

To the Graduate Council:

I am submitting herewith a thesis written by Scott Glenn Beaird entitled "Traffic Signal Phase Truncation in the Event of Traffic Flow Restriction." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Thomas Urbanik II

Major Professor

We have read this thesis
and recommend its acceptance:

Arun Chatterjee

Lee D. Han

Accepted for the Council:

Anne Mayhew

Vice Chancellor and Dean of Graduate Studies

(Original signatures are on file with official student records.)

**TRAFFIC SIGNAL PHASE TRUNCATION IN THE EVENT OF TRAFFIC
FLOW RESTRICTION**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

SCOTT GLENN BEAIRD

May 2005

DEDICATION

Dedicated to my wife, Tracey, who makes me a better man and has been an incredible source of support and to the Lord who strengthens me.

ACKNOWLEDGEMENTS

First and foremost, I would like to acknowledge the support and guidance of Dr. Thomas Urbanik II. He encouraged me to see the big picture but also kept me focused. I consider it a privilege to have worked with him and value our professional and personal relationships.

I would also like to thank Dr. Lee Han and Dr. Arun Chatterjee for serving on my graduate committee. The personal attention that Dr. Han, Dr. Chatterjee, and Dr. Fred Wegmann have shown during my time at the University of Tennessee has made the process even more enjoyable.

A special thanks is due to all of my colleagues at Kittelson & Associates, Inc., who have been extremely supportive of my return to school. Special acknowledgement is also due to Kiel Ova at PTV America, Inc. for his endless support in answering my questions.

The research for this thesis was conducted as part of the NCHRP 3-66 research project. I thank all of the project team members for their ideas and insights.

ABSTRACT

This thesis presents a proposed improvement to traffic signal controller logic. The concept consists of truncating a phase on which there is demand but zero or minimal flow due to a restriction of traffic. The logic presented in this thesis recognizes such a flow restriction and, consequently, terminates the phase in favor of a conflicting call for service. The theory of the concept is addressed and methods of implementation are explored.

An experimental analysis was conducted in order to qualify the benefit of the phase truncation concept. This analysis was conducted using the VISSIM simulation software in conjunction with a hardware-in-the-loop configuration. This permitted the simulation to be run using an actual traffic signal controller. The simulation analysis was conducted using an eight-phase actuated intersection. Based upon the results of this analysis, it was concluded that the phase truncation concept could result in reduced vehicle delay.

TABLE OF CONTENTS

CHAPTER I	INTRODUCTION	1
	Problem Statement	2
	Research Objectives	3
CHAPTER II	BACKGROUND.....	5
	Sensors	5
	Adaptive Signal Control	10
CHAPTER III	EXPLANATION OF CONCEPT.....	17
	Causes of Flow Restriction	18
	Conditions Warranting Truncation	23
	Implementation of Logic.....	25
	Methods of Truncation.....	27
CHAPTER IV	STUDY DESIGN.....	30
	Modeling Software.....	30
	Hardware-in-the-Loop	31
	Study Intersection	34
	Simulation Modeling Methods	36
CHAPTER V	STUDY RESULTS	41
	Experimental Objective	41
	Experimental Hypothesis	41
	Statistical Analysis.....	42
	Experimental Results	43
	Analysis of Results	45
CHAPTER VI	CONCLUSIONS AND RECOMMENDATIONS.....	48
	Conclusions and Summary	48
	Recommendations.....	50
REFERENCES.....		52
APPENDICES		56
	Appendix A: VAP Logic Code	57
	Appendix B: Results of VISSIM Simulation Runs	60

Appendix C: Summary of Statistical Tests	61
Appendix D: SAS Statistical Analysis Output.....	63
VITA.....	72

LIST OF TABLES

TABLE 1 Simulation Traffic Volumes.....	37
TABLE 2 VISSIM Results: Average Delay per Vehicle by Phase	44
TABLE 3 VISSIM Results: Average Green Time per Phase	45

LIST OF FIGURES

FIGURE 1 Normal vs. restricted flow profiles.....	4
FIGURE 2 Vehicle detection: gapout vs. max out.	8
FIGURE 3 Events resulting in flow restrictions.....	20
FIGURE 4 Possible logic architecture.....	26
FIGURE 5 Hardware-in-the-loop system.....	32
FIGURE 6 Study intersection: Irving, TX.....	35
FIGURE 7 VISSIM simulation of phase truncation logic.....	38
FIGURE 8 VISSIM results: benefit of logic by phase.....	47

CHAPTER I

INTRODUCTION

Traffic congestion has become a major quality-of-life issue in cities throughout the United States. However, the traditional method of relieving congestion, construction of new lane-miles of roadway, has been unable to keep pace with increasing vehicle demand. The Federal Highway Administration estimates that between 1980 and 2000, the total highway vehicle miles of travel increased by 80 percent. During the same time period, the total highway lane-mileage increased by only 2 percent (1). In many places, adding additional capacity in the form of new lane-miles of roadway is no longer physically, economically, or politically feasible. Therefore, other methods of congestion relief must be explored.

One way to relieve congestion is to improve the operating efficiency of the existing transportation system. There are a variety of actions that can be undertaken to improve operational efficiencies. These improvements are often relatively simple and cost-effective. The optimization of traffic signals, used as a method of control to improve flow at intersections, is one such improvement that can be very cost-effective. Benefit-cost ratios of 20:1 can often result from the optimization of a traffic signal system (2). Two-thirds of all vehicle-miles traveled in the U.S. are on facilities controlled by traffic signals (2); therefore, improvement in the operation of those signals can yield significant results.

However, the basic operation of most traffic signals is based on relatively limited application of available technology. Therefore, even if existing systems

are optimized, they are often still not operating at their full potential. Fundamental changes to the way traffic signal controllers operate are necessary to provide benefits that traditional methods of optimization cannot provide.

Problem Statement

Vehicle actuated detection has been implemented at many signal-controlled intersections in order to respond to variances in the flow of traffic. Through detector actuation, a traffic signal controller is provided with real-time information about traffic. At the majority of signalized intersections, the detectors are relaying nothing more than vehicle presence, or lack thereof. The presence of a vehicle in the detection zone results in a call for service to the controller. Actuated traffic controllers and detection schemes are designed to keep the traffic flowing at some optimal rate, typically near saturation. Under normal operating conditions, this generally results in satisfactory operations.

However, the nature of the data supplied by the detection sensors can be limiting given certain conditions. The Federal Highway Administration's *Signalized Intersection: Informational Guide*, states the following (3):

Actuated signals are dependent on the proper operation of detectors; therefore, they are affected by a stalled vehicle, vehicles involved in a collision, or construction work. This may disrupt operations at a signalized intersection.

It is possible that a detection zone may, for a variety of reasons, be continuously occupied, but the flow of traffic through that zone is minimal or nonexistent due

to some flow restriction. The result could be a green signal indication for a movement that is not efficiently utilizing that green time. FIGURE 1 contrasts a normal flow profile against a restricted flow profile. Shown in FIGURE 1.a is a normal flow profile in which the flow begins to decrease as the sensor is intermittently occupied and then goes to zero when the sensor is no longer occupied. FIGURE 1.b shows a flow profile in which, although the sensor is continuously occupied, the flow goes to zero due to some type of flow restriction. This thesis proposes a method by which a controller would be able to recognize the occurrence of such a restriction and, as a result, terminate the current phase and move on to a conflicting call for service.

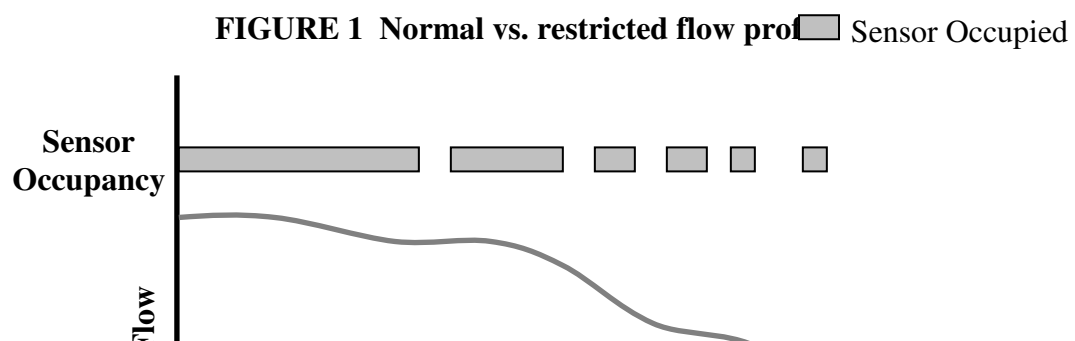
Research Objectives

The goal of this thesis is to examine the concept of traffic signal phase truncation in the event of a flow restriction. The specific objectives of this research are:

- to clearly establish the theory of the concept;
- to identify conditions under which the concept should be implemented;
- to examine ways in which the concept might be implemented; and
- to qualify the benefit of phase truncation.

a) Normal flow profile.

b) Restricted flow profile.



CHAPTER II

BACKGROUND

This chapter examines both the state-of-the-practice and state-of-the-art with respect to traffic sensors and alternative signal control strategies. This chapter begins with an overview of sensors, examining both the current technology and ways in which that technology is being applied. The chapter concludes with an overview of alternative traffic control algorithms that have been developed to improve flow.

Sensors

An important element in the implementation of the concept presented in this thesis is vehicle detection. In order for the algorithm to be applied and to operate correctly, it is necessary to have accurate and efficient means for detection. The following sections provide an overview of current sensor technologies available for vehicle detection.

Current Technology

The majority of sensors currently deployed in traffic control applications are inductive loop detectors. However, in recent years a variety of new detection technologies, which offer an alternative to the traditional inductive loop detector, have been introduced into the market. A 1997 study completed by Middleton et al. provided a comprehensive review of the sensor technologies available and

summarized their performance (4). Several additional reports have recently been published that summarize and evaluate current sensor technologies (5,6,7). The technologies evaluated in these studies include:

- Inductive loop detectors
- Video image detection systems
- Active and passive infrared
- Passive magnetic
- Radar
- Doppler microwave
- Passive acoustic
- Laser
- Sonic
- Piezo electric

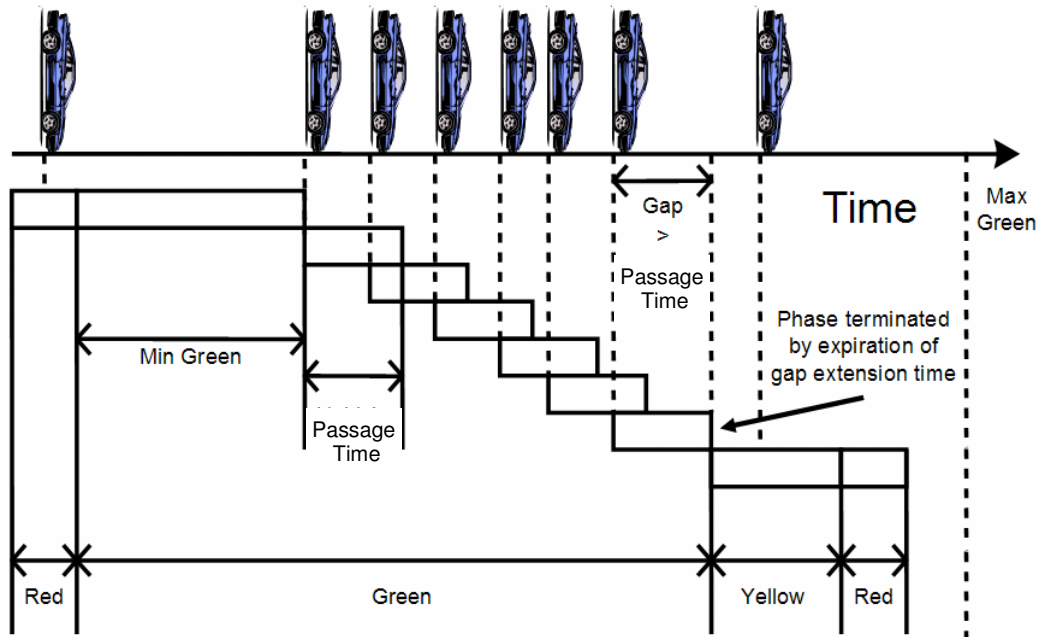
While each of the sensor technologies identified in these studies has unique elements, the intent of this research is to maintain a technology-neutral perspective. Therefore, the concepts and algorithms developed for this project are based upon generic concepts and do not identify the applicability of specific technologies. Implementation of the concept is possible with any sensor that can provide the necessary information, specifically occupancy and flow rate.

Current Applications

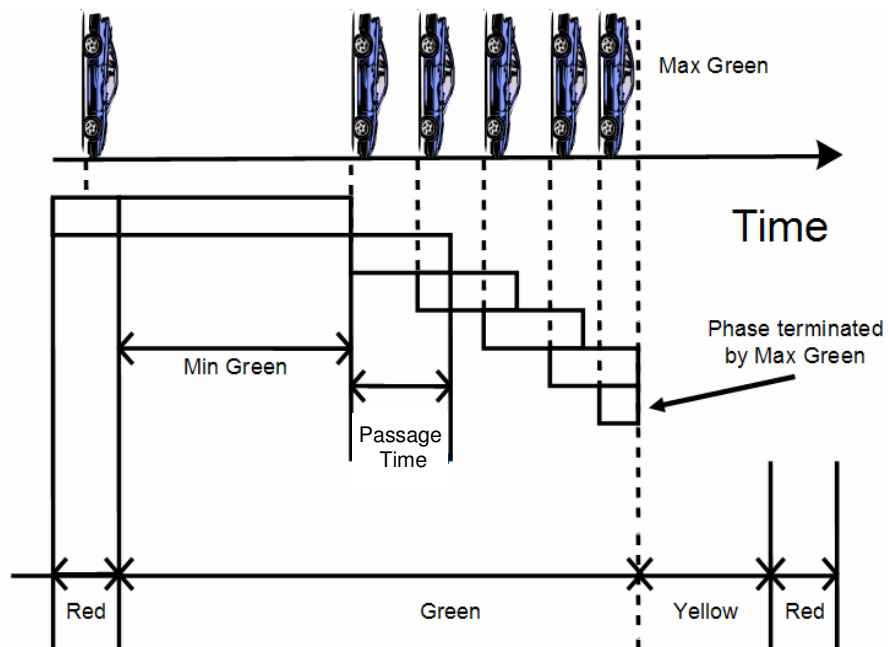
Regardless of the sensor technology used, current detection practice typically utilizes a contact closure to provide information to the controller. The sensor

observes a vehicle's presence in the detection zone and relays that presence to an actuated controller. The corresponding phase is then called to discharge any standing queue. If the time required to discharge the queue is greater than the programmed minimum green interval, the phase is extended by one of several detection schemes and associated controller timings. Dependent upon the ensuing traffic volume and its characteristics, the phase will either gap out or max out, at which point the controller will serve the next phase. FIGURE 2 contrasts these two modes of phase termination using small area detection and a passage time setting (8). FIGURE 2.a details the termination of a phase due to gapout, which occurs when the gap between vehicles is greater than the programmed passage time. Passage time is officially defined by the NTCIP 1202 standard as "the time allowed for a vehicle to travel at a selected speed from the detector to the stop line" (9). This time is added by the controller to the minimum green time for each vehicle actuation not serviced during the minimum green time. FIGURE 2.b demonstrates a phase termination due to the phase reaching the specified maximum green time, also known as max out.

Historically, sensors have been used only to detect the arrival of a vehicle, through either pulse or presence detection. Pulse detection was the original form of detection and provided only a brief contact closure as vehicles passed over the sensor. Presence detection results in a call being placed for the duration of time a vehicle occupies the sensor, reducing the probability of a premature gap out and, depending on the sensor configuration, the need for a significant passage time.



a) Calling and extending a phase until gapout



b) Calling and extending a phase until max out

FIGURE 2 Vehicle detection: gapout vs. max out.

These two detection types, pulse or presence, have also been used in conjunction with controller algorithms to calculate other data such as volume, lane occupancy, gap, headway, and speed. However, with the advent of alternative sensor technologies, it is now possible to directly measure these parameters.

Recent research has identified additional and improved capabilities of existing sensor technologies. Klein reported that some sensor technologies are now capable of providing direct measurement of density, link travel time, vehicle path, vehicle classification, and origin-destination pairs (10). Klein also stated that, using new sensor technology, it is possible to collect vehicle queue, turning movement, and delay information automatically rather than manually. Hellinga reported improved methods for using single-loop and dual-loop detector stations to determine vehicle speed (11). Finally, the Jet Propulsion Laboratory (JPL) conducted a research program to identify the necessary capabilities of sensors for deployment in ITS applications (12). The report found that sensors already deployed or near deployment were capable of reporting vehicle flow rate, average vehicle speed, link travel time, vehicle classification, lane changes, queue length, spatial headway, vehicle deceleration, and origin-destination tracking. Some sensor technologies, such as side fire radar, may not currently operate well as stopbar detectors but are capable of providing flow rate information (8).

Sensors have, for quite some time, been capable of counting the number of vehicles passing through a detection zone. However, this was typically done using point or pulse detection. Advances in detection technology have made vehicle

counting possible using presence detection. Video detection accomplishes this with an algorithm that detects pixel changes in the video feed. Inductive loops utilize an inductive signature of vehicles passing over the loops to count individual vehicles.

The ability to use presence detection to perform vehicle-counting functions has several benefits. First, it allows for the collection of count data while maintaining the benefit of presence detection. Second, it can provide the data necessary to calculate a real time vehicle flow rate. The controller can then use this flow rate information to determine whether a particular intersection is operating at an acceptable flow rate or if some inefficiency is occurring.

Adaptive Signal Control

The majority of traffic signal control systems deployed today are based on pre-determined timing parameters. As explained in the previous section, these parameters are used in a call and extend approach to actuated signal control. The parameters are developed based on experience or a limited amount of historical data and are generally fixed. Therefore, they are not sensitive to random, unforeseen incidents. The result is traffic signal controllers that cannot adapt well to events such as flow restrictions.

To overcome the limitations of current traffic control, a variety of next-generation traffic control strategies have been developed. Included among these is adaptive signal control. A number of adaptive control strategies have been developed and some have been implemented, with varying degrees of success.

The following is a brief summary of several of the more common traffic adaptive control strategies.

SCOOT

SCOOT (Split Cycle Offset Optimisation Technique) was developed by the Transport Research Laboratory in the late 1970's. SCOOT is an on-line traffic control system, which means that it is continuously collecting data and using that data to make changes to the timing control parameters. The SCOOT system is comprised of three optimizers: split, cycle, and offset. The split optimizer generates a decision on split times before the beginning of each phase change and is capable of implementing incremental split changes of 1 to 4 seconds. The offset optimizer operates once per cycle at each intersection. It analyzes the flow profiles for upstream and downstream links and determines whether the offset time should remain the same or if the offset should be advanced or delayed in 4-second increments. The cycle time optimizer operates once every 2.5 to 5 minutes. It considers an entire region and adjusts the cycle time based on the critical intersection in the region. SCOOT is capable of making 4, 8, or 16-second incremental changes. More recent versions of SCOOT have allowed for transit priority. SCOOT has been implemented in more than 170 jurisdictions worldwide (13).

SCATS

SCATS (Sydney Coordinated Adaptive System) was originally developed in Australia. SCATS utilizes a historical traffic model to make real-time adjustments to the signal timings. Information from the previous cycle is used to make adjustments to the upcoming cycle. The SCATS system utilizes a library of predetermined cycle lengths, offsets, and splits, which are selected based upon the current traffic conditions. SCATS seeks to optimize the degree of saturation on each approach to an intersection. Split times are selected to attempt to maintain equal degrees of saturation on competing approaches. The program adjusts offsets such that they complement the current cycle length, phase splits, and directional flow of traffic (14). SCATS is currently being used in over 50 cities worldwide (15).

MOVA

MOVA (Microprocessor Optimised Vehicle Actuation) is another control strategy developed by Transport Research Laboratory. Unlike the SCOOT system, MOVA is designed to operate only at isolated intersections. MOVA operates in one of two modes. Under congested conditions it employs a capacity-maximizing routine, while during uncongested conditions, the system seeks to minimize delay and stops (16).

SPOT

SPOT (Signal Progression Optimization Technology) is an adaptive control system marketed by Peek Traffic and mainly deployed in European countries (17). The SPOT algorithm allows for the system to operate locally at individual intersections or as part of a central system. The SPOT algorithm differs from others in that it was developed primarily as a system to provide public transit priority while still minimizing the overall cost for private vehicles (18). The SPOT system provides priority to transit and emergency vehicles by measuring the relative need versus the potential disruption.

VS-PLUS

The VS-PLUS control system is unique in the way that it defines traffic demand and in the approaches used to service that demand. Rather than defining traffic demand into phases as is traditionally done, VS-PLUS defines demand into traffic streams. These streams can be segmented such that a bus on the same approach as general-purpose traffic can be defined separately. Because individual streams can be serviced by individual control elements (signals), this scheme allows the flexibility to provide transit priority along with a host of other applications. VS-PLUS is also unique in that it replaces the typical ring and barrier structure with a frame signal plan. This control strategy allows VS-PLUS to provide traffic adaptive signal control (19).

Adaptive Left Turn Phasing

While the systems mentioned above provide adaptive signal control in response to all movements, the opportunity also exists to provide selective adaptive control to certain movements. The application of adaptive control to left-turn phasing is one such example. The addition of a protected left-turn phase at an intersection is generally based upon demand during peak periods of traffic flow. Although this protected movement may be necessary for safety and efficiency during the peak period, it is often unnecessary during other parts of the day that experience less left-turn demand and/or larger gaps in opposing through traffic. Traffic engineers often overcome this by omitting the left-turn phase during certain time-of-day plans. However, typical traffic signal controllers are unable to determine whether a protected left-turn phase is necessary based upon real-time traffic conditions. In response to this limitation, researchers at the Texas Transportation Institute have developed an adaptive left-turn algorithm. The routine is designed to measure inputs from sensors and 1) determine if there are adequate gaps in the opposing through traffic and 2) determine if there is adequate left-turn demand to justify a protected turn phase. This adaptive left-turn control strategy has been implemented in Eagle Signal's EPAC 300 controller (20).

Other Adaptive Control Strategies

Numerous other research efforts have resulted in conceptual adaptive control algorithms. TACOS (Traffic Adaptive Control for Oversaturated Intersections Strategy) is a hybrid optimization and rule-based control system that is

unconstrained by cycle times or phase splits (21). Decisions are made at the end of each green interval and are based on queue information. Phases are chosen from a library of phase options and a green time is assigned based on necessary green time to serve the observed queue. TACOS is able to select and serve phases in any order that is deemed necessary.

Researchers at the University of California, Irvine, have developed an adaptive control strategy that seeks to minimize delay for all vehicles (22). The algorithm makes real-time adjustments to phase splits in order to optimize the timings while maintaining a fixed, pre-determined cycle time. The optimization process is heavily dependent on advanced vehicle detection. Sensors identify individual vehicles both upstream and downstream of the signal. Delay calculations are based on this detailed input from the sensors.

Dynamic Split

A concept generally known as Dynamic Split has been implemented by a few traffic controller vendors (23). Essentially, the concept transfers unutilized green time from phases that are not using it to phases in need of additional time. Phase information from the previous two cycles is used to make a determination whether or not to adjust the splits. If a phase terminates prior to the end of its split two cycles in a row, it is placed on a candidate list of phases to lose time allocated to its split. If a phase is forced to terminate two cycles in a row, it is placed on a candidate list of phases to receive extra time. Phases either receive or lose time in specified increments depending on how many times in a row they have been

forced off or have gapped out. A similar concept, known as Dynamic Max Green, adjusts the maximum green time within a predefined range (23).

These are interesting and potentially useful concepts. However, the split and max time adjustments are still made based on historical data (i.e. the previous two cycles). The algorithms for these features do not allow instantaneous responses to traffic incidents. Therefore, split times may not be adjusted until traffic volumes are significantly less than saturation flow. Furthermore, the adjustments are limited to small, incremental changes. Finally, these concepts are limited in that they rely on occupancy rates rather than flow rates.

CHAPTER III

EXPLANATION OF CONCEPT

Although conceptually simple, the notion of phase truncation during flow restriction is significant for several reasons. First, it is a small, incremental approach to better signal timing. Other signal control strategies, developed to be more responsive to traffic conditions and including a variety of adaptive control methods, are complicated and not easily understood or frequently implemented. The concept presented in this thesis, however, works within the current framework of modern signal controllers. Rather than implementing an entirely new control strategy, this concept seeks only to improve the logic of the current strategy, which is largely a call and extend approach.

Second, there are a variety of situations in which this concept would benefit the overall operations of a signalized intersection. Opportunities for benefit from this concept occur wherever there is a flow restriction due to some blockage of traffic. Potential situations in which application of this concept would benefit operations are varied and are presented later in this chapter.

Finally, this concept could be implemented fairly easily and would not require major advancements in traffic controllers. Depending on the control and detector scheme, the logic needed to implement this concept could reside within the sensor hardware, in the controller, or somewhere in between. More detail on the implementation of logic is presented later in this chapter.

Causes of Flow Restriction

There are a variety of events that may lead to a restriction of vehicle flow. These events can vary greatly in length of time. However, the result is the same; green time, which could be utilized by competing phases, is wasted and capacity is reduced. The following section outlines some of the events that could result in a flow restriction.

Disabled or Stalled Vehicles

It is not uncommon for vehicle crashes to occur at signalized intersections. When these crashes occur, drivers are often unable or unwilling to move damaged vehicles out of the travel lane until emergency services arrive. If one or more of the involved vehicles is located in a detection zone, the result could be a constant call for service with no capable flow. This situation could result in multiple cycles during which the corresponding phase reaches the max green without actually serving any vehicles. A similar situation can occur when vehicles stall or experience a mechanical breakdown in the detection zone and are unable to restart quickly.

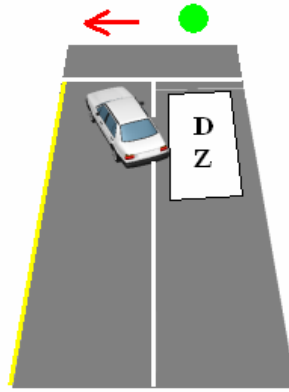
Some jurisdictions have begun using cameras linked to traffic management centers (TMCs) to observe incidents at signalized intersections (24,25). Decisions can then be made to manually adjust the signal timing to account for the interrupted flow until the flow restriction is cleared. However, the cost associated with installing and operating such a system generally limits

application to large, urban areas. Furthermore, this system requires TMC staff to observe and respond to the incident, make a determination of the proper response, implement the temporary changes, and then return the intersection to normal operations once the incident is cleared. If the incident is short-lived (i.e. one or two cycles in length) this manual process may be insufficient.

Detection Zone Encroachment and Crosstalk

Although detection zones are designed on a lane-by-lane basis, actual operation of sensors is not always as precise as designed. It is possible that a vehicle may inadvertently place a call on a detection zone in an adjacent lane. For instance, if a left-turning vehicle is encroaching on a through lane for some reason, that vehicle could be placing a call for service on the through lane but not utilizing the green-time. An example of lane encroachment is shown FIGURE 3.a where a vehicle has made a late lane-change decision and is not fully in the left-turn lane.

Crosstalk can also be an issue with inductive loop sensors. Crosstalk occurs when an inductive loop is activated by the vehicle actuation of a loop in an adjacent lane. The electro-magnetic fields of the two detectors become coupled, thereby resulting in a call on both detectors (10). This effect is of particular concern when lane-widths are less than 10 feet (26). Although crosstalk can generally be avoided through good design and installation, it does still occur and can do so intermittently based on a variety of factors.



a) Encroachment of detector zone by vehicle in adjacent lane.



b) Queues between closely spaced intersections.



c) Flow blockage caused by downstream train.

FIGURE 3 Events resulting in flow restrictions.

Sensor Failures or Misreads

Sensors are susceptible to failure, which may result in a constant call in the absence of any actual traffic. Inductive loops can become “stuck”, which results in a constant call for service. Video image detection systems can experience hanging when a detector indication remains on after a vehicle exits the detection zone and is not reset until another vehicle enters the zone (10). Video detection may also experience misreads when non-vehicle objects (e.g. shadows, debris, etc.) move into the field of detection. Although many detection systems employ algorithms to observe and adapt to sensor failures or misreads, the process is not always instantaneous and may result in several cycles of lost green time. Furthermore, the failure detection algorithms do not explicitly address the problem of flow restriction, which is the focus of this thesis.

Queue Spillback

One of the most common causes of flow restriction at congested intersections is queue spillback. Queue spillback occurs when traffic queued at a downstream intersection backs up and fills the space between the intersections, resulting in vehicles with a green indication but no where to go. Uncoordinated or poorly timed signals are especially likely to experience queue spillback, particularly as the intersection spacing decreases. Queue spillback affects any movement for which the intended destination is being blocked by downstream traffic. FIGURE 3.b depicts an example of a flow restriction caused by queues between closely

spaced signals. In this case, left-turning traffic is unable to utilize available green time due to queuing at a downstream signalized intersection.

Railroad Blockage

The presence of an at-grade railroad crossing near a signalized intersection can have a significant impact on traffic flow. When trains cross at-grade, particularly long and slow-moving freight trains, traffic flow can be significantly restricted. The train preemption sequence in most signal controllers located near a grade crossing omits the movements that would be blocked by a train. However, there are at least two situations in which traffic flow could be restricted but the associated phase would not be omitted.

The first situation in which traffic may be restricted by a train would be on the parallel roadway. During the preemption sequence, the parallel through movement is one of the phases that would receive a green indication. However, if there is a large proportion of right-turning vehicles in a shared through-right lane, a queue of vehicles waiting to turn could develop. These vehicles would be placing a constant call but not moving.

A second scenario could occur when an intersection is close enough to a grade crossing to be impacted by excessive queues but not close enough to be part of a preemption sequence. The Manual on Uniform Traffic Control Devices suggests that all signalized intersections within 200 feet of a railroad grade crossing should be equipped with preemption (27). However, queues at railroad grade crossings often extend further than 200 feet. Therefore, a controller that is

more than 200 feet from the grade crossing and is not being preempted may be giving a green indication to a movement that cannot move due to a train blockage, as shown in FIGURE 3.c.

Other

There are a variety of other events that could result in a disruption of flow at a signalized intersection. Some of these events may be short-term disruptions, only one or two cycle lengths in duration. These events may be caused by temporary blockage from service vehicles including:

- construction vehicles,
- delivery trucks parked on-street,
- school buses, and
- public transit vehicles.

Conditions Warranting Truncation

Before the decision to truncate a phase is made, two conditions must be met: (a) the phase must be green and (b) the detection zone is occupied, but flow is zero or minimal. It is necessary to monitor phase status to ensure that a phase is green before deciding to truncate. Clearly, it would be undesirable to drop a call for service on a phase that is not flowing because vehicles are stopped for a red indication. After confirming the phase status, it is necessary to determine whether the flow across a sensor is adequate to warrant continued service of that phase.

Quality of Traffic Flow

Once the sensor has determined the rate of flow, it is necessary to translate that information into a decision whether or not to truncate the phase. This decision should be based on a user-definable value for what is considered to be a minimum acceptable flow rate. It is beyond the scope of this thesis to define the flow rate at which termination of a restricted phase should occur. In fact the minimum acceptable flow rate will likely vary by jurisdiction and even by location. This number should be user-definable and, ideally, variable by time period and/or event.

It is important to consider where the flow rate is measured. Ideally, the flow rate should be measured at or near the stopbar. This would result in the most responsive and accurate flow rate estimation. If the flow rate estimation is made at a considerable distance from the stopbar, it is conceivable that traffic could be flowing between the detection zone and the stopbar, but the sensor would not detect the flow. This could result in a premature truncation decision.

Consecutive Cycle Truncation

One issue that arises is what should happen to a truncated phase during the next cycle following the initial truncation. Ideally, some mechanism would, prior to the next service of the phase, indicate whether the flow restriction still exists. If the flow was still restricted, the phase could be skipped. However, determining the status of the flow restriction prior to the phase receiving a green indication can be difficult. Until technology advances such that vehicles are able to individually and

directly communicate with traffic control systems, determining whether certain flow restrictions, such as stalled vehicles, are ready to be cleared is not feasible. This would indicate that the phase should be serviced during the following cycle in anticipation that the flow restriction has been cleared. However, other types of flow restriction, such as those resulting from queues at downstream intersections, could be detected using downstream sensors. If the controller is able to determine, using additional detection information, that a restriction has not been cleared, the phase could then be omitted from the next cycle. The ability to determine whether a phase should be served again following truncation is largely dependent on sensor functionality and the nature of the flow restriction.

Implementation of Logic

As mentioned at the beginning of this chapter, implementation of the flow restriction concept would be fairly simple. Assuming that the proper sensor configuration is in place, implementation of the concept would be as simple as applying the necessary algorithm to the information flow between the sensor and the core controller logic. FIGURE 4 diagrams two possible structures for implementation of this concept.

External Logic Structure

The phase truncation algorithm could be located in one of two places external to the controller: as part of the sensor hardware or in a logic evaluation unit between the sensor and the controller. If the algorithm was made part of the sensor

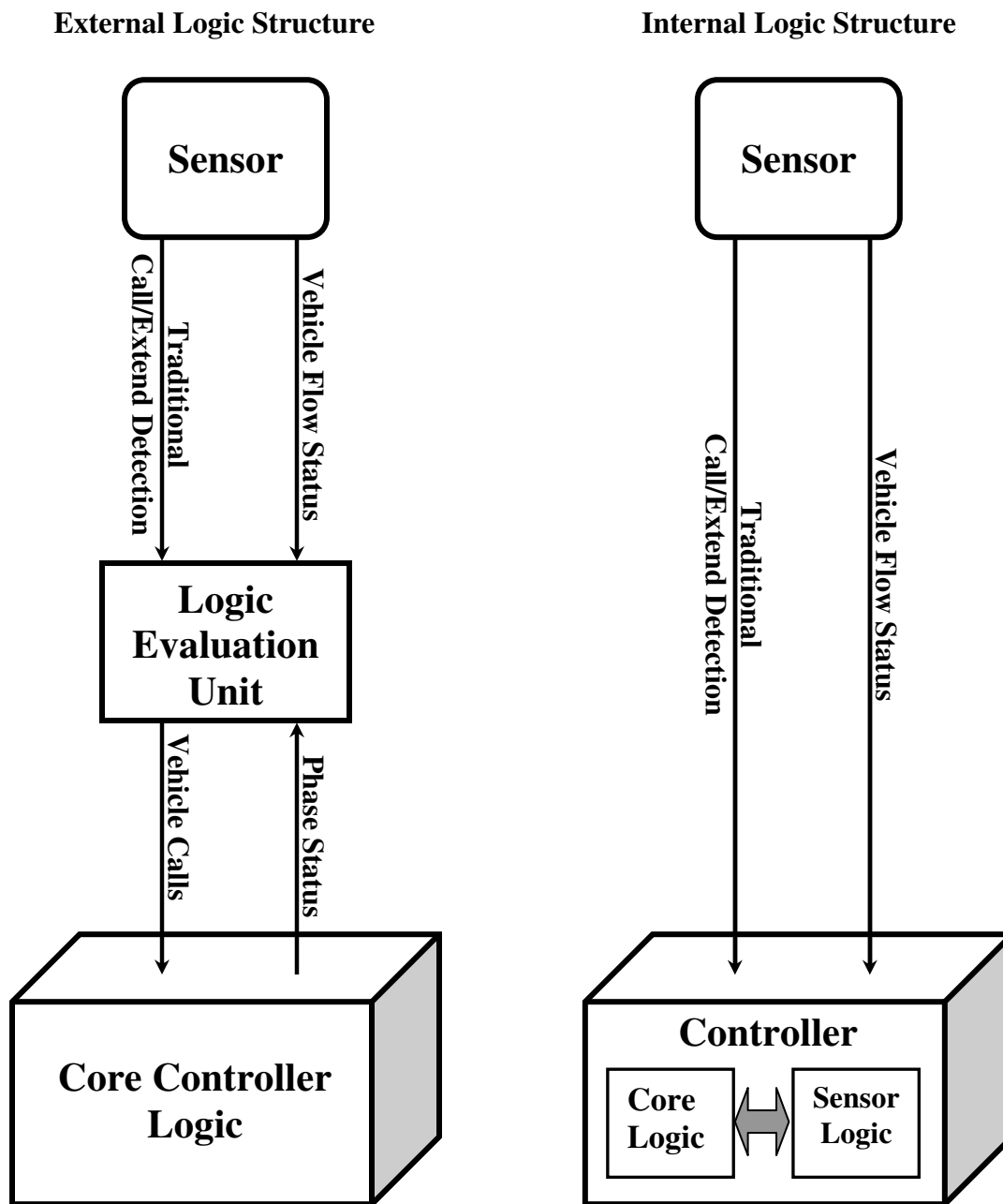


FIGURE 4 Possible logic architecture.

hardware, the sensor would monitor occupancy and flow rate and receive the phase status from the controller to make a decision whether to pass on a call for service. Alternatively, the sensor could pass occupancy and flow rate information to a separate evaluation unit, which would also be monitoring phase status from the controller. This unit would determine whether to relay the call for service on to the controller.

Internal Logic Structure

A second option is to locate the logic internal to the controller, allowing the controller to decide whether or not to truncate a phase. This would require controller manufacturers to implement the phase truncation logic either as part of the core controller logic or as an internal module that monitors sensor information. Locating the logic within the controller would allow advanced control concepts under which the controller could weigh the decision to truncate against other inputs and demands.

Methods of Truncation

Once the decision has been made to truncate, there are a variety of ways in which to terminate a restricted phase. Truncation can be achieved by either dropping the call, forcing off the phase, or in the future, by providing an input into a strategic scheduling algorithm. The method chosen for truncation depends largely upon the type of controller and current operation and the desired result in the event of a flow restriction. The following section briefly outlines three methods for truncation.

Drop the Call

The most basic method for truncating a phase is to simply drop the call for service. Once the determination has been made that a given flow is insufficient due to a restriction, the call can be removed from the controller. This strategy most closely represents what would occur under normal operating conditions when the traffic flow drops below the desired flow and the phase gaps out. Furthermore, it allows the controller to move on to the next phase only if there is not sufficient demand on the complimentary phases and there is a serviceable call on a conflicting phase.

Force-Off the Phase

A more aggressive method for truncating a restricted movement is to apply a force-off to the phase. The force-off method ensures that the phase ends subject to a serviceable conflicting call. However, care should be taken to ensure that the use of a force-off is not detrimental to coordinated operations.

Strategic Control Decision

In future generation controllers, the decision to truncate could be one input into a strategic control algorithm. This strategic algorithm would weigh the input against other factors and decide whether or not to truncate. This method would prevent the controller from moving on to a phase that may be equally restricted. A recent NCHRP research project, 3-66, has examined the application of strategic control in the form of a scheduling algorithm (8). The decision to truncate a phase would

be a tactical input into the strategic scheduler and would be examined against other tactical inputs.

CHAPTER IV

STUDY DESIGN

This chapter outlines the experimental design that was developed to test the phase truncation concept. It should be noted that the experimental portion of this research was intended only to *qualify* the benefit of phase truncation in the event of a flow restriction, not to explicitly *quantify* the benefit. The results of the simulation experiments are helpful as a general indicator of benefit but not as an absolute measure of performance. The possible permutations of volume, intersection geometry, and flow restriction combinations that could be evaluated in order to specify specific conditions requiring phase truncation were beyond the scope of this research.

Modeling Software

Computer simulation was used as a tool to conduct this research. The use of simulation in experimental research has several benefits including:

- the ability to test logic that cannot be implemented in an uncontrolled environment such as the field,
- the ability to test various alternatives under the same traffic volumes and driver characteristics, and
- the ability to easily collect a wealth of data.

The simulation model VISSIM 3.70 was used in this laboratory analysis. VISSIM is used extensively for research applications and allows a great deal of flexibility in modeling capabilities. One of the major advantages of VISSIM is the ability to employ user-defined control algorithms using a language specific to VISSIM, known as vehicle actuated programming (VAP). Because no logic has previously been developed to implement the phase truncation concept, it was necessary to have the ability to develop and implement the logic into the simulation model. The VAP structure allowed this opportunity. The VAP code used to implement this concept will be discussed in more detail later in this chapter. An additional advantage of using VISSIM is the ability to interface the program with an actual traffic controller using hardware-in-the-loop, as discussed in the following section.

Hardware-in-the-Loop

As mentioned previously, a hardware-in-the-loop (HITL) system was used in conjunction with the VISSIM simulation model. The HITL system was developed to overcome the limitations of traffic simulation modeling software. Although each simulation model has built-in logic to emulate signal controllers, none of the software packages available today are capable of emulating the full functionality of a real traffic controller. Therefore, the HITL configuration was developed to replace the internal control logic of the modeling software with an actual controller, thereby allowing simulation software to be used with full controller functionality. The basic configuration of a HITL system is shown in FIGURE 5.

FIGURE 5 Hardware-in-the-loop system.

As shown, the process is a loop of information being sent between three main components: a simulation model, a controller interface device, and a traffic signal controller.

Simulation Model Component

The simulation model component of HITL consists of the software package used to simulate traffic flow and the response of that flow to control mechanisms. The simulation model produces outputs, such as detector calls, and receives inputs, such as phase status. Any simulation package for which a HITL interface has been developed can be used. The most common are CORSIM and VISSIM. As previously mentioned, this research utilized VISSIM in conjunction with a VAP algorithm.

Controller Interface Device Component

The controller interface device (CID) was developed to interface a simulation modeling software with a piece of actual hardware, such as a traffic signal controller (28). The CID process uses a translation file, a text file with the “.cid” extension, to convert inputs and outputs between the modeling software and the controller hardware. The flow of information is passed through the CID hardware, which provides the physical connection between the controller and the computer on which the software is located. The NIATT CID II was used for this research.

Traffic Signal Controller Component

The traffic signal controller component of HITL receives inputs, such as detector calls, and processes those inputs using the internal controller logic. Based on that logic, the controller then produces outputs, such as phase status, to be sent back to the simulation model through the CID. The use of a controller in the process allows the testing of actual signal controller logic including vendor-specific functionalities. Any type of modern traffic controller can be used in a HITL configuration including NEMA, 170, and 2070 controllers. The Econolite ASC/2S-2100 was used in this research.

Study Intersection

The study intersection used for this research was MacArthur Boulevard/Rock Island Road in Irving, TX. A view of the VISSIM model for this intersection, with an overlay of the phase number assignment, is shown in FIGURE 6. The intersection is an eight-phase intersection with Phase 2 being in the southbound direction and the remaining phases following the typical NEMA convention. The intersection was modeled with protected-only left-turns. Although a railroad is shown, no trains were included in the model in order to minimize the variables between simulation runs.

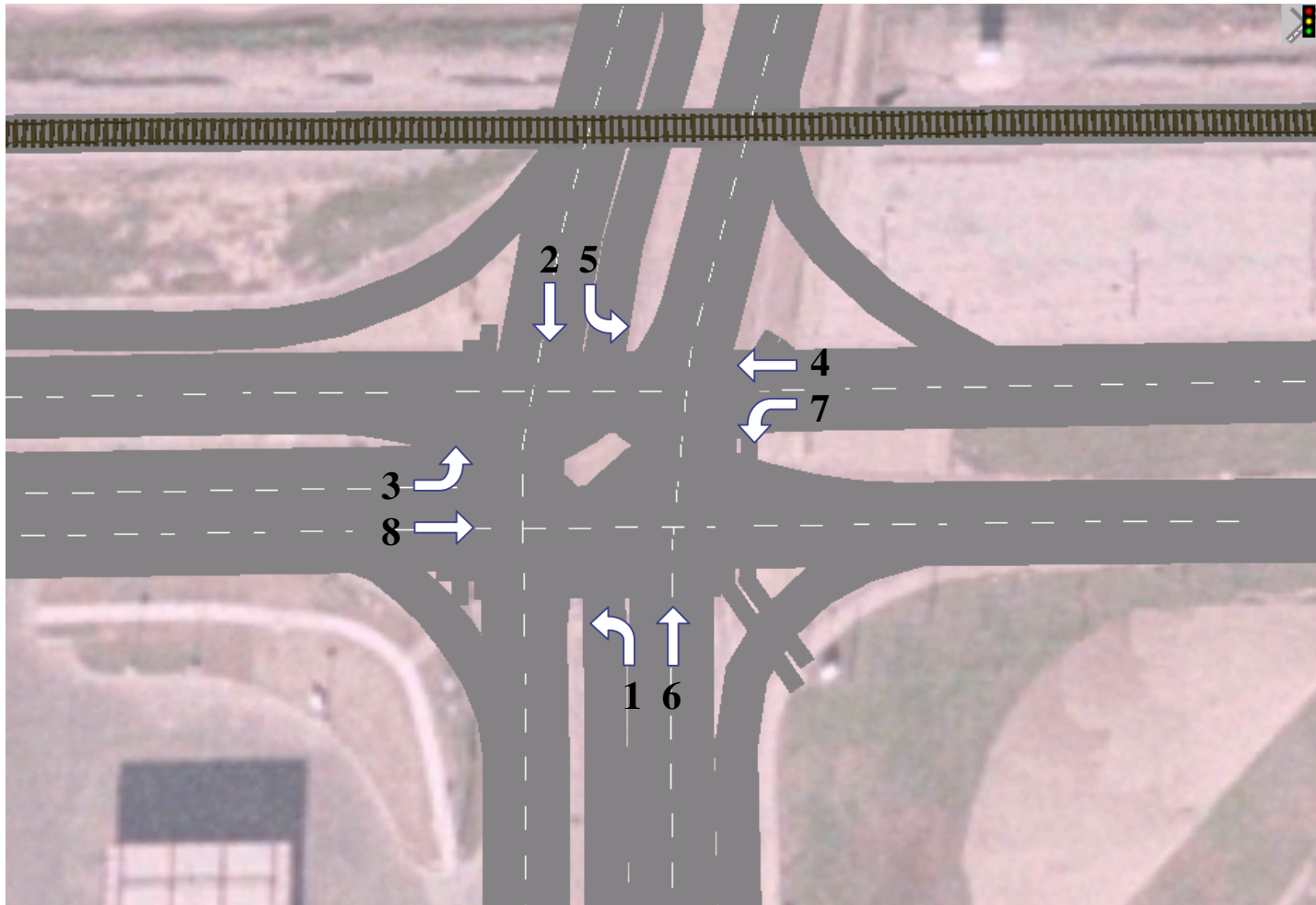


FIGURE 6 Study intersection: Irving, TX.

Simulation Modeling Methods

The following section outlines the methods used to design the VISSIM experiment and to collect the evaluation data.

Traffic Volumes

The purpose of this experiment was to test a concept rather than evaluate the real-world operation of the study intersection. Therefore, experimental traffic volumes were derived using an iterative process. It was necessary to develop traffic volumes that would not cause queues to extend outside the study area but still resulted in conflicting calls such that the phase truncation logic would be sufficiently tested. TABLE 1 summarizes the traffic volumes used in this experiment.

Flow Restriction Method

As was outlined in Chapter 3, there are a variety of conditions under which it would be desirable to truncate a phase due to a flow restriction. For this experiment, it was decided to use a stalled vehicle. Compared to other restrictions, a stalled car provided the most reliable and predictable method of flow restriction for modeling purposes. The model was designed such that a single vehicle would stall on the same approach during the same time period in each of the simulation runs.

TABLE 1 Simulation Traffic Volumes

Northbound			Southbound			Eastbound			Westbound		
<i>LT</i>	<i>TH</i>	<i>RT</i>	<i>LT</i>	<i>TH</i>	<i>RT</i>	<i>LT</i>	<i>TH</i>	<i>RT</i>	<i>LT</i>	<i>TH</i>	<i>RT</i>
125 vph	1100 vph	100 vph	75 vph	775 vph	100 vph	150 vph	975 vph	150 vph	145 vph	475 vph	100 vph

Phase 3, the eastbound left-turn movement, was chosen as the phase on which the restriction would occur. The VISSIM model was designed such that a single vehicle would stall at the Phase 3 stopbar. The stalled vehicle event occurred approximately 15.5 minutes into the simulation and was five minutes in duration. Phase 3 was serviced each cycle following the initial truncation in anticipation that the flow restriction event had been cleared. If, in fact, the flow restriction was still present, the phase was truncated again.

Phase Truncation Logic

As was mentioned, the phase truncation logic was implemented in VISSIM using a VAP algorithm, which was written specifically for this experiment. The basic structure of the logic was as follows:

IF Phase 3 is green,

AND IF Phase 3 detector has been occupied 10 seconds or more,

AND IF there is no flow over the detector,

THEN Drop the call.

The detector information available from the VISSIM model, including occupancy and the number of vehicle front ends passing over the detector, was transmitted to the VAP logic file and used to determine flow. Ten seconds of occupancy was chosen for this experiment and equates to an equivalent flow of 360 vehicles per hour. Also transmitted to the VAP file was the signal status for Phase 3 from the controller. These pieces of information were used by the logic to determine if the conditions for phase truncation had been met. If phase truncation was warranted, the call being placed by the Phase 3 detector was terminated. FIGURE 7 shows a side-by-side simulation of the operational effect of this logic when a vehicle stalls at the stopbar. The simulation on the left is without truncation logic while the one on the right is with logic. It can be observed that the green phase for the with logic simulation is truncated after ten seconds of restricted flow, while the without logic simulation shows the phase being held until the max green period expires. The full VAP code is included in [Appendix A](#).

Click on each video to begin playback.

INSERT No Logic MOVIE CLIP

INSERT Logic MOVIE CLIP

Without truncation logic

With truncation logic

FIGURE 7 VISSIM simulation of phase truncation logic.

Observation Period

Each simulation run was one hour in duration. Of the one-hour simulation period, only the second fifteen minutes was used for evaluation. The first fifteen-minute period (0 – 900 seconds) was used to populate the model and ensure that equilibrium had been achieved before data collection began. As mentioned, the actual data collection occurred during the second-fifteen minute period (900 – 1800 seconds). The third fifteen-minute period (1800 – 2700 seconds) was used to ensure that there were no queues at the end of the evaluation period. The final fifteen-minute period (2700 – 3600 seconds) was used as a clear-out period during which no new traffic was introduced into the model. During this time, all vehicles that had entered the model during the previous time periods were able to exit the model. This period was used to ensure that at the end of each simulation run, there would be no vehicles in the model and, therefore, no calls being placed on the controller. This was desired because a multiple run utility was used to automate the simulation process. To ensure consistency and minimize the number of variables between runs during the multiple run process, it was necessary to ensure that the controller was in the same state at the beginning of each run. This clear-out period ensured that the controller was resting in Phase 2 and 6 green at the beginning of each run.

Data Collection

The VISSIM modeling software allows a variety of data to be collected during the simulation process. The stated purpose of the phase truncation concept presented

in this thesis is to reduce unnecessary delay due to flow restrictions. Therefore, the measure of effectiveness (MOE) chosen for this experiment was average delay per vehicle. The average delay per vehicle values were collected using the node evaluation function in VISSIM. The node evaluation allows a user-defined cordon to be placed around the study intersection. Delay information was collected for all vehicles within the boundaries of the node. The node boundaries were specified such that no queues extended beyond the edges of the node.

CHAPTER V

STUDY RESULTS

This chapter presents the results of the experimental test, which was outlined in the previous chapter. The objective and hypothesis are presented, followed by the experimental results and an analysis of those results.

Experimental Objective

The objective of the VISSIM experiment was to determine if phase truncation in the event of a flow restriction results in reduced delay. Specifically, the experiment was designed to evaluate the average delay per vehicle. As mentioned previously, the intent of the experiment was not to quantify the benefit of the concept. Rather, the objective was only to show that implementation of the concept could be beneficial, using one test scenario as an example.

Experimental Hypothesis

The hypothesis of this experiment is twofold. First, it is hypothesized that the intersection-wide average delay per vehicle will decrease. If the truncation algorithm works as intended, operation of the intersection as a whole should benefit from less green time being wasted on a restricted phase. The second part of the hypothesis contends that the restricted phase, the phase being truncated, will not experience a significant increase in average delay per vehicle. Because the restricted movement is not moving, regardless of whether or not the logic is

being applied, it would be logical that the average delay per vehicle for that phase would not change significantly.

Statistical Analysis

For each logic scenario, both with and without the phase truncation algorithm, 25 simulation runs were made resulting in a total of 50 runs. Each of the 50 runs was made using a different random seed number. Different random seed numbers result in a variance of the distribution of vehicles entering the simulation network. This is done in an attempt to model the stochastic nature of traffic flows.

Using different random seed numbers for each run meant that the two scenarios could not be evaluated as paired samples. Therefore, non-paired statistical tests were used to determine if there was a significant difference between the logic scenarios. The 25 runs for each scenario were broken into nine data sets: one for each phase and one for the intersection as a whole. Each data set was analyzed for normalcy, assuming an $\alpha = 0.01$. If the data was determined to be normal, a non-paired t-test was used to test the means. If the data was deemed to be not normally distributed, the non-parametric Wilcoxon two-sample test was used. The following hypotheses were developed for testing the difference in means between the two scenarios:

- Null hypothesis = $H_0: \mu_1 = \mu_2$
- Alternative hypothesis = $H_a: \mu_1 \neq \mu_2$

If the null hypothesis was accepted, the means were determined to be equal. This indicated there was not a significant benefit derived from using the truncation

logic. If the null hypothesis was rejected, and the alternative hypothesis accepted, the means were found to be different, implying the logic had an impact on intersection operations. The SAS statistical analysis package was used for all statistical tests.

Experimental Results

The average delay for each phase was averaged over the 25 simulation runs. TABLE 2 summarizes the average delay per vehicle for each phase and for the intersection as a whole. The delay values are reported for both the with truncation logic scenario and the without logic scenario. The total average delay per vehicle is weighted to account for the differing volumes on each phase and includes the restricted phase. The delay values for each of the 25 simulation runs for each phase are included as [Appendix B](#).

The statistical tests described in the preceding section were applied to the 25 runs for each phase. TABLE 2 identifies which phases experienced a significant difference, assuming an $\alpha = 0.1$, when the truncation logic was applied. As shown, three out of eight phases, Phases 4, 5, and 8, received a statistically significant benefit from the logic being applied. Furthermore, the intersection as a whole showed a statistically significant benefit with the logic applied. Although the average delay per vehicle for Phases 1, 2, 6, and 7 did decrease, the difference over the 25 runs was not statistically significant. A summary table in [Appendix C](#) provides a detailed description of which phases were found to have a significant

TABLE 2 VISSIM Results: Average Delay per Vehicle by Phase

Phase	Average Delay per Vehicle (s)		Significant Difference*
	<i>No Logic</i>	<i>Logic</i>	
1	94.4	89.8	No
2	53.3	51.8	No
3	184.4	191.9	No
4	83.6	71.2	Yes
5	118.0	106.6	Yes
6	77.0	70.5	No
7	79.5	75.4	No
8	92.3	68.1	Yes
Total	81.7	72.1	Yes

* Alpha = 0.1

difference and which statistical test was used for each data set. [Appendix D](#) contains the SAS output for each data set.

Green Time Allocation

Although the measure of effectiveness used in this research was average delay per vehicle, it is interesting to observe how much the green time allocation for each phase changed with application of the logic. It is logical that with application of the logic, the green time allocation for the restricted phase should decrease while the allocation for all other phases should increase. The results presented in TABLE 3 seem to confirm this hypothesis. The large increases in green time

TABLE 3 VISSIM Results: Average Green Time per Phase

Phase	Average Green Time per Phase (s)		% Change
	<i>No Logic</i>	<i>Logic</i>	
1	6.7	9.4	39 %
2	13.4	23.2	74 %
3	17.9	16.8	-6 %
4	30.6	39.1	28 %
5	4.8	6.6	38 %
6	15.1	25.7	70 %
7	13.3	14.1	7 %
8	39.8	41.8	5 %

allocation shown for Phases 2 and 6 may be skewed due to the operating mode of the controller and the design of the simulation experiment. The controller was set to rest in green for Phases 2 and 6 absent of calls on any other phases. Furthermore, the average green times shown in TABLE 3 were calculated over the entire simulation period rather than the 15-minute observation period for which the average delay per vehicle data was reported. Therefore, no direct relationships or conclusions are being drawn between an increase in green time and a decrease in average delay per vehicle. However, it is intuitive that the two share a relationship and the data in TABLE 3 appears to support this notion.

Analysis of Results

The results presented in the previous section confirm the two-part experimental hypothesis. The intersection did experience a decrease in the total average delay

per vehicle when the truncation logic was applied to the flow restriction. Furthermore, three of the eight phases experienced a reduction in delay with the logic. Although additional analysis under different volume, flow restriction, and signal operating conditions would be needed to draw definitive conclusions, some conclusions can be drawn with regards to the benefit experienced by these three phases. As shown in FIGURE 8, Phase 4 directly conflicts with Phase 3. It is logical that if Phase 3 is truncated, Phase 4 is very likely to directly benefit from that truncation. Phases 5 and 8 likely benefited from a reduced overall cycle length due to the truncation of Phase 3, which was being driven to max green under the scenario without logic. However, this raises the question as to why Phases 1, 2, 6, and 7 did not also show a statistically significant benefit from a reduced cycle length. It is possible that the volume distributions on these phases during the analysis period were not sufficient to result in a statistically significant benefit.

The second part of the hypothesis, which states that the delay for the restricted phase would not increase significantly, was also confirmed. Although not statistically significant, there was a slight increase in the average delay per vehicle for Phase 3, the restricted phase. This could be a result of the truncation logic being applied. Without the logic, the restricted phase is driven to the max green time, resulting in significantly more green time for the phase. This increases the probability that the phase would be green when the restriction was removed and flow continued again. When the logic is applied and the probability of the

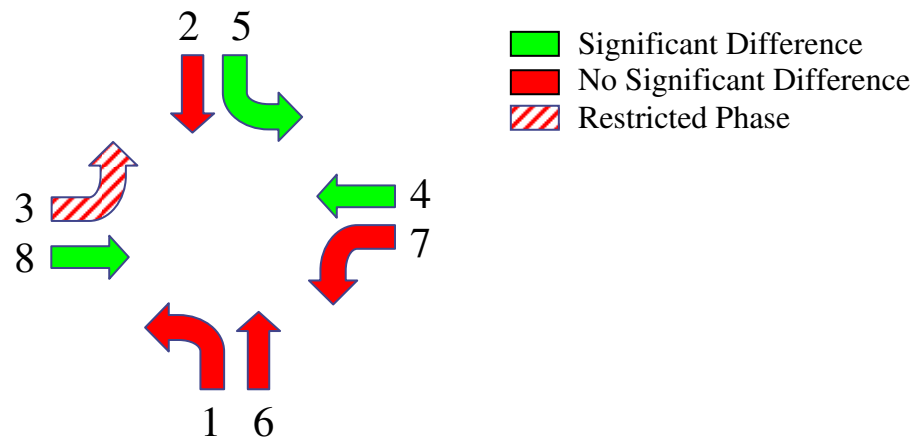


FIGURE 8 VISSIM results: benefit of logic by phase.

phase being green when the restriction is removed decreases, the probability that the queued vehicles will need to wait through another cycle increases. This would result in additional delay being incurred by the vehicle on that phase. It should be noted once again, however, that the increase in average delay per vehicle experienced by Phase 3 was not statistically significant in this experiment.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

As operational efficiency has become increasingly important, relatively small improvements to traffic signal control theory have become proportionately more beneficial. The intent of this thesis has been to present a concept that could be easily implementable and would result in improved traffic signal operations. The following sections summarize the phase truncation concept and the conclusions and recommendations resulting from this research.

Conclusions and Summary

The objective of this thesis was to introduce the phase truncation concept and qualify its benefit under flow restriction events. Based on this research, the following conclusions are drawn.

- The phase truncation concept is a simple, incremental approach to improved signal timing. Other advanced signal control strategies, including a variety of adaptive control methods, are complicated and not easily understood or frequently implemented.
- The phase truncation concept would not require a departure from the current framework of modern signal controllers; rather the concept works within the current call and extend framework by dropping or forcing off

the call in the event of a flow restriction. Furthermore, the concept could be implemented using current detection technology.

- The location of the logic algorithm required for this concept is flexible. The algorithm could be located within the sensor hardware, as a component of the traffic signal controller or as an external logic unit located between the sensor and the controller.
- The phase truncation concept will fit well into future control systems, including the notion of scheduling competing requests for service. The algorithm will be able to make a tactical suggestion to the intelligent scheduler, which can weigh the suggestion against other inputs.
- There are a variety of events that would result in a flow restriction. The algorithm presented in this thesis allows the concept to be applied independent of the nature of the restriction.
- The flow rate at which a phase truncation should occur will likely vary by jurisdiction and even by location. Any algorithm developed to implement this concept should allow the flow rate trigger to be user definable.
- The experimental analysis conducted for this research confirms qualitatively that the application of this concept can result in improved operations under flow restriction events. As shown in this experiment, significant benefit can be achieved when a flow-restricted phase is truncated. The twofold hypothesis presented in this thesis was confirmed. The average delay per vehicle for the intersection decreased when the

phase truncation logic was applied, while the average delay per vehicle for the truncated phase did not increase significantly.

- It should be stated once again that the benefit attributable to the phase truncation logic would most certainly vary at each individual and unique intersection. The derived benefit will likely be dependent on the nature of the flow restriction and the intersection volumes and geometry.

Recommendations

The intent of this thesis was to introduce the phase truncation concept and qualify the benefit of such a concept. Although the concept is fairly simple in theory, additional research would be necessary to develop the concept to the point of implementation. Furthermore, additional experimental analysis would need to be conducted in order to provide a more complete analysis of the potential benefit of this concept. The following suggestions are made in order to guide future research and development of the phase truncation concept.

- As mentioned in this thesis, the algorithm for implementing this concept could potentially be located in one of three places: in the sensor hardware, internal to the controller, or in a logic evaluation unit placed between the sensor and the controller. Additional research may reveal that one of these locations is preferable and would increase the likelihood of implementation.
- Successful implementation of this concept is largely dependent on adequate and reliable vehicle detection schemes. Future research should be

focused on developing recommendations for ideal detection zone configurations for the identification of flow restrictions.

- Defining the minimum flow rate that would trigger a phase truncation was beyond the scope of this research. Furthermore, the flow rate trigger will likely vary by jurisdiction, location, type of flow restriction, and even time of day. However, future research could develop general guidelines to define a range of conditions that warrant phase truncation.
- A more extensive experimental analysis would provide further qualification and, potentially, quantification of the benefit derived from the phase truncation concept. An expanded analysis of volume, geometric, and flow restriction scenarios would further define the potential benefit of this concept. Furthermore, it is recommended that future research should evaluate application of the concept in a coordinated system in order to evaluate the impact on coordination between multiple intersections.

REFERENCES

REFERENCES

1. Federal Highway Administration. FHWA Administrator Testifies That Growing Traffic Congestion Threatens Nation's Economy, Quality of Life. May 21, 2002. <http://www.fhwa.dot.gov/pressroom/fhwa0220.htm>. Accessed February 27, 2005.
2. Federal Highway Administration. Signal Timing Program Plan. November 8, 2004. http://ops.fhwa.dot.gov/traffic_sig_timing/tst_progplan.htm. Accessed February 27, 2005.
3. Rodegerdts, L. A., et al. *Signalized Intersection: Informational Guide*. Report FHWA-HRT-04-091. FHWA, U.S. Department of Transportation, 2004.
4. Middleton, D., M. Shafer, and D. Jasek. *Initial Evaluation of the Existing Technologies for Vehicle Detection*. Report 1715-1. TTI, Texas A&M University, 1997.
5. Middleton, D., and H. Charara. *Detection-Control Strategies for Rural Signalized Intersections TM No. 2: Evaluate Available Technology and Define Detection-Control System*. Report TxDOT Project 0-4022. TxDOT, 2000.
6. Detection Systems: Elemental Approach. *ITS International*, Vol. 23, July/August 1999, pp. 47-50.
7. Middleton, D., and R. Parker. *Vehicle Detector Evaluation*. Report FHWA/TX-03/2119-1. FHWA, U.S. Department of Transportation, 2002.
8. Urbanik, T., et al. *Traffic Signal State Transition Logic Using Enhanced Sensor Information*. NCHRP 3-66 Interim Report. National Cooperative Highway Research Program, 2003.
9. AASHTO, et al. *Object Definitions for Actuated Traffic Signal Controller Units*. NTCIP 1202 v02.18. National Transportation Communications for ITS Protocol, 2004.
10. Klein, L. A. *Sensor Technologies and Data Requirements for ITS*. Artech House, Boston, 2001.
11. Hellinga, B. Improving Freeway Speed Estimates from Single-Loop Detectors. *Journal of Transportation Engineering*, Vol. 128, No. 1, January/February 2002, pp. 58-67.

12. Laboratory, Jet Propulsion. *Traffic Surveillance and Detection Technology Development: Sensor Development Final Report*. FHWA, U.S. Department of Transportation, 1997.
13. United Kingdom Department for Transport. The SCOOT Urban Traffic Control System. Aug. 19, 1999. http://www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_504797.hcsp. Accessed Oct. 20, 2003.
14. Garbacz, R. M. Adaptive Signal Control: What to Expect. Presented at ITE 2002 Annual Meeting and Exhibit, Philadelphia, Pennsylvania, 2002.
15. Tyco Integrated Systems. Traffic Management: SCATS. Undated. http://www.tycointegratedsystems.com.au/products_&_systems.html. Accessed October 15, 2003.
16. Vincent, R. A., and J. R. Pierce. *MOVA: Traffic Responsive, Self-Optimizing Signal Control for Isolated Intersections*. Report 170. Road Research Laboratory, Crowthorne, Berkshire, England, 1988.
17. Pesti, G., et al. *Demonstration of State-of-the-Art Integrated Traffic Management System: Evaluation of the SPOT Adaptive Traffic Control System*. FHWA Priority Technology Project No. 97068. FHWA Nebraska Division, 1999.
18. Kronborg, P., and F. Davidsson. *Improvements for a Scandinavian SPOT Urban Traffic Control System*. Report 2000:4E. TFK – Transport Research Institute, 2000.
19. Verkehrs-Systeme AG. The VS_Plus Control Ideas. June 17, 2003. <http://www.vs-plus.com/e/vsintro.htm>. Accessed Oct. 20, 2003.
20. Urbanik II, T., S. R. Sunkari, K. Barnes, A. C. Meadors. Adaptive Left Turn Phasing. Presented at ITE 2000 Annual Meeting and Exhibit, Nashville, T.N., 2000.
21. Li, H., and P. D. Prevedouros. Traffic Adaptive Control for Oversaturated Isolated Intersections: Model Development and Simulation Testing. *Journal of Transportation Engineering*, Vol. 130, No. 5, September 2004, pp. 594-601.

22. Liu, H. X., J. S. Oh, and W. Recker. Adaptive Control System with On-Line Performance Measure. Presented at 81st Annual Meeting of the Transportation Research Board, Washington, D.C., 2002.
23. Engelbrecht, R. J., S. P. Venglar, and Z. Z. Tian. *Research Report on Improving Diamond Interchange Operations using Advance Controller Features*. Report FHWA/TX-02/4158-1. FHWA, U.S. Department of Transportation, 2001.
24. Peoria Focus Online. Peoria Plans Intelligent Traffic Signals. Fall 2004. <http://www.peoriaaz.com/focus/bulletin1.htm>. Accessed March 10, 2005.
25. Marconi Corporation. Cruise Control. November 22, 2004. http://www.marconi.com/Home/customer_center/Case%20Stud/Enterprise%20Solutions/Transportation/US%20Municipal. Accessed March 10, 2005.
26. Bhagat, V., and D. L. Woods. Loop Detector Crosstalk. *Institute of Transportation Engineers (ITE) Journal*, Vol. 67, No. 2, February 1997, pp. 36-49.
27. *Manual on Uniform Traffic Control Devices: Millennium Edition*. FHWA, U.S. Department of Transportation, Dec. 2002.
28. Bullock, D., and T. Urbanik II. Hardware-in-the-Loop Evaluation of Traffic Signal Systems. Proceedings of the 10th International Conference on Road Transport Information and Control, Commonwealth Institute, London, U.K., 2000.

APPENDICES

Appendix A: VAP Logic Code

```

PROGRAM SCJCOM;
CONST
    Det3Delay = 10.0, /* seconds */
    Det3Flow_Trigger = 360.0, /* vph */
    Time_Period = 110, /* tenth of second */

/* Detectors */

P3Det = 3;

SUBROUTINE SCCOMREC;

/**** Recieve Signal Head State From Controller Communication ****/
/**** 0 = red, 1 = green, 2 = yellow ****/

ch103 := Marker_get( 103 ).

SUBROUTINE SCCOMSEND;

/**** Send Detector State To Controller Communications ****/

Marker_put( 203 , ch203 );
Marker_put( 303 , ch303); /*Long detector*/

/**** SCJ_Detector Record Variables ****/

record_value( 203, ch203 );
record_value( 103, ch103 );
record_value( 3, HW ).

SUBROUTINE Compute_Expressions;

/**** Flow Rate Trigger ****/

IF NOT Init THEN
    SR := 0;
    Init := 1;
    HW := 0;
END;

```

```
/** Headway Timer **/
```

```
start(headwaytimer);
IF (front_ends(P3Det) > 0) THEN
    reset(headwaytimer);
    clear_front_ends(P3Det);
END;
HW := headwaytimer/10;
```

```
/** Forceoff Determination **/
```

```
IF (ch103 = 1) THEN
    IF (SR >= Time_Period) THEN
        IF (HW > (3600/Det3Flow_Trigger)) THEN
            R1FO := 1;
        END;
    ELSE
        R1FO := 0;
        SR := SR + 1;
    END;
ELSE
    SR := 0;
    R1FO := 0;
END;
```

```
/** Conditional Detection **/
```

```
IF detection(4) THEN
    ch303 := 1;
ELSE
    ch303 := 0;
END;
```

```
IF detection(P3Det) THEN
    IF (ch103 = 0) THEN
        IF (occupancy(P3Det) > DeT3Delay) THEN
            ch203 := 1;
        END;
    ELSE
        IF R1FO THEN
            ch203 := 0;
            ch303 := 0; /*Long detector*/
        ELSE
```

```
                ch203 := 1;  
            END;  
        END;  
    ELSE  
        ch203 := 0;  
    END.
```

```
/** Main Program **/
```

```
GOSUB SCCOMREC;  
GOSUB Compute_Expressions;  
GOSUB SCCOMSEND.
```

Appendix B: Results of VISSIM Simulation Runs

Phase 1	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	83.1	163.6	96.8	80.5	137.4	72.0	89.7	104.7	161.5	86.0	112.5	83.9	88.0	78.8	79.6	91.9	71.1	100.3	88.1	80.2	82.9	68.0	94.1	79.3	86.3	94.4
Logic	80.7	73.3	84.4	87.5	87.9	80.0	93.1	107.7	96.9	83.9	82.8	79.4	112.6	169.4	119.8	80.4	77.6	81.7	82.8	74.1	77.8	101.2	84.1	75.0	70.7	89.8
Phase 2	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	60.1	55.2	60.4	54.2	51.2	51.9	49.7	50.9	48.5	52.7	49.0	46.6	55.7	56.9	56.3	51.8	47.2	57.4	46.3	56.6	56.3	53.4	53.0	56.3	54.3	53.3
Logic	44.5	47.3	54.1	52.3	50.2	53.3	49.8	48.8	47.2	50.8	49.2	48.6	44.2	50.2	49.9	48.6	53.9	57.3	52.9	61.1	53.6	67.5	61.3	54.9	42.8	51.8
Phase 3	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	173.3	260.1	153.8	193.3	170.4	147.1	163.0	168.8	142.4	143.7	168.2	207.1	273.9	213.4	235.3	273.7	143.7	112.4	107.7	183.5	191.7	182.6	221.1	167.3	212.5	184.4
Logic	277.4	197.2	160.4	228.3	148.4	206.0	212.8	163.9	169.1	210.7	235.0	243.8	253.4	179.9	150.9	143.1	295.5	103.2	168.6	226.0	150.2	181.9	181.5	128.5	181.9	191.9
Phase 4	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	57.5	88.5	75.1	90.6	143.1	54.2	98.0	99.6	62.7	103.7	72.8	141.3	57.3	94.4	61.6	80.3	55.2	90.4	77.4	67.0	57.2	65.2	108.8	111.4	76.7	83.6
Logic	105.0	63.7	54.2	75.7	42.2	82.1	59.8	73.6	123.5	52.0	103.2	69.6	101.5	58.9	62.5	44.4	77.8	61.1	51.5	90.6	56.9	102.7	61.3	62.5	44.8	71.2
Phase 5	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	127.8	113.2	135.8	96.7	122.3	139.4	112.7	115.8	111.6	109.4	111.5	107.1	115.4	117.3	130.9	119.3	114.6	126.4	133.0	125.0	105.7	127.1	109.0	109.8	113.6	118.0
Logic	102.2	131.0	112.1	110.0	103.8	113.1	106.8	106.0	123.3	113.5	102.5	92.1	108.3	111.8	102.0	82.9	99.1	111.9	104.0	115.5	69.0	128.1	116.4	99.4	101.4	106.6
Phase 6	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	87.9	152.1	78.7	75.2	124.6	60.2	54.5	59.6	127.7	58.1	107.1	85.7	62.0	49.1	63.1	72.8	55.4	79.3	83.4	70.5	57.5	58.1	55.7	62.1	84.6	77.0
Logic	70.0	56.1	60.7	72.6	70.8	60.5	89.6	95.0	56.0	73.0	56.7	61.7	93.7	149.2	98.7	57.4	57.7	64.9	56.0	52.5	69.1	78.7	57.1	56.2	48.7	70.5
Phase 7	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	90.5	67.1	67.5	93.7	69.2	84.2	50.0	113.3	64.8	78.3	70.4	80.4	67.7	85.5	84.7	112.4	62.9	81.7	87.6	75.3	78.3	72.5	115.5	62.2	71.2	79.5
Logic	68.9	89.2	71.8	83.5	72.9	70.4	57.9	94.8	62.2	81.1	68.5	92.1	87.1	77.0	79.1	73.3	66.4	84.7	84.0	64.9	62.9	67.6	88.5	67.3	68.0	75.4
Phase 8	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	90.7	147.3	58.4	59.8	97.4	60.7	67.8	58.0	90.4	67.6	175.1	66.5	207.0	128.1	63.6	91.8	141.6	83.3	89.1	103.5	89.3	62.6	66.9	62.2	78.4	92.3
Logic	65.5	127.6	57.4	67.2	51.9	54.5	45.0	53.9	62.7	64.9	62.1	59.5	61.5	52.2	65.3	53.1	89.1	65.2	62.9	123.0	77.4	69.1	73.9	64.4	72.8	68.1
All Phases	Average Delay per Vehicle (s)																									
Run	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	Mean
No Logic	82.5	122.1	72.3	75.7	104.1	64.7	66.7	70.7	90.5	70.3	106.5	83.2	103.1	85.9	70.0	84.4	82.4	79.7	78.5	83.0	72.5	64.6	77.5	71.8	80.5	81.7
Logic	77.1	81.8	62.2	74.9	60.6	67.3	68.0	75.0	72.5	70.3	72.5	69.1	84.0	89.8	76.1	56.8	80.2	66.9	63.2	86.7	69.2	82.6	70.4	62.9	61.7	72.1

Appendix C: Summary of Statistical Tests

Test	α
Normality	0.01
Equality of Variances	0.1
Equality of Means	0.1

PHASE 1	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	94.4	89.8
Normal	No	No
Equal Variances	Yes	
T-Test or Wilcoxon	Wilcoxon	
Equal Means	Yes	

PHASE 2	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	53.3	51.8
Normal	Yes	Yes
Equal Variances	Yes	
T-Test or Wilcoxon	T-test	
Equal Means	Yes	

PHASE 3	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	184.4	191.9
Normal	Yes	Yes
Equal Variances	Yes	
T-Test or Wilcoxon	T-test	
Equal Means	Yes	

PHASE 4	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	83.6	71.2
Normal	Yes	Yes
Equal Variances	Yes	
T-Test or Wilcoxon	T-test	
Equal Means	No	

PHASE 5	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	118.0	106.6
Normal	Yes	Yes
Equal Variances	Yes	
T-Test or Wilcoxon	T-test	
Equal Means	No	

PHASE 6	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	77.0	70.5
Normal	No	No
Equal Variances	Yes	
T-Test or Wilcoxon	Wilcoxon	
Equal Means	Yes	

PHASE 7	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	79.5	75.4
Normal	Yes	Yes
Equal Variances	No	
T-Test or Wilcoxon	T-Test	
Equal Means	Yes	

PHASE 8	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	92.3	68.1
Normal	No	No
Equal Variances	No	
T-Test or Wilcoxon	Wilcoxon	
Equal Means	No	

ALL PHASES	<i>No Logic</i>	<i>Logic</i>
Mean Delay per Vehicle (s)	81.7	72.1
Normal	No	Yes
Equal Variances	Yes	
T-Test or Wilcoxon	Wilcoxon	
Equal Means	No	

Appendix D: SAS Statistical Analysis Output

Phase 1

```

                                Average Delay per Vehicle (s)
                                Test for Normality on No Logic Data
NORMALITY TESTS FOR VARIABLE Delay

                                N    = 25

Skewness    G1 =    1.889    SQRT(B1) =    1.774    Z =    3.450    P = 0.0006

Kurtosis    G2 =    3.118            B2 =    5.298    Z =    2.342    P = 0.0192

Overall Omnibus Test            K**2 = CHISQ(2 DF) =    17.390    P = 0.0002

                                Average Delay per Vehicle (s)
                                Test for Normality on Logic Data
NORMALITY TESTS FOR VARIABLE Delay

                                N    = 25

Skewness    G1 =    2.664    SQRT(B1) =    2.501    Z =    4.314    P = 0.0000

Kurtosis    G2 =    8.707            B2 =    9.830    Z =    3.714    P = 0.0002

Overall Omnibus Test            K**2 = CHISQ(2 DF) =    32.407    P = 0.0000

                                Average Delay per Vehicle (s)
                                Equality of Variances

                                The GLM Procedure

                                Levene's Test for Homogeneity of Delay Variance
                                ANOVA of Squared Deviations from Group Means

Source              DF      Sum of Squares      Mean Square      F Value      Pr > F

Scenario              1         451096         451096          0.28      0.5972
Error                48      76493351         1593611

                                Wilcoxon Two-Sample Test

                                Statistic              679.5000

                                Normal Approximation
                                Z              0.8053
                                One-Sided Pr > Z              0.2103
                                Two-Sided Pr > |Z|              0.4207

                                t Approximation
                                One-Sided Pr > Z              0.2123
                                Two-Sided Pr > |Z|              0.4246

```

Phase 2

Average Delay per Vehicle (s)
Test for Normality on No Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	-0.133	SQRT(B1) =	-0.125	Z =	-0.305	P =	0.7601
Kurtosis	G2 =	-0.704	B2 =	2.198	Z =	-0.834	P =	0.4046
Overall Omnibus Test			K**2 = CHISQ(2 DF)	=	0.788		P =	0.6744

Average Delay per Vehicle (s)
Test for Normality on Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.996	SQRT(B1) =	0.935	Z =	2.095	P =	0.0361
Kurtosis	G2 =	1.448	B2 =	3.943	Z =	1.501	P =	0.1335
Overall Omnibus Test			K**2 = CHISQ(2 DF)	=	6.642		P =	0.0361

Average Delay per Vehicle (s)
Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	2999.2	2999.2	1.91	0.1733
Error	48	75342.8	1569.6		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > t
Delay	Pooled	Equal	48	1.09	0.2805
Delay	Satterthwaite	Unequal	43	1.09	0.2811

Phase 3

Average Delay per Vehicle (s)
Test for Normality on No Logic Data
NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.488	SQRT(B1) =	0.458	Z =	1.092	P =	0.2749
Kurtosis	G2 =	-0.146	B2 =	2.651	Z =	0.050	P =	0.9603
Overall Omnibus Test			K**2 = CHISQ(2 DF)	=	1.195		P =	0.5503

Average Delay per Vehicle (s)
Test for Normality on Logic Data
NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.404	SQRT(B1) =	0.380	Z =	0.912	P =	0.3618
Kurtosis	G2 =	-0.175	B2 =	2.627	Z =	0.012	P =	0.9906
Overall Omnibus Test			K**2 = CHISQ(2 DF)	=	0.832		P =	0.6598

Average Delay per Vehicle (s)
Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	455304	455304	0.07	0.7990
Error	48	3.3316E8	6940851		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > t
Delay	Pooled	Equal	48	-0.58	0.5652
Delay	Satterthwaite	Unequal	47.9	-0.58	0.5652

Phase 4

Average Delay per Vehicle (s)
Test for Normality on No Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.938	SQRT(B1) =	0.881	Z =	1.989	P =	0.0467
Kurtosis	G2 =	0.503	B2 =	3.177	Z =	0.768	P =	0.4423
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	4.547			P =	0.1029

Average Delay per Vehicle (s)
Test for Normality on Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.809	SQRT(B1) =	0.760	Z =	1.747	P =	0.0806
Kurtosis	G2 =	-0.197	B2 =	2.609	Z =	-0.018	P =	0.9855
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	3.053			P =	0.2173

Average Delay per Vehicle (s)
Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	226812	226812	0.39	0.5363
Error	48	28065911	584706		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > t
Delay	Pooled	Equal	48	1.86	0.0692
Delay	Satterthwaite	Unequal	47.2	1.86	0.0693

Phase 5

Average Delay per Vehicle (s)
Test for Normality on No Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	0.314	SQRT(B1) =	0.295	Z =	0.713	P =	0.4756
Kurtosis	G2 =	-0.349	B2 =	2.486	Z =	-0.234	P =	0.8153
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	0.564			P =	0.7544

Average Delay per Vehicle (s)
Test for Normality on Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	-0.802	SQRT(B1) =	-0.753	Z =	-1.733	P =	0.0831
Kurtosis	G2 =	2.179	B2 =	4.536	Z =	1.919	P =	0.0550
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	6.685			P =	0.0353

Average Delay per Vehicle (s)
Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	44188.2	44188.2	0.76	0.3864
Error	48	2775545	57823.9		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > t
Delay	Pooled	Equal	48	3.40	0.0014
Delay	Satterthwaite	Unequal	45.8	3.40	0.0014

Phase 6

Average Delay per Vehicle (s)
 Test for Normality on No Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 1.535 Sqrt(B1) = 1.441 Z = 2.968 P = 0.0030
 Kurtosis G2 = 1.987 B2 = 4.381 Z = 1.818 P = 0.0690
 Overall Omnibus Test K**2 = CHISQ(2 DF) = 12.115 P = 0.0023

Average Delay per Vehicle (s)
 Test for Normality on Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 2.260 Sqrt(B1) = 2.122 Z = 3.892 P = 0.0001
 Kurtosis G2 = 6.496 B2 = 8.037 Z = 3.313 P = 0.0009
 Overall Omnibus Test K**2 = CHISQ(2 DF) = 26.125 P = 0.0000

Average Delay per Vehicle (s)
 Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
 ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	511524	511524	0.34	0.5598
Error	48	71200575	1483345		

Wilcoxon Two-Sample Test

Statistic 689.5000

Normal Approximation

Z 0.9993

One-Sided Pr > Z 0.1588

Two-Sided Pr > |Z| 0.3176

t Approximation

One-Sided Pr > Z 0.1613

Two-Sided Pr > |Z| 0.3225

Phase 7

Average Delay per Vehicle (s)
 Test for Normality on No Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 0.825 Sqrt(B1) = 0.775 Z = 1.778 P = 0.0755

Kurtosis G2 = 0.532 B2 = 3.200 Z = 0.795 P = 0.4266

Overall Omnibus Test K**2 = CHISQ(2 DF) = 3.792 P = 0.1501

Average Delay per Vehicle (s)
 Test for Normality on Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 0.294 Sqrt(B1) = 0.276 Z = 0.668 P = 0.5044

Kurtosis G2 = -1.063 B2 = 1.908 Z = -1.636 P = 0.1018

Overall Omnibus Test K**2 = CHISQ(2 DF) = 3.123 P = 0.2098

Average Delay per Vehicle (s)
 Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
 ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	296254	296254	3.67	0.0614
Error	48	3874678	80722.5		

T-Tests

Variable	Method	Variances	DF	t Value	Pr > t
Delay	Pooled	Equal	48	1.06	0.2937
Delay	Satterthwaite	Unequal	40.6	1.06	0.2947

Phase 8

Average Delay per Vehicle (s)
 Test for Normality on No Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 1.607 Sqrt(B1) = 1.509 Z = 3.072 P = 0.0021
 Kurtosis G2 = 2.204 B2 = 4.556 Z = 1.932 P = 0.0534
 Overall Omnibus Test K**2 = CHISQ(2 DF) = 13.167 P = 0.0014

Average Delay per Vehicle (s)
 Test for Normality on Logic Data
 NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness G1 = 2.151 Sqrt(B1) = 2.020 Z = 3.768 P = 0.0002
 Kurtosis G2 = 4.800 B2 = 6.662 Z = 2.902 P = 0.0037
 Overall Omnibus Test K**2 = CHISQ(2 DF) = 22.618 P = 0.0000

Average Delay per Vehicle (s)
 Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
 ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	15172249	15172249	3.45	0.0692
Error	48	2.108E8	4391651		

Wilcoxon Two-Sample Test

Statistic 786.5000

Normal Approximation

Z 2.8814
 One-Sided Pr > Z 0.0020
 Two-Sided Pr > |Z| 0.0040

t Approximation

One-Sided Pr > Z 0.0029
 Two-Sided Pr > |Z| 0.0059

All Phases

NORMALITY TESTS FOR VARIABLE Delay

N = 25

Skewness	G1 =	1.293	SQRT(B1) =	1.214	Z =	2.599	P =	0.0093
Kurtosis	G2 =	1.564	B2 =	4.037	Z =	1.574	P =	0.1156
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	9.232			P =	0.0099

Average Delay per Vehicle (s)
Test for Normality on Logic Data

NORMALITY TESTS FOR VARIABLE Delay

N = 24

Skewness	G1 =	0.294	SQRT(B1) =	0.275	Z =	0.656	P =	0.5121
Kurtosis	G2 =	-0.741	B2 =	2.165	Z =	-0.879	P =	0.3795
Overall Omnibus Test			K**2 = CHISQ(2 DF) =	1.202			P =	0.5482

Average Delay per Vehicle (s)
Equality of Variances

The GLM Procedure

Levene's Test for Homogeneity of Delay Variance
ANOVA of Squared Deviations from Group Means

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scenario	1	170596	170596	2.66	0.1098
Error	47	3017763	64207.7		

Wilcoxon Two-Sample Test

Statistic 472.0000

Normal Approximation

Z	-2.5501
One-Sided Pr < Z	0.0054
Two-Sided Pr > Z	0.0108

t Approximation

One-Sided Pr < Z	0.0070
Two-Sided Pr > Z	0.0140

VITA

Scott Glenn Beaird was born in Mesa, Arizona on April 24, 1978. He graduated from Northern Arizona University with a Bachelor of Science Degree in Civil Engineering in 2001. During his undergraduate education, Scott completed internships with both the Oregon and Arizona Departments of Transportation and with the Federal Highway Administration. Following graduation, Scott accepted a position as a Transportation Analyst with Kittelson & Associates, Inc. in Portland, Oregon.

In 2003 Scott took a leave of absence in order to pursue a Master of Science Degree in Civil Engineering at the University of Tennessee. During his graduate studies, Scott was employed as a Graduate Research Assistant and worked primarily on the NCHRP 3-66 research project, *Traffic Signal State Transition Logic Using Enhanced Sensor Information*. While at the University of Tennessee, Scott served as secretary of the ITE student chapter. Scott was also selected as a Dwight D. Eisenhower Transportation Fellow during the course of his graduate studies.

Upon graduation in May 2005, Scott returned to work with Kittelson & Associates, Inc.