periods.

Table 24 shows the resulting Pearson correlation coefficient that provided an indication of the proportion of the variance in *y* attributable to the variance in *x*. The result show, for the most part, the simulated throughput matches that of the throughput collected from the video data in the field. When viewed in context of the calibrated signal timing, presented in the next section, it can be inferred that the simulated intersection approach demand was similar to that observed during the data collection periods.

Table 24: Vehicle Calibration Results

Intersection:	$P>\|z\|$	R^2
N & R 10/13	0.08	0.984
N & R 11/03	0.42	0.992
N & R 11/10	0.29	0.996
N & R 11/17	0.83	0.997
N & L 11/03	0.22	0.983
N & L 11/10	0.00	0.930
S & P 11/10	0.00	0.986
S & P 11/17	0.00	0.930
183 & 27 01/07	0.00	0.986

5.1.2 Signal Timing Calibration

The logit model coefficients estimated in the previous chapter provided a range of values within the 95% confidence interval. The values of the coefficients that resulted in the correct phase length could fall anywhere within this range. Therefore, the coefficient values for each variable used in the logit model was modified within the range of the 95% confidence interval until the average phase length for each phase in the simulation model was approximately equal to the average phase length observed in the videos. Adjusting the coefficient values primarily effected the mean value of the simulated signal. However, to adjust the variance of this mean the cut-point calibration factor (α_p) had to be calibrated as well. The value was estimated through an iterative calibration process until the standard deviation of each phase length, approximately match the standard deviation of observed in the field.

The signal timing calibration results for each observation event are provided in Table 25 through Table 33. These tables display the observed average phase length, the simulated average phase length and their respective standard deviations. To compare the observed phase length and standard deviation from the video footage to the simulation model, a two-sample student t-test and f-test was conducted, respectively. The p-value for both of these test are also provided. P-values larger than 0.05 indicated that the observed phase length and the simulated phase length were indistinguishable at a 95% confidence interval.

Table 25: Nicholson and Roosevelt 10/13/12 Calibration

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBL & SBL	10.11	6.42	10.45	2.68	0.87	0.09
NBT & SBT	224.69	110.02	218.37	81.89	0.86	0.32
WBT & EBT	69.77	33.4	70.14	19.11	0.97	0.20
Cycle Length	304.65	107.43	299.13	85.62	0.87	0.36

Table 26: Nicholson and Roosevelt 11/03/12 Calibration

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBL & SBL	16.18	22.34	17.75	13.03	0.84	0.20
NBT & SBT	232.45	91.38	237.24	55.03	0.88	0.22
WBT & EBT	56.82	32.9	59.18	37.49	0.86	0.58
Cycle Length	305.45	104.7	314.46	69.87	0.81	0.27

Table 27: Nicholson and Roosevelt 11/10/12 Calibration

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBL & SBL	9.07	1.67	9.05	0.72	0.98	0.10
NBT & SBT	164.27	31.16	161.36	35.69	0.83	0.58
WBT & EBT	51.27	17.4	54.53	16.62	0.64	0.47
Cycle Length	224.6	34.03	225.53	39.56	0.95	0.59

Table 28: Nicholson and Roosevelt 11/17/12 Calibration

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBL & SBL	8.33	1.11	9.51	0.53	0.00	0.13
NBT & SBT	158.81	45.16	167.81	46.03	0.63	0.51
WBT & EBT	46.2	20.43	40.55	19.74	0.49	0.48
Cycle Length	216.67	56.88	217.62	49.61	0.97	0.42

Table 29: Nicholson and Lee 11/03/12 Calibration

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBT & SBT	139.26	35.41	128.33	25.2	0.37	0.30
NBL & SBL	22.6	10.7	23.91	10.76	0.74	0.50
WBT & EBT	75.16	41.1	80.81	47.2	0.72	0.58
Cycle Length	235.74	69.4	232.77	55.58	0.9	0.37

Table 30: Nicholson and Lee 11/10/12 Calibration

	Observed		*Simulated*		*P>|z|*	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBT & SBT	210.13	77.03	230.91	74.77	0.51	0.48
NBL & SBL	20.94	4.23	20.64	2.43	0.84	0.20
WBT & EBT	76.6	56.11	73.53	47.24	0.89	0.40
Cycle Length	302.07	75.78	327.01	91.08	0.46	0.61

Table 31: Stanford and Perkins 11/10/12 Calibration

	Observed		*Simulated*		*P>|z|*	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
EBL WBL	44.44	27.36	31.06	28.56	0.31	0.53
EBT WBT	68.56	30.24	67.4	29.4	0.93	0.48
NBL SBL	34.5	6.16	32.62	9	0.62	0.72
NBT SBT	294.88	103.78	287.2	79.73	0.86	0.34
Cycle Length	455	106.24	416.76	83.63	0.4	0.36

Table 32: Stanford and Perkins 11/17/12 Calibration

	Observed		*Simulated*		*P>|z|*	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
EBL WBL	53.69	24.31	58.69	17.16	0.59	0.30
EBT WBT	80.08	33.89	64.34	27.98	0.25	0.38
NBL SBL	36.92	8.41	38.96	9.74	0.6	0.59
NBT SBT	211.62	81.19	203.23	67.2	0.8	0.39
Cycle Length	398.92	102.42	366.08	85.07	0.43	0.39

Table 33: NW 183 St. and NW 27 Ave. 01/07/13 Calibration

	Observed		*Simulated*		*P>|z|*	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
EBL WBL	20.43	15.07	22.98	12	0.63	0.36
EBT WBT	27.59	11.94	32.43	10.98	0.26	0.45
NBL SBL	34.7	19.68	36.66	22.2	0.79	0.57
NBT SBT	111.35	32.64	112.57	25.75	0.91	0.36
Cycle Length	194.08	50.38	204.64	37.64	0.55	0.33

The results showed that in all but one instance, the analysis must accept the null hypothesis that the simulated phase lengths were statistically similar to the observed. The exception to this was observed in Table 28 for the intersection of Nicholson and Roosevelt collected on 11/17/12. In this table, the Northbound left, Southbound left phase did not statistically match the simulated phase length. The average values was approximately 8.33 seconds with a standard deviation of 1.11 while the simulate intersection had a phase length of 9.51 seconds with a standard deviation of 0.14. Due to the short duration and relatively small standard deviation observed in the field, the simulation model had difficultly matching this phase. Despite this single T-test failure, the results of the calibration suggest that the simulated models statistically replicated the observed phase length and deviation of this length, within a 95% confidence interval. The model calibration results showed, with statistical certitude, that the simulation matched the observed video data with respect to 15-minute approach counts, signal phase length and standard deviation of this length.

5.2 Validation

The goal of the simulation validation process was to evaluate the consistency of simulated police officer control with those observed in the field. Validation was undertaken using *model transfer*, whereby the logit model developed to represent officer actions at one intersection was used to simulate the same actions at another intersection. In effect, this process would be like moving an officer directing traffic from one intersection to another in the study. This was accomplished by transferring the calibrated V.A.P. files from one intersection to another. Validation, for the purposes of this research, was achieved when the transferred model produced statistically similar results, both temporally and spatially, with the observations made in the field. The calibration and validation intersection pairing was identical to that used to validate the logit models in the previous chapter and is shown in Table 21.

Table **34** provided the results of the 15-minute vehicle count validation. The $P>|z|$ column was the p-value results of a Chi-squared test. Values greater 0.05 suggest that the validation model and the observations taken on the validation day were statistically indistinguishable at a 95% confidence interval. Only the intersection of Nicholson and Roosevelt was able to achieve this level of consistency. This was likely due to larger sample size of the calibration dataset, which combined observations from multiple events. The R^2 column showed the regression analysis results of the 15-minute count information. Values closer to one indicate better model fit than others. The results suggest the simulation model preformed reasonably well in replicating the 15-minute vehicle counts collected in the validation dataset.

Table 34: Vehicle Validation

Intersection:	***P*>|*z*|**	***R²***
N & R	0.79	0.997
N & L	0.00	0.975
S & P	0.00	0.957
183 & 27	0.00	0.962

Table 35 through Table 38 displayed the traffic signal timing results for the validation dataset. Present in the tables are the average time/phase length, the standard deviation of this length, the two sample, two tailed t-test results comparing the mean values and a two sample, f-test comparing the standard deviations. P-values larger than 0.05 suggest that the signal timings were statistically equivalent at a 95% confidence interval. In general, the validation model was successful at replicating the observed signal timings.

Table 35: Nicholson and Roosevelt Signal Validation

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBL & SBL	8.33	1.11	10.57	1.95	0	0.81
NBT & SBT	158.81	45.16	200.27	56.97	0.05	0.64
WBT & EBT	46.2	20.43	67.42	22.13	0.02	0.55
Cycle Length	216.67	56.88	277.68	65.31	0.02	0.58

Table 36: Nicholson and Lee Signal Validation

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
NBT & SBT	210.13	77.03	235.59	71.02	0.41	0.45
NBL & SBL	20.94	4.23	21.02	2.32	0.96	0.18
WBT & EBT	76.6	56.11	83.57	49.88	0.75	0.43
Cycle Length	302.07	75.78	340.4	87.2	0.26	0.59

Table 37: Stanford and Perkins Signal Validation

	Observed		***Simulated***		***P*>|*z*|**	
Phase	**Ave. Time**	**St.D.**	**Ave. Time**	**St.D.**	**T-Test**	**F-Test**
EBL WBL	53.69	24.31	37.33	24.2	0.12	0.50
EBT WBT	80.08	33.89	79.7	23.22	0.98	0.28
NBL SBL	36.92	8.41	34.26	8.27	0.47	0.49
NBT SBT	211.62	81.19	303.52	77.91	0.01	0.47
Cycle Length	398.92	102.4	456.62	81.94	0.17	0.37

Table 38: NW 183 St. and NW 27 Ave. Signal Validation

Phase	*Observed* Ave. Time	St.D.	*Simulated* Ave. Time	St.D.	*P*>|*z*| T-Test	F-Test
EBL WBL	20.43	15.07	20.85	21.09	0.95	0.70
EBT WBT	27.59	11.94	61.4	27.09	0	0.89
NBL SBL	34.7	19.68	32.16	12.66	0.7	0.25
NBT SBT	111.35	32.64	323.24	86.01	0	0.93
Cycle Length	194.08	50.38	438.25	88.43	0	0.81

The validation results showed that the calibrated models preformed reasonably well in estimating the parameters for the validation datasets. While some instances failed the statistical test conducted, overall the models showed a trend of consistency. Do to the stochastic nature of traffic and of simulation modeling, the results presented here showed a significant relationship between the simulated data and the observed validation dataset.

5.3 Comparative analysis

The simulation model was used compare manual traffic control to the actuated signal controllers currently deployed in the field. The signal controller data for the intersections located in Baton Rouge, LA was obtained from the Baton Rouge Department of Public Works and provided in a Traffic Signal Inventory (TSI) sheet. The TSI sheets were not provided in this document, as they propriety to the Baton Rouge Department of Public Works. The signal timing information was not available for the intersection of NW 183 St and NW 27 Ave in Miami Gardens, FL. The signal timing for this intersection was estimated from the video footage collected prior to the arrival of the police officer. The gap extension was assumed to be equal to the Baton Rouge intersections. The intersections were evaluated using three metrics, total throughput volume, signal timing and network wide performance measures. The actuated controllers were simulated 10 times and their results averaged.

5.3.1 Total Throughput

The total throughput was collected from the intersections and converted into volumes (veh/hr). The results are presented in Table 39. The *Actuated* column displays the average throughput volume of the intersection under fully actuated signal control. The *Observed* column shows the total throughput volume observed in the field under manual traffic control. The *MTC* column shows the total throughput volume of the simulated manual traffic control model. The table indicated that the actuated controller, the observed and the manual traffic control model produced around the same amount of throughput. This was to be expected since the simulation model was calibrated based on 15-minute count data. This indicated that the actuated controller was performing as least as well as the manual traffic control model. Had the actuated controller not performed as well this would of likely caused a reduction in throughput.

Table 39: Intersection Throughput Volumes

	Controller Type		
Intersection:	**Actuated**	**Observed**	**MTC**
N & R 10/13	1092	1092	1090
N & R 11/03	1019	1033	1015
N & R 11/10	1640	1692	1645
N & R 11/17	1982	1983	1973
N & L 11/03	1540	1546	1535
N & L 11/10	1567	1544	1381
S & P 11/10	2516	2622	2613
S & P 11/17	3393	3197	3157
183 & 27 01/07	3390	3460	3640

5.3.2 Signal Timing

The average signal timing for the actuated controllers and the manual traffic control model is present in Table 40 through Table 48. The *Ave. Time* column displays the average phase length, the *St.D* column shows the standard deviation of this time and the *Obs.* column shows the number of times this phase was observed during the simulation. The actuated controller displayed lower cycle length and standard deviation when compared to the manual traffic control model. Furthermore, the number of observations suggested that the actuated controller was able to skip over phases, resulting in a lower number of observations for phases with low demand. This was not present in the manual traffic control model, as officers directing traffic using the “clicker” method do not have the ability to skip over phases. Therefore the number of observations for the manual traffic control model is the same for each phase.

Table 40: Nicholson and Roosevelt 10/13/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBL SBL	16.75	1.10	15	10.45	2.68	27
NBT SBT	44.14	0.05	92	218.37	81.89	26
EBT WBT	15.83	0.29	92	70.14	19.11	26

Table 41: Nicholson and Roosevelt 11/03/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBL SBL	13.97	0.76	7.3	17.75	13.03	19
NBT SBT	44.20	0.09	74.2	237.24	55.03	19
EBT WBT	13.96	0.37	75.3	59.18	37.49	19

Table 42: Nicholson and Roosevelt 11/10/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBL SBL	14.83	0.94	6	9.05	0.72	15
NBT SBT	44.04	0.08	44	161.36	35.69	15
EBT WBT	14.76	0.27	45	54.53	16.62	14

Table 43: Nicholson and Roosevelt 11/17/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBL SBL	17.14	0.83	16	9.51	0.53	18
NBT SBT	43.98	0.00	49	167.81	46.03	17
EBT WBT	14.71	0.78	50	40.55	19.74	17

Table 44: Nicholson and Lee 11/03/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBT SBT	63.58	0.54	73	128.33	25.20	29
NBL SBL	11.68	0.16	66	23.91	10.76	29
EBT WBT	25.09	0.42	72	80.81	47.20	28

Table 45: Nicholson and Lee 11/10/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBT SBT	65.34	1.05	46	230.91	74.77	12
NBL SBL	11.70	0.39	40	20.64	2.43	12
EBT WBT	22.94	1.02	45	73.53	47.24	11

Table 46: Stanford and Perkins 11/10/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBT SBT	103.87	27.16	21	287.20	79.73	8
NBL SBL	16.71	3.58	21	32.62	9.00	9
EBT WBT	31.54	11.81	21	67.40	29.40	9
NBL SBL	19.33	3.83	21	31.06	28.56	9

Table 47: Stanford and Perkins 11/17/12 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBT SBT	82.74	23.39	28	203.23	67.20	13
NBL SBL	25.49	8.31	28	38.96	9.74	13
EBT WBT	44.89	11.03	27	64.34	27.98	13
NBL SBL	21.19	4.88	27	58.69	17.16	13

Table 48: NW 183 and NW 27 Ave. 01/07/13 Actuated Signal Timing

	Simulated Actuated Control			***Simulated Manual Control***		
Phase	**Ave. Time**	**StD.**	**Obs.**	**Ave. Time**	**StD.**	**Obs.**
NBT SBT	65.39	11.77	56	112.57	25.75	35
NBL SBL	24.03	10.30	55	36.66	22.20	35
EBT WBT	20.40	4.54	55	32.43	10.98	36
NBL SBL	19.86	0.68	55	22.98	12.00	36

The actuated controller was then evaluated for overall network performance and compared to the manual traffic control model. The network evaluation metrics used were average delay, average number of stops, average speed, average stop delay, total delay, total number of stops, total stop delay and total travel time. The parameter values corresponding to manual control are compared to actuated signal control for each intersection in Table 49 through Table 57. These tables show the average parameter value for each of the 10 simulation runs under the column headers *MTC* and *ACT*, respectively. Also shown is the percent difference $(\frac{MTC-ATC}{MTC})$ between the control types for each metric and the p-value of a two-sample, two tailed student T-test.

Table 49: Nicholson and Roosevelt 10/13/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	42.1	11.7	72.15%	0.00
Ave Num. of Stops	0.4	0.4	14.98%	0.00
Ave. Speed (mph)	12.3	22.4	-81.69%	0.00
Ave. Stop Delay (s)	37.9	8.0	78.90%	0.00
Total Delay (h)	30.3	8.4	72.12%	0.00
Total Number of Stops	1112	946	14.89%	0.00
Total Stop Delay (h)	27.2	5.8	78.88%	0.00
Total Travel Time (h)	48.5	26.7	44.98%	0.00

Table 50: Nicholson and Roosevelt 11/03/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	33.7	7.7	77.12%	0.00
Ave Num. of Stops	0.4	0.3	27.99%	0.00
Ave. Speed (mph)	13.7	24.9	-81.23%	0.00
Ave. Stop Delay (s)	30.3	5.0	83.40%	0.00
Total Delay (h)	17.2	3.9	77.12%	0.00
Total Number of Stops	670	482	28.05%	0.00
Total Stop Delay (h)	15.4	2.6	83.40%	0.00
Total Travel Time (h)	29.5	16.3	44.82%	0.00

Table 51: Nicholson and Roosevelt 11/10/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	27.7	12.5	54.70%	0.00
Ave Num. of Stops	0.4	0.4	2.29%	0.35
Ave. Speed (mph)	15.2	21.6	-41.82%	0.00
Ave. Stop Delay (s)	23.0	7.5	67.33%	0.00
Total Delay (h)	16.9	7.7	54.58%	0.00
Total Number of Stops	875.4	857.6	2.03%	0.45
Total Stop Delay (h)	14.1	4.6	67.25%	0.00
Total Travel Time (h)	31.7	22.7	28.27%	0.00

Table 52: Nicholson and Roosevelt 11/17/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P>|z|***
Ave Delay (s)	44.7	19.4	56.67%	0.00
Ave Num. of Stops	0.7	0.6	12.32%	0.00
Ave. Speed (mph)	13.6	20.4	-49.44%	0.00
Ave. Stop Delay (s)	39.4	14.5	63.08%	0.00
Total Delay (h)	36.6	15.9	56.68%	0.00
Total Number of Stops	1927	1690	12.28%	0.00
Total Stop Delay (h)	32.3	11.9	63.09%	0.00
Total Travel Time (h)	62.8	42.1	32.96%	0.00

Table 53: Nicholson and Lee 11/03/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P>|z|***
Ave Delay (s)	61.2	18.2	70.23%	0.00
Ave Num. of Stops	0.7	0.6	17.51%	0.00
Ave. Speed (mph)	11.1	20.7	-86.40%	0.00
Ave. Stop Delay (s)	56.0	13.4	76.02%	0.00
Total Delay (h)	32.3	9.6	70.25%	0.00
Total Number of Stops	1277	1052	17.59%	0.01
Total Stop Delay (h)	29.5	7.1	76.04%	0.00
Total Travel Time (h)	48.7	26.1	46.34%	0.00

Table 54: Nicholson and Lee 11/10/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P>|z|***
Ave Delay (s)	24.0	8.3	65.51%	0.00
Ave Num. of Stops	0.4	0.3	28.03%	0.00
Ave. Speed (mph)	16.3	24.3	-48.87%	0.00
Ave. Stop Delay (s)	19.8	4.9	75.32%	0.00
Total Delay (h)	11.2	3.9	65.52%	0.00
Total Number of Stops	668.7	481.1	28.05%	0.00
Total Stop Delay (h)	9.2	2.3	75.34%	0.00
Total Travel Time (h)	22.4	15.1	32.72%	0.00

Table 55: Stanford and Perkins 11/10/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	97.6	72.3	25.91%	0.00
Ave Num. of Stops	1.0	1.5	-49.55%	0.00
Ave. Speed (mph)	9.1	11.4	-25.87%	0.00
Ave. Stop Delay (s)	89.7	60.8	32.13%	0.00
Total Delay (h)	75.0	51.5	31.43%	0.00
Total Number of Stops	2757	3814	-38.36%	0.00
Total Stop Delay (h)	68.9	43.3	37.18%	0.00
Total Travel Time (h)	103.8	79.1	23.79%	0.00

Table 56: Stanford and Perkins 11/17/12 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	122.6	80.9	34.02%	0.00
Ave Num. of Stops	2.6	2.2	16.27%	0.00
Ave. Speed (mph)	7.9	10.8	-36.34%	0.00
Ave. Stop Delay (s)	107.6	65.3	39.30%	0.00
Total Delay (h)	143.9	94.6	34.30%	0.00
Total Number of Stops	11075	92230	16.66%	0.00
Total Stop Delay (h)	126.4	76.4	39.55%	0.00
Total Travel Time (h)	190.0	141.3	25.64%	0.00

Table 57: NW 183 St and NW 27 Ave 01/07/13 Network Performance

Parameter	***MTC***	***ACT***	***Percent Diff.***	***P*>|*z*|**
Ave Delay (s)	58.0	56.9	1.93%	0.13
Ave Num. of Stops	1.5	2.2	-42.59%	0.00
Ave. Speed (mph)	13.2	13.4	-1.31%	0.08
Ave. Stop Delay (s)	46.4	42.0	9.42%	0.00
Total Delay (h)	132.9	127.2	4.27%	0.00
Total Number of Stops	12649	17607	-39.20%	0.00
Total Stop Delay (h)	106.4	94.0	11.58%	0.00
Total Travel Time (h)	223.6	215.8	3.47%	0.00

The result showed that the actuated controller outperformed the police officer in nearly every metric. The exception to this was seen in the average number of stops and total number of stops at the intersection of Stanford and Perkins on 11/17/12 and NW 183 St. and NW 27 Ave on 01/07/13. Other than two instances, ever metric indicated that the actuated controller would have performed better than the officer directing traffic. The T-test results showed, for the most part that these findings are statistically significant at a 95% confidence interval.

There are two likely causes for the poor performance of manual traffic control when compared to the actuated controller. The first of which was a substantial decrease in saturation flow rate as phase length progressed. This finding was consistent with the previous literature on manual traffic control (May and Montgomery, 1988). The other likely cause was the ability of the actuated controller to skip phases when demand was not present. Historically, police officers have been able to decrease lost time by extending phase length, resulting in fewer phases per cycles per hour and thus less lost time overall. However, when using the “clicker” method the officer did not have the ability to skip phases and therefore had to service the minimum green time for phases even when demand was not present. Continually serving phases without demand negates any benefit the officer has in decreasing lost time. The inability of the officer to skip phases resulted in an overall increase of lost time despite having fewer cycles per hour. An example of this was presented in Figure 14.

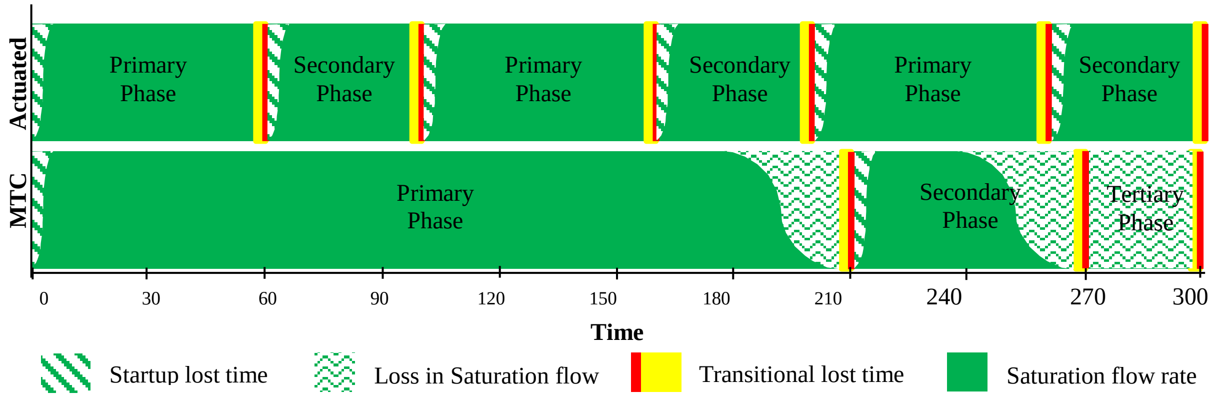


Figure 14: Saturation and Lost Time Diagram

Figure 14 was a five-minute (300 second) phase diagram illustration of a hypothetical example of what was likely occurring during the simulation. Two controller strategies for the same intersection were shown, actuated and manual traffic control. Both controllers were three phase but the actuated controller could skip phases if demand was not present. The actuated controller had a 100 seconds cycle length and the manual traffic control shown here had a 300 second cycle length. The time when the intersection was operating at saturation flow was shown in green. Lost time and loss in saturation flow were also presented in the diagram. For this example, demand was not present for the *Tertiary* phase. This illustration showed how the decrease in saturation flow rate and the inability to skip phases has a drastic impact on the total lost time of the intersection when compared to actuated signal control. The officer directing traffic has the ability to minimize the saturation loss but, cannot eliminate the lost time seen in the *Tertiary* phase.

5.4 Summary of Simulation Model Findings

The manual traffic control model was shown to be statistically indistinguishable from the observed police controlled intersections with regard to phase length, standard deviation of phase length and intersection throughput. These results were validated on a separate dataset, which also showed a trend of consistency. After the manual control model was calibrated and validated in the simulation, it was used to compare manual traffic control to an actuated controller. The results of the simulation showed that actuated control outperformed police control in nearly every metric. This performance was likely the result of the actuated controller's ability to skip phases when demand was not present. A police officer directing traffic using the "clicker" method does not have a similar capability. As a result, any lost time saved by the officer was negated.

CHAPTER 6. CONCLUSION

Manual intersection control is a key part of managing traffic during emergencies and planned special events. It is widely assumed that the flow of traffic through intersections can be greatly improved by the direction given from police officers who can observe and respond to change conditions by allocating green time to the approaches that require it the most. Despite the long history of manual traffic control throughout the world and its assumed effectiveness, there have been no quantitative, systematic studies of when, where, and how it should be used or compared to automated signals. The goal of this research was to study manual traffic control and develop methods to make quantitative evaluations and comparison of its performance.

Based on these goals a primary objective of this research was to quantify the effects of manual traffic control on intersection operations to develop a quantitative model to describe the decision making actions of police officers directing traffic. This was accomplished by collecting video data of police officers directing traffic at several special events in Baton Rouge, LA and Miami Gardens, FL. This data were used to develop a discrete choice model (logit model) capable of estimating police officer’s choice probabilities on a second-by-second basis. This model was able to be programmed into a microscopic traffic simulation software system to serve as the signal controller for the Baton Rouge and Miami Gardens intersections, effectively simulating the primary control decision activities of the police officer directing traffic. This model was then used to compare the performance of the police officer to an actuated traffic signal.

From a choice modeling standpoint, the research findings suggested police officers in Baton Rouge, LA and Miami Gardens, FL, tended to direct traffic in a similar fashion; extending green time for high demand directions while attempting to avoid long gaps or waste in the traffic stream. This was expected and is quite consistent with the general concept of a traffic signal. The research also found that *Phase, Time* and *Gap* variables estimated by the various logit models had statistically equivalent values at a 95% confidence interval irrespective of the data collection day or location. While some level of similarity was expected, this degree of consistency was remarkable and indicates that when officers are placed in similar situation they are likely to make the same primary control decisions. This was important because it suggests that a properly trained and experienced police officer in Baton Rouge, LA would be just as effective directing traffic in Miami Gardens FL, and vice-versa.

The practical implication is that after a disaster, officers from outside the effected area can be brought in for traffic control without a drop in effectiveness. This finding was likely the result of the standard training police officers receive in which police are taught to assess priority, avoid waste, coordinate with neighboring signals, and equitably distribute green time between movements based on volume. If true, then the discrete choice model developed in this research could provide a starting point for the development of a generic use manual traffic control simulation model applicable to any location. The implication of this result are also of particular interest to the Nuclear Regulatory Commission, as the simulation of manual traffic control is a critical component in the development of evacuation time estimates for nuclear power plants.

From a simulation modeling standpoint, the manual traffic control model was shown to be statistically indistinguishable from the observed police controlled intersections with regard to phase length, standard deviation of phase length and intersection throughput. This was the goal of the calibration process and was an expected outcome. These results were validated on a separate dataset, which showed a trend of consistency. With this validity established, the model can be applied to simulate “what if” scenarios within the two jurisdictions. Although the model cannot predict the precise effect of manual traffic control, it can be used to compute reliable estimates of its likely effect. In terms of generalizability, while it is understood that the model was developed from Baton Rouge and Miami Gardens locations, it is likely that the model may also be applicable outside of these regions. Applying the models developed for this research to intersections outside of Baton Rouge or Miami Gardens would be like having a police officer from Baton Rouge or Miami Gardens go to another jurisdiction and direct traffic. Another application of the model would be to evaluate the effect of policy changes to manual traffic control. For example, if a policy was put in place that mandated a maximum cycle length of five minutes, the model could be modified to reflect this and estimate the likely impact on traffic.

After the manual control model was calibrated and validated in the simulation, it was used to compare manual traffic control to an actuated controller. The results of the simulation showed that actuated control outperformed police control in nearly every metric. For instance, the average travel speed during actuated control was as much as 9.6 mph faster than under manual control. This constituted an 86% increase in travel speed under actuated control. Similar results were observed for total travel time and average delay. This performance was likely the result of the actuated controller’s ability to skip phases when demand was not present. A police officer directing traffic using the “clicker” method does not have a similar capability. As a result, any lost time saved by the officer was negated. In a field application this limitation could be addressed by adjusting the programming of the signal controller. Specifically, permitting the officer to skip phases, as is done with actuated controllers, an equal benefit can be realized under police control. Based on the analytical results it was concluded that without the ability to skip phases, Baton Rouge and Miami Gardens would be better served by not using the “clicker” method of manual traffic control. However, the inefficiencies of the “clicker” method will need to be weighed against the risk posed to the police officer by using the “officer in the intersection” approach.

6.1 Future Work

The research findings presented several opportunities for future work. In general, there is a need for technology development to address the limitations of manual traffic control as practiced in the field and there also is a need for additional simulation modeling tools for emergency traffic. The opportunities presented by these problems are discussed in the following sections.

6.1.1 Technology Development

There is a need to develop technology that provides an officer the ability customize to lane groups and phase sequence to better meet the challenges of a dynamic traffic environment. One of the major findings of the research was that officers lacking the ability to skip phases did not perform as well as actuated signals because the officer increased overall lost time by servicing the minimum green on low demand approaches. Simply providing an officer with the ability to skip phases would address this issue immediately, increasing the effectiveness of manual traffic control. However, beyond skipping phases, an officer needs the ability to customize control strategies, allowing the officer flexibility in traffic control solutions. One possible way to address this problem would be to implement the “clicker” as a secure mobile app, able to communicate with the controller. This app could display the detector information to the police officer as well as wait times, queue length and phase length. The app could also prompt the officer to change phases when it detects waste and make suggestions as to which phase should be green next. This approach would allow for maximum efficiency and flexibility by providing the officer with more information but still allow the officer to make the final right-of-way allocations decision and overall traffic control strategy.

6.1.2 Traffic Simulation Tools

To better capture the dynamics of emergency traffic, several additional simulation tools should be considered for further development. The simulation was programed to start and stop at a specific time, to accurately reflect the field observations. This research did not consider identifying the starting and stopping criteria of the police officers. Future work should consider this as it would open research to the idea of minimizing the time and number of officers required for an effective overall manual traffic control plan. Another possible avenue for future work is in exploring the distribution of the cut-point to vary the signal phase lengths. The cut-point distribution in this research was assumed to be uniform. However, it is likely this distribution is more closely related to an exponential or normal distribution. The assumption of a uniform distribution was necessary because the VISSIM's Vehicle Actuated Programming language did not allow for many mathematical operations such as power functions or exponential expressions. A future avenue of research could explore the effect of altering the cut-point distribution or estimating its distribution from field observations. And finally, research is needed to determine how police officers provided signal priority to emergency vehicles. It was observed that some officers permitted a green extension or red truncation but this was not always the case. However, there were insufficient observations in the population to conduct any meaningful analysis with regards to the emergency vehicles.

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APPENDIX A. INTERSECTION GEOMETRIC DESIGN

This appendix provides the geometric design of the study intersections. The drawings were rendered in Autocad™.

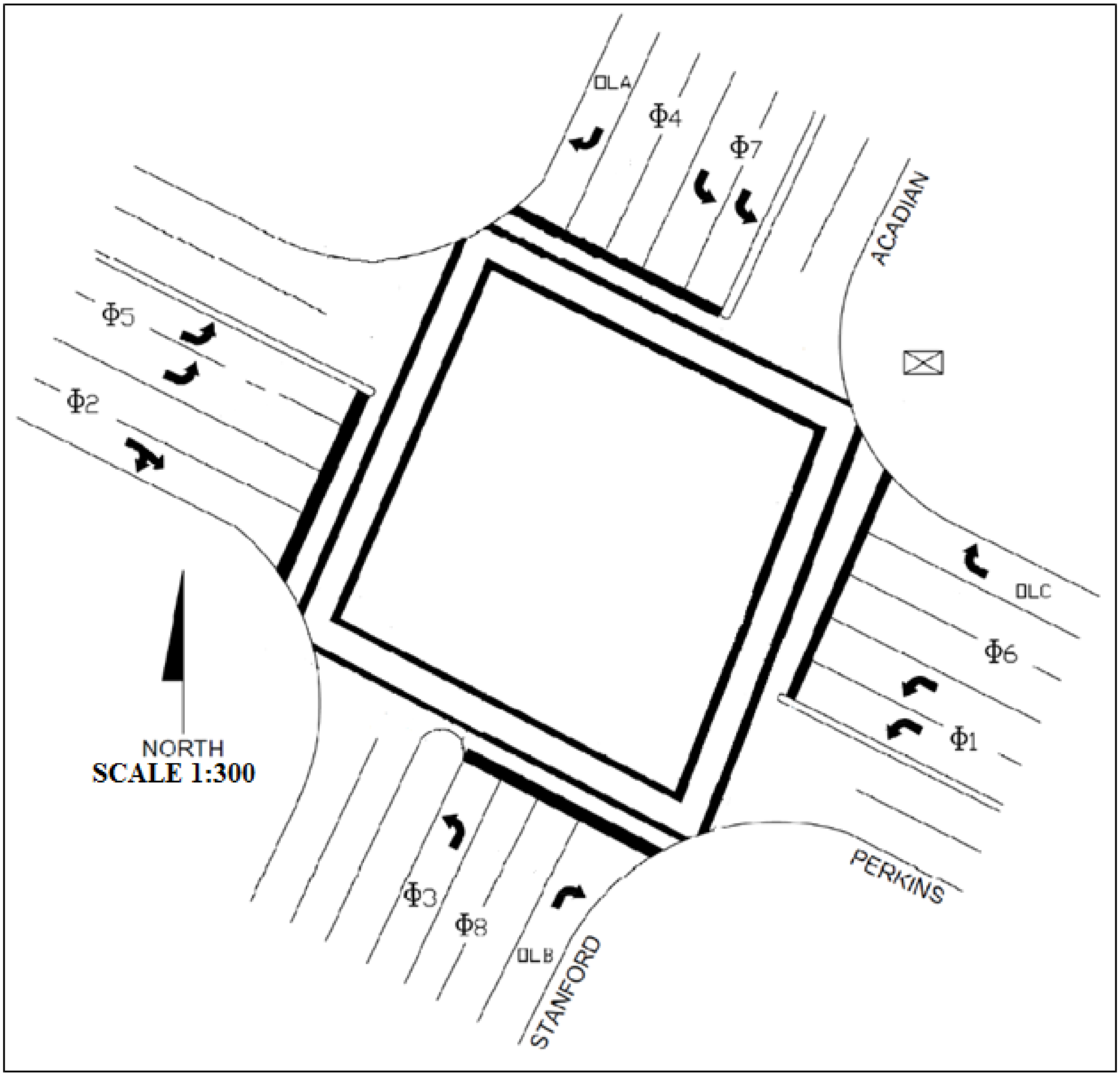

Figure 15: Geomtric Design of Stanford and Perkins

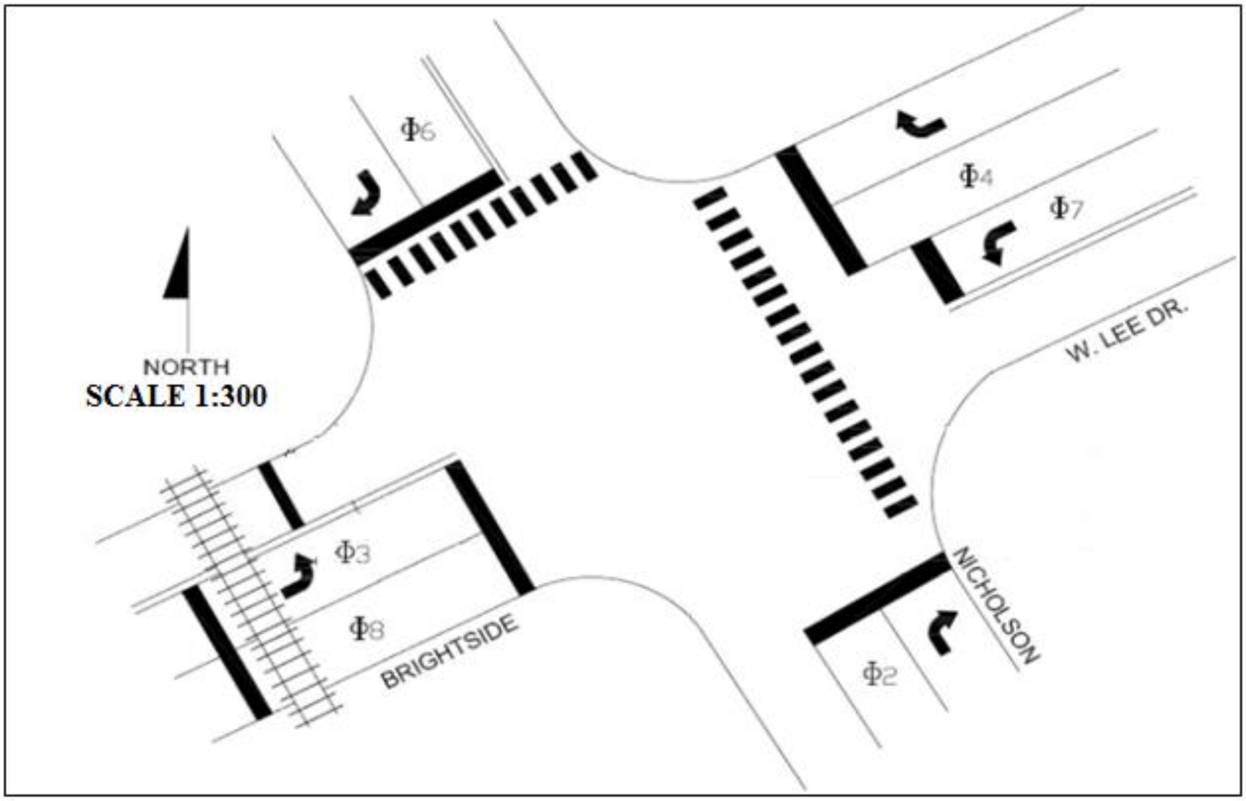

Figure 16: Geometric Design of Nicholson and Lee

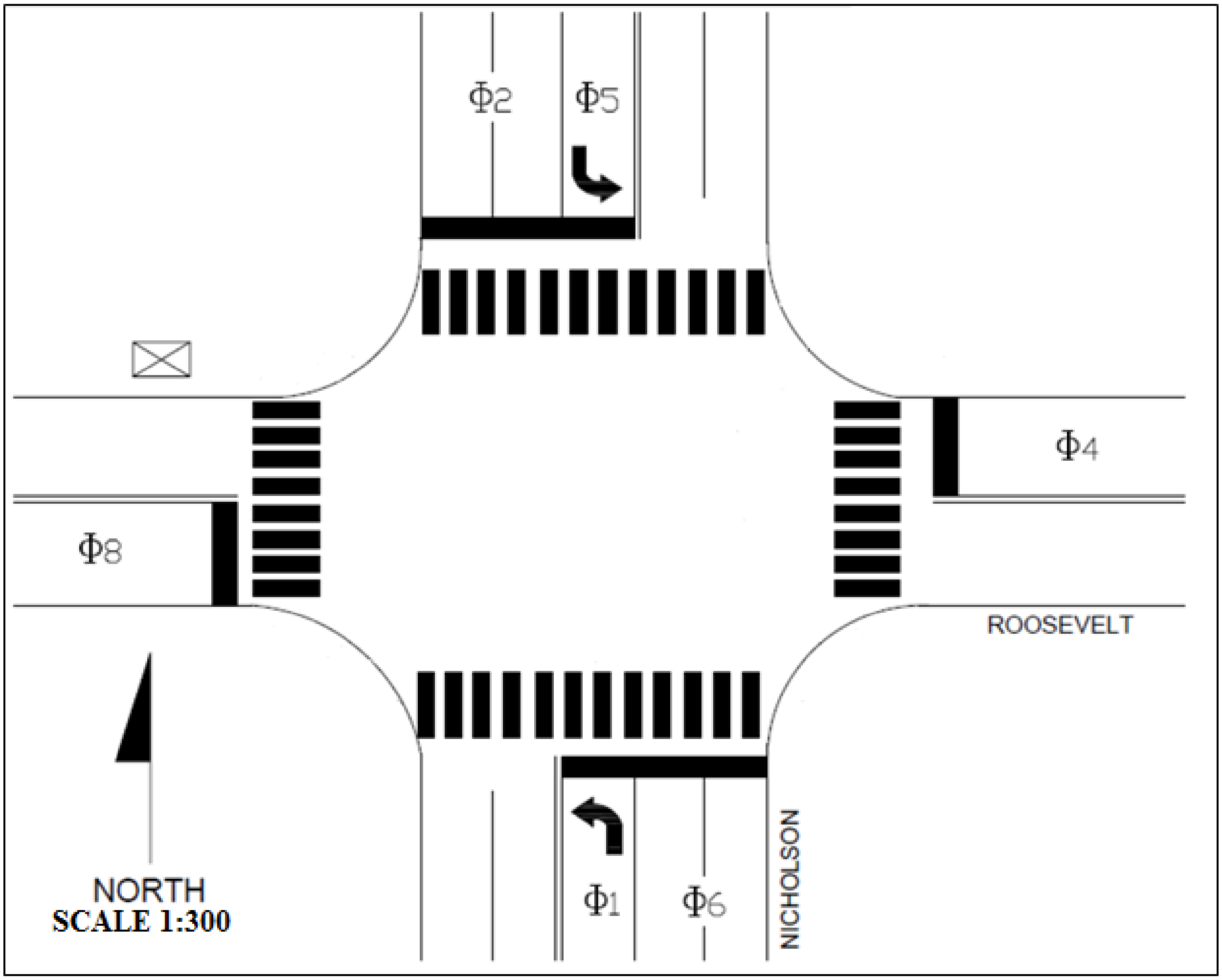

Figure 17: Geometric Design of Nicholson and Roosevelt

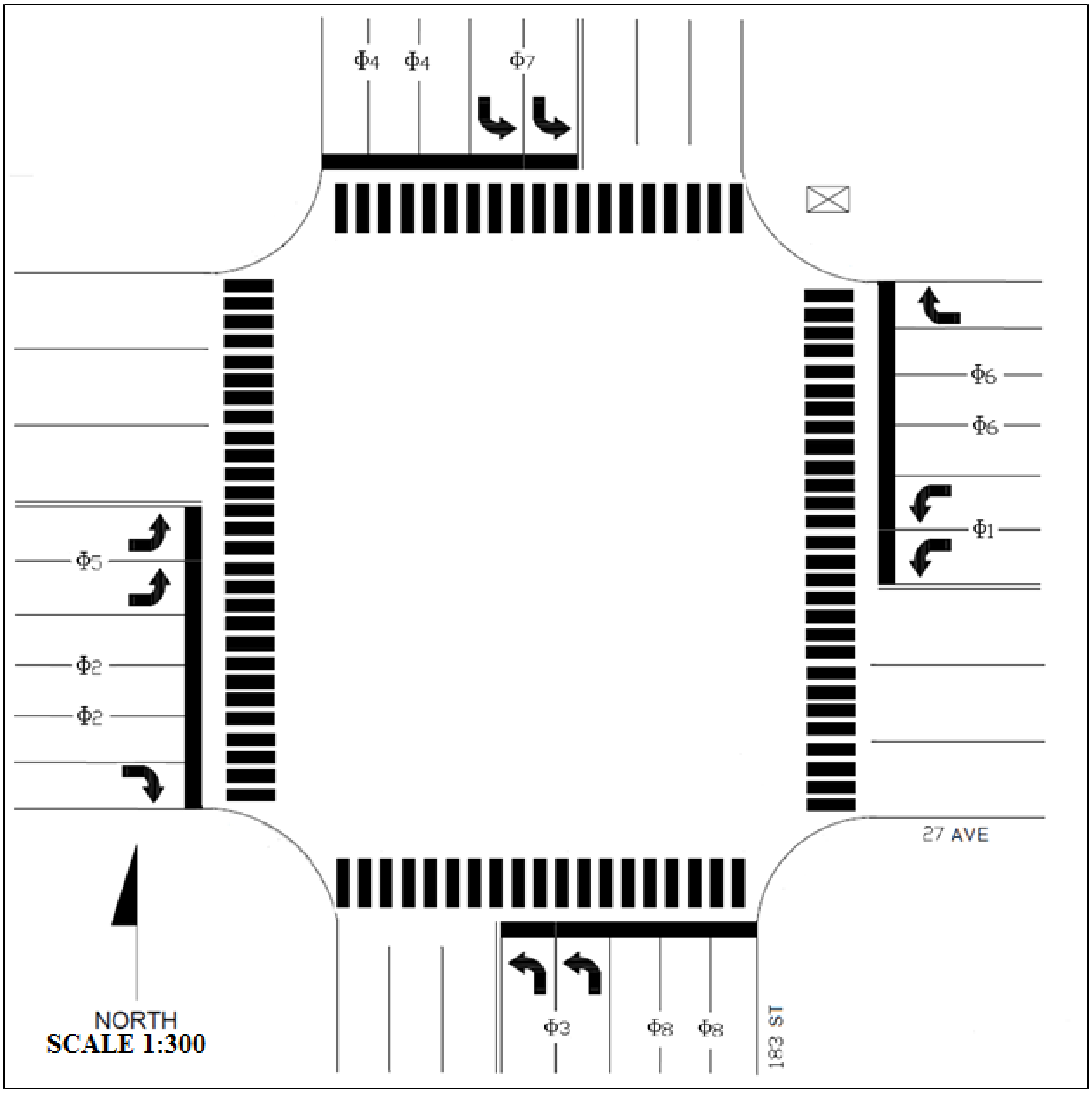

Figure 18: Geometric Design of NW 183 St and NW 27 Ave