5-2005

An Evaluation of Alternative Permissive Periods on Non-Coordinated Phase Performance in Coordinated Traffic Signal Systems

Manoel Mendonca de Castro-Neto
University of Tennessee - Knoxville

Recommended Citation

de Castro-Neto, Manoel Mendonca, "An Evaluation of Alternative Permissive Periods on Non-Coordinated Phase Performance in Coordinated Traffic Signal Systems. " Master's Thesis, University of Tennessee, 2005.
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To the Graduate Council:

I am submitting herewith a thesis written by Manoel Mendonca de Castro-Neto entitled "An Evaluation of Alternative Permissive Periods on Non-Coordinated Phase Performance in Coordinated Traffic Signal Systems." 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:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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Accepted for the Council:

Anne Mayhew

Vice Chancellor and Dean of Graduate Studies

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An Evaluation of Alternative Permissive Periods on Non-Coordinated Phase Performance in Coordinated Traffic Signal Systems.

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

Manoel Mendonca de Castro-Neto

April, 2005

ACKNOWLEDGMENTS

I would to like express my appreciation to those who made substantial contributions to the development of this thesis. First of all, I am very thankful to my academic advisor, Dr. Thomas Urbanik II, for his invaluable help and support during the elaboration of this research. I also would like to extend my gratitude to the other members of my thesis committee: Dr. Arun Chatterjee, Dr. Lee D. Han, and Dr. Felipe Loureiro, for revising and evaluating this work. I also would like to thank my friend, Scott Beaird, for providing me help in many phases of this research.

I am very grateful to Professor Felipe Loureiro for exerting tremendous influence on my academic and professional career.

In conclusion, I am deeply indebted to my parents, Mendonca and Eliane, to my brothers, Abelardo and Vinícius, and to my dear Lina, for having patiently dealt with my absence over the last two years. Without their endless understanding and support, I would have never been able to complete this work.

ABSTRACT

Currently, there are some concerns regarding coordinated-actuated traffic signal operations. First of all, there is no consistent nomenclature to describe coordination modes. Different traffic signal controller manufacturers use different terminologies and their terms are not necessarily meaningful or intuitive. Actually, one can find inconsistency in the terminology used even by a specific manufacturer just by trying to understand (or decipher) the manual. Secondly, and this might be just a consequence of the first concern, it seems that many traffic engineers and technicians are not aware of the particularities and differences among the coordination modes.

The main purpose of this study was to investigate the main issues related to non-coordinated movements of coordinated-actuated traffic signals. A set of terms and definitions including *permissive point* and *permissive period* was proposed. Based on this terminology, three coordination modes were presented and their performances were evaluated for three different volume/capacity (v/c) ratios by using hardware-in-the-loop (HITL) simulation.

Using average vehicle delay as the measure of effectiveness (MOE), statistical analyses indicated that for moderate v/c ratios (0.50), the three coordination modes did not perform differently. For lower v/c ratios, differences among the modes were observed.

The results of this thesis research provides some guidance on the use of coordinated-actuated traffic signal operation by letting traffic engineers and professionals be aware of the various effects that different coordination modes might cause on the intersection performance.

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1. INTRODUCTION

1.1 RESEARCH PROBLEM

In many cities throughout the world, the number of traffic signals in urban areas has been growing in response to the increase in traffic demand, which has been a natural consequence of socio-economic development of most communities. When “properly designed, located, operated, and maintained,” traffic signals generally improve capacity, mobility and safety of the intersections in which they are implemented (1). On the other hand, poorly designed and/or operated traffic signals can cause excessive delay and significantly increase the frequency of collisions (1).

As the number of signalized intersections increases, traffic signal coordination becomes more necessary. Even with well designed signal splits, excellent pavement quality, and good geometry, an arterial street will not provide a good level of service if its closely spaced traffic signals are uncoordinated.

Coordination is often thought and characterized by only three factors: split, cycle, and offset. Based on these three factors, a time-space diagram is developed and the coordination plan is ready to be implemented, which is probably adequate enough when dealing with two-phase fixed-time intersections. However, when the intersections to be coordinated are actuated, i.e., when its non-coordinated movements are actuated, many issues regarding those movements have to be addressed. In fact, a literature review indicated that many studies related to traffic signal coordination have been conducted but just a few of them have dealt with the effects of coordination on the side streets traffic.

As opposed to those with fixed-time type of operation, coordinated-actuated intersections can be controlled by a variety of coordination modes. These modes differ from each other basically in the way they service the non-coord[1] phases and also the pedestrians on the coord phases.

Currently, there are some concerns regarding the use of coordination modes. First of all, there is no consistent nomenclature to describe them. Different traffic signal controller manufacturers use different terminologies and their terms are not necessarily meaningful or intuitive. Actually, one can find inconsistency in the terminology used even by a specific manufacturer just by trying to understand (or decipher) the manual. Secondly, and this might be just a consequence of the first concern, it seems that many traffic engineers and technicians are not aware of the particularities and differences among the coordination modes.

1.2 OBJECTIVES

Based on the problems explained in section 1.1, the objectives of this research are as follows:

1. Provide a concise, consistent, and intuitive terminology and its definitions for traffic signal coordination modes for actuated intersections.
2. Based on the terminology and its definitions, present the operation and issues of three coordination modes
3. Evaluate and ultimately explain the main differences among these modes so they can be properly applied in different traffic situations

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[1] Throughout this text, the term *coord phase* will be often used as an abbreviation of *coordinated phase*.

1.3 ORGANIZATION OF THESIS

This thesis is organized in six chapters. Chapter I includes the research problem and the objectives. Chapter II presents a literature review of traffic signal coordination and hardware-in-the-loop (HITL) traffic simulation. Chapter 3 shows the traffic signal coordination terms and definitions proposed by the author. Chapter 4 presents the three coordination modes considered in this study. Chapter 5 describes the experiment used to compare the modes. Chapter 6 includes summary, conclusions, and recommendations.

2. LITERATURE REVIEW

This chapter presents a literature review about two subjects: traffic signal coordination and hardware-in-the-loop simulation. More emphasis will be given to hardware-in-the-loop simulation because it is a relatively new topic when compared to traffic signal coordination, which has been used since the 1920s (2).

2.1 TRAFFIC SIGNAL COORDINATION

When traffic signals are closely spaced, coordination among them should be provided so that vehicle platoons can efficiently move through the intersections with minimum interruption. It has been common practice to coordinate traffic signals less than one mile apart on major streets (3).

Coordinated intersections can be controlled as either non-actuated (fixed-time), or actuated. While these types of operation result in similar performances for intersections with oversaturated traffic conditions, the type of control chosen may have a strong effect on the performance of the intersections for low traffic periods (4). Each type of control has its pros and cons that should be fully assessed before choosing the one to be implemented.

2.1.1 Fixed-time Traffic Signal Control

In fixed-timed operations, the cycle length, phase sequence and timings (splits) are held constant for each timing plan. Therefore, no vehicle detectors are needed. For fixed-time coordinated intersections, a common cycle length is usually adopted to maintain the reference points (offsets) among the intersections.

2.1.2 Coordinated-actuated Traffic Signal Control

Coordinated-actuated traffic signal control has been used to control many arterial streets. This type of operation normally consists of a non-actuated coordinated phase and one or more actuated phases. The traffic signal dwells (rests) on the non-actuated coordinated phase if there are no calls placed on the actuated ones. Therefore, the non-actuated phases services the major intersection movements while the actuated phases services the minor ones. It should be noted, for completeness, that the coordinated phase may also have an actuated interval following the non-actuated interval. This type of operation is not common.

For typical coordinated operation of actuated traffic signals, the coord movements are usually non-actuated and the non-coord movements are actuated. Besides split, cycle, and offset, other coordination parameters affect how phases of a coordinated-actuated intersection are serviced. A review of the literature indicates that a general and consistent terminology of these parameters is lacking. Terms such as *permissive period* and *force-off point* have been used without good definitions. Besides, different traffic signal controllers and micro-simulation packages manuals do not provide a clear understanding of how those parameters affect the intersection operation.

2.2 HARDWARE-IN-THE-LOOP (HITL) TRAFFIC SIMULATION

Many traffic simulation software packages have been developed and used over the last three decades due to ready availability of computer processing power (5). Although simulation cannot exactly replicate field characteristics, traffic simulation has attracted many traffic engineers and analysts for several reasons. First of all, microscopic traffic simulation has provided transportation professionals a relatively easy and cost-effective way of testing different traffic control strategies before field deployment. Secondly, simulation packages provide several measures of effectiveness (MOE), which can be used to evaluate which control strategies should be implemented.

Current microscopic simulation packages include internal traffic control logic (emulators) that provide only basic real-time control functions. Current traffic controllers contain many advanced features such as advanced signal coordination modes, signal preemption capabilities, cycle transition algorithms, and diamond interchange control that those simulators do not adequately emulate.

Implementing those advanced algorithms included in modern controllers in the traffic simulation models might not be feasible by the fact that each controller has its own specific algorithms, features and peculiarities. Researchers and professionals have successfully addressed this problem by using hardware-in-the-loop (HITL) simulation. Generally speaking, HITL simulation consists of a computer simulation in which a part of the simulation is replaced with a piece of hardware. It has been used for many years by several industry fields such as aerospace, and defense (6).

Hardware-in-the-loop *traffic* simulation consists of replacing the emulation logic included in the simulation model with real traffic controller (hardware). Vehicles and detectors modeled in the simulation software generate detector actuations that are sent to the controller, which reacts to them as if they were real calls and sends back updated phase indication to the simulation model. A third component is required to interface the computer running the simulation software with the controller, called a Controller Interface Device (CID).

Figure 2-1 illustrates the HITL traffic simulation concept. In this type of system, every detector and phase indication used in the simulation model corresponds to a detector and a phase on the controller.

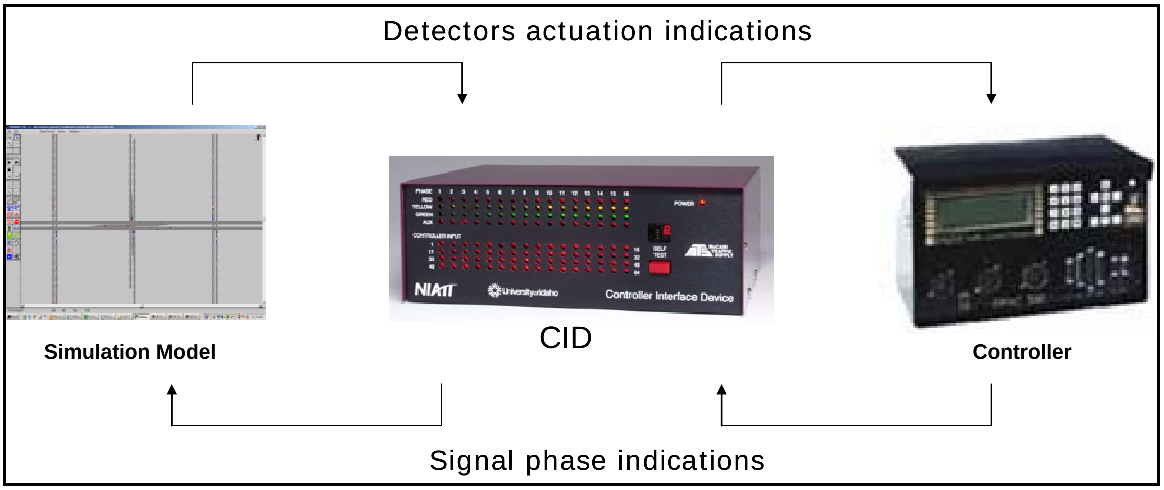

Figure 2-1: HITL traffic simulation concept

2.2.1 Controller Interface Device (CID)

As previously stated, the CID is a critical part of the system as it allows communication between the simulation model and the traffic controller. The CID used in this research project is the Idaho CID II developed by the National Institute for Advanced Transportation Technology (NIATT), University of Idaho. This CID provides interface between 170, 2070, NEMA TS1 and TS2 controllers, and a PC running Windows 98, Windows ME, Windows 2000, or Windows XP (7).

The data flow between the PC and the CID is made over a Universal Serial Bus (USB) cable and the data flow between the CID and the controller is made over cables connecting them.

Besides providing an interface between controllers and microscopic simulation models, the NIATT CID II also works as a programmable suitcase tester. This PC-based programmable suitcase tester software provides an easy way of testing the traffic controller features by allowing controller inputs to be placed from the PC. Displays of phase and detector call indications are displayed on both the suitcase tester software screen and the CID front panel.

Experimental studies have been conducted in order to assess whether the implementation of traffic signal control hardware (external controller) introduces errors in the MOE results. Bullock et al (8, 9) compared MOE data for fixed time and actuated control using both internal simulation model and the hardware-in-the-loop simulation. No statistically significant differences were found, which suggests that the HITL environment did not affects the simulation results.

2.2.2 Some HITL Traffic Simulation Applications

One of the first successful HITL applications in traffic studies was done by Urbanik et al (10) in 1995 as part of a Texas A&M University Research Center project. This study evaluated new real-time control concepts for diamond interchanges and used the TexSIM simulation model interfaced with a controller by using wires to connect the PC to the controller. At that time a commercial CID such as the CID II had not been developed yet.

Also at the Texas A&M University ITS Research Center of Excellence, another HITL experiment was conducted by Koonce et al (11) in 1998. This research basically evaluated different control strategies for diamond interchange operations. Because of the controller features and settings used, it would have been impossible to conduct the simulations without using a HITL system. The HITL procedure in the study was validated by a comparison of delays estimated by the simulation model with delays observed in the field.

Since these pioneering efforts, HITL traffic simulation has been used in many traffic signal system projects including ramp metering control, bus priority, traffic signal transition algorithms, preemption strategies, and alternative timing. Some recent research projects involving HITL procedures have been conducted at the ITS Laboratory of the University of Tennessee Knoxville, including three experiments that were part of the National Cooperative Research Program (NCHRP) project 3-66 entitled Signal State Transition Logic Using Enhanced Sensor Information (12). The HITL system consisted of the VISSIM 3.70 software, a NIATT CID II and an Econolite ASC2 controller. The first experiment evaluated the benefit of advanced railroad preemption with gate-down confirmation, concluding that this type of preemption system eliminates the preempt-trap problem. The second experiment evaluated the benefits of lane-by-lane operation, which permits multiple lanes of an approach to gap out independently. In the third experiment, the “downstream flow restriction” concept was analyzed, which allows the controller to terminate or skip a phase in case the traffic on that phase can not leave the intersection due to congestion, accident, or any other reason. For both the railroad preemption and the downstream flow restriction experiments, external VAP (Vehicle Advanced Programming) logics were implemented because the controller itself did not provide the advanced strategies that were evaluated.

2.2.3 Advantages and Disadvantages of HITL Simulation

When compared with regular traffic simulation, HITL traffic simulation offers valuable advantages. For instance: they can be used to:

- Increase realism of simulation. A real controller is used to control the signal timing of the simulation model, making the simulation more realistic than the simulations without the hardware-in-the-loop implemented. In a HITL system, the controller responds to detector calls generated by the simulation model as if they were generated by real detectors;
- Evaluate and test if a controller feature works as expected before field deployment;

- Compare, evaluate, and analyze in the laboratory different advanced control alternatives before implementing them in the field;
- Train traffic signal control professionals. HITL procedure can be an excellent education tool by allowing students and professionals to learn from “what-if” scenarios. New professionals can learn specific controller functionalities without being concerned about making mistakes.

Among the disadvantages of using HITL systems, it can be said that:

- HITL simulations are more time-consuming as they have to run in real time. As opposed to software-only simulations, in which the simulation model runs a simulation time interval as fast as it can, hardware-in-the-loop simulations require that the simulation run in real time to ensure that the external controller and the simulation are synchronized;

In simulations with large networks, more computer power may be required to ensure that the simulations run In real time.

3. TERMS AND DEFINITIONS

As mentioned in chapters 1 and 2, different traffic controller manufacturers use their own terminologies to describe their signal coordination features. Therefore, the first need in this research is to propose a set of precise terms and definitions for the purpose of better understanding of the issues involved in the coordinated-actuated control. While there might not be agreement on the “correctness” of the definitions, focus is on being as precise as possible.

For the purposes of this study, the traditional definition of offset reference, the beginning of the coord phase, will be used. However, the basic issues being explored are independent of the reference used. Even tough the main topic of this study is traffic signal coordination, the main issues in this study is not the coordinated movements themselves, but on the actuated non-coordinated movements of a single intersection.

3.1 CHARACTERIZING COORDINATED PHASES

A coord phase can be characterized according to its beginning and to its end. The *beginning* of a coord phase can be characterized as either:

- *Fixed*: coord phase starts exactly at t=0 (beginning of the cycle), or
- *Floating*: coord phase can start earlier, but no later, than t=0 (early return to the green is possible).

The *end* of a coord phase can be either:

- *Non-Actuated*: the controller decides to release[2] as soon as calls are placed on a non-

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[2] The controller *releases* when it leaves the coord phases to service a non-coord phase.

coord phase during its Permissive Period (PPer) which is defined in section 3.2, or

- Actuated: the end portion of the coord phase is actuated. After the programmed fixed-time for the coord phase has timed, the controller checks if passage timer on the coord phase has expired. If any unexpired calls are still present, the controller will extend the coord phase for as long as the maximum time period for the actuated period has not been reached. Obviously, this type of operation requires vehicle detection on the main street to extend the coord phase during the actuated period.

It is also important to realize that there are different ways to handle pedestrian walk interval during the coord phase relative to the coordination modes discussed in chapter 4. All variations will not be discussed in this text.

3.2 PERMISSIVE POINT (PPT) AND PERMISSIVE PERIOD (PPER) DEFINITIONS

The first definition to be proposed is the definition of Permissive Point. The *Permissive Point (PPt)* of a non-coord phase is defined, with respect to the offset, as the first moment when the controller is able to release to service that non-coord phase if there is a call on it.

The next definition is for the term *Permissive Period (PPer)*. The PPer of a non-coord phase is the portion of the cycle length during which the controller is able to release to service that phase. This period begins timing at the PPt. Therefore, if the controller is in the coord phase, it will release from the coord phase to service a non-cord phase as long as a call is placed no later than the end of its PPer.

The complexity with the PPer’s occurs when more than one non-coord phase exists. The beginning and ending times of the PPer’s can be selected in order to determine both when and how long each non-coord phase can run when there is slack.

Slack occurs when either the cycle length is longer than required due to system considerations at other intersections or when the traffic demand is less than current cycle length can accommodate.

The service of an individual phase can be constrained so it does not operate early by definition of its PPt. Once a phase is operating, the alternatives include extending or dwelling in the current phase, or moving on to another phase. Early return to the coord phase, commonly called as ”early return to the green”, occurs when one or more of the non-coord phases end early (or skip) due to demand less than the splits can accommodate. While early return to the green is common, it can be avoided. The controller could dwell in a non-coord phase if desired. One case where dwelling might be desirable would be if a cross street coordination plan was desired.

As illustrated in chapter 4, the PPer’s, may be opened for all non-coord phases either simultaneously or sequentially. Their duration might also vary.

It is essential to state that both PPt and PPer apply just to the first non-coord phase to be serviced. In other words, once the controller releases and a non-coord phase is serviced, the subsequent ones will be serviced normally if calls exist without following their PPer´s. The reason for that is, once the coord phases releases, the controller must dwell in the current phase, sequence to the next phase with a call, or return to the coordinated phase. This is the basic nature of most existing controller logic.

3.3 CHARACTERIZING NON-COORDINATED PHASES

The *beginning* of a non-coord phase depends either on its PPer, when this phase is the first one to be serviced in the cycle, or on the end of the previous non-coord phase serviced. In a coordinated-actuated intersection, a non-coord phase can have either a:

- *Fixed PPer*: the PPer starting (PPt) and ending positions occurs at the same points in every cycle, or a
- *Floating PPer*: the PPer starting (PPt) and ending positions can vary cycle by cycle due to the actuated portion of the coord phases.

The ending position of a non-coord phase is determined from the starting position subject to either a selected maximum duration based on a phase based maximum or a split based maximum.

Depending on the specific times and traffic demand, the ending points of a non-coord phase may vary. For example, under heavy traffic on all phases, phases should run for their assigned programmed split time. However, if a preceding non coord phase is shorter than programmed due to demand, or skipped due to absence of calls, there is slack that has to be allocated to some phase. In this sense, the *end* of a non-coordinated phase depends on one of the following force-off types:

- *Floating force-offs*: the non-coord phase can not run longer than its programmed split time. In other words, none of the non-coord phases get any slack time. That is to say, if there is slack from a previous non-coordinated phase, the slack is assigned to the beginning of the next coordinated phase.
- *Fixed force-offs*: the non-coord phase can be extended beyond its programmed split time, but end no later than a fixed position in the cycle. In this case, the phase would get extra time if needed by using the slack from an earlier phase.

These definitions and concepts will hopefully become clearer to the reader in chapter 4, where three possible coordination modes will be graphically presented and explained

4. THREE COORDINATION MODES

A myriad of coordination modes could be created just by varying PPt position, PPer length, and force-off types and points. This chapter presents the three coordination modes analyzed in this study. Each coordination mode is named according to the terminology proposed in chapter 3. These three modes can be implemented in a number of different ways. They may not all be available in every controller software.

The intersection that will be used to illustrate the operation of the coordination modes has the following timing characteristics:

- Dual ring, equal duration in both rings for simplicity. Coord phases: 2+6. Non-coord phases: 3+7, 4+8, and 1+5 (see Figure 4-1).
- Cord phases (non-actuated): minimum green of 35 sec.
- Vehicle clearance interval (yellow plus all red) for all phases: 5 sec.
- Non-coord phases (actuated): programmed split time 20 sec (15 sec of green plus 5 sec of vehicle clearance) and minimum green of 10 sec.
- Flashing don’t walk (FDW), if any: 10 sec.

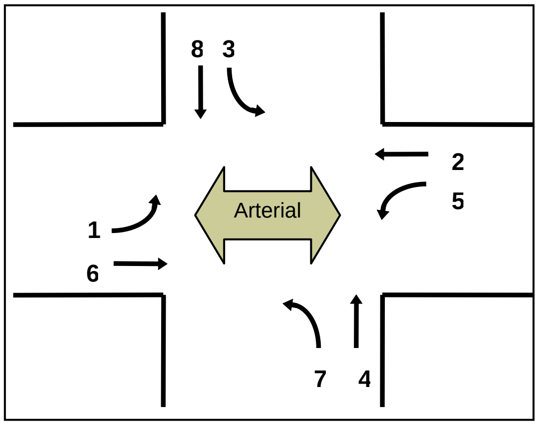

Figure 4-1: Intersection phasing.

4.1 MODE 1 (M1): SIMULTANEOUS FIXED PPt WITH MAXIMUM PPer'S AND COORD RESTING IN WALK.

Coord Phases:

- *Beginning*: floating.
- *End*: non-actuated.
- *Pedestrian*: Rest (dwell) in walk.

Non-Coord Phases:

- *Beginning*: fixed PPer's and simultaneous PPt's.
- *End*: either floating force-off or fixed force-off can be selected.
- *PPer Duration*: Maximum.

Considerations about the Mode 1 (M1)

In this mode, the PPer of a non-coord phase opens as soon as the controller is able to service the programmed time of that phase and that of the subsequent ones. The PPer of a non-coord phase closes no later than the controller is still able to service the minimum time for that phase and the programmed time for all subsequent phases.

The coord phase walk dwells in WALK until the controller decides to release. As soon as the controller decides to leave the coord phases, FDW starts timing, followed by vehicle clearance (yellow plus all red), and then the non-coord phase is serviced. Whereas this is a pedestrian friendly mode, non-coord phase calls need to occur earlier in the cycle in order to be serviced. Besides, non-coord calls have to wait at least the pedestrian clearance time (FDW) and the vehicle clearance time to be serviced. Figure 4-2 shows all PPer´s opening simultaneously at 25 sec, which is the PPt point for all non-coord phases. In this mode the controller needs to decide earlier whether either to

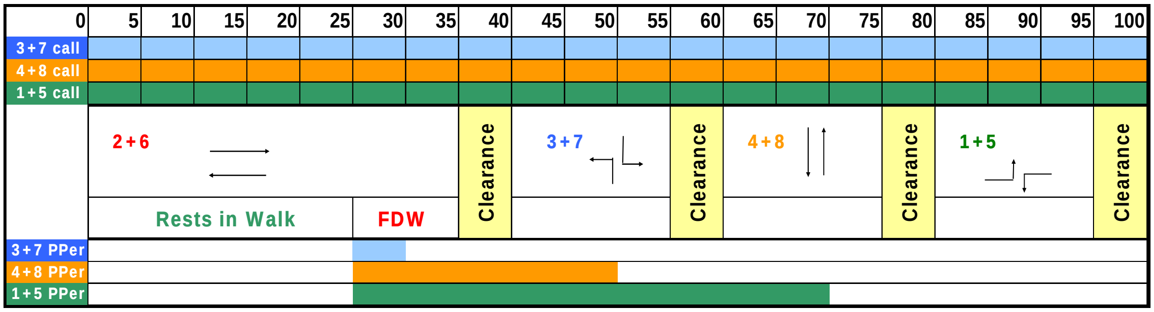

Figure 4-2: Mode 1. Constant calls on all phases.

service or skip a phase, which may lead to non-coord phase being skipped on the current cycle under very light traffic.

Figure 4-2 shows a congested traffic situation in which constant calls are placed in all phases. The coord phase displays WALK until t=25 sec. At that time, the controller decides to release because there is a non-coord call at the beginning of 3+7 PPer. Therefore, the controller brings up FDW for ten seconds and vehicle clearance for 5 seconds. Then at t=40 sec phases 3+7 are serviced. They run for their programmed split time (20 sec) and phases 4+8 are serviced at t=60 sec. They also run for their programmed split time and is forced-off so phases 1+5 are serviced at t=80 sec. The coord phases 2+6 returns at t=100 sec.

Figure 4-3 shows a case where the *floating force-off* is provided. Calls on phases 1+5 are placed at t=40sec, which is within 1+5 PPer. Then, at that time the controller decides to release, bringing up pedestrian and vehicle clearance intervals. The controller services phases 1+5 at t=55 sec. Even though constant calls are still being placed on phases 1+5, these phases are forced-off after their programmed split time (20 sec.). Therefore, the coord phases 2+6 returned 25 seconds earlier at t=75 sec. Notice there would still be available time within the cycle for the controller to continue servicing phases 1+5.

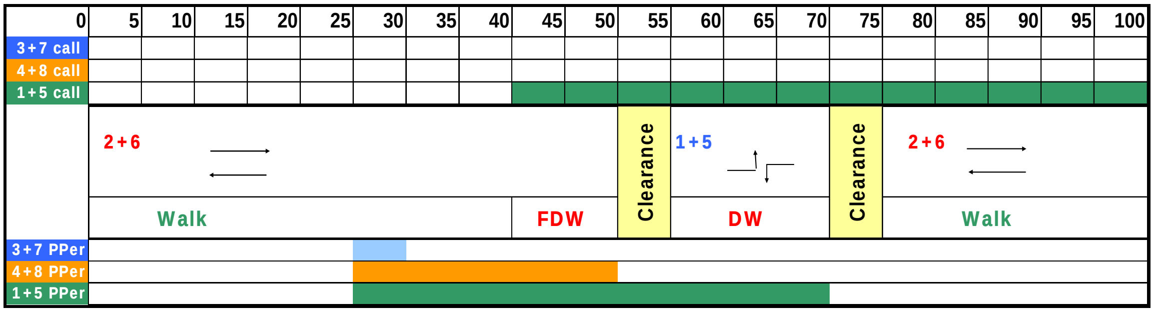

Figure 4-3: Mode 1 with floating force-off. Constant calls on phases 1+5 starting at 40 seconds.

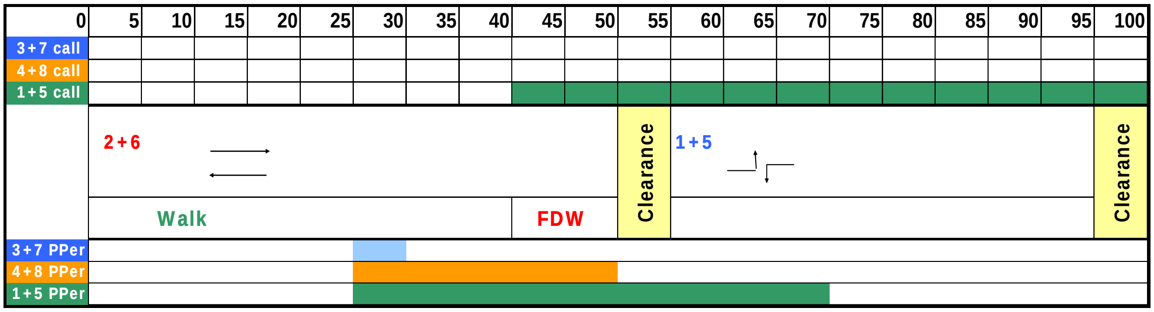

Figure 4-4: Mode 1 with fixed force-off. Constant calls on phases 1+5 starting at 40 seconds.

In order to allow phases 1+5 to continue beyond its programmed split time, *fixed force-off* could be selected for the non-coord phases, allowing phases 1+5 in the example to be extended until a fixed position in the cycle, which in this case is at the end of the cycle for phases 1+5. This case is shown in figure 4-4.

4.2 MODE 2 (M2): SEQUENTIAL FIXED PPt WITH SHORT PPer'S. COORD RESTING IN DON'T WALK

Coord Phases:

- *Beginning:* floating.
- *End*: non-actuated
- *Pedestrian*: Rest (dwell) in Don't Walk.

Non-Coord Phases:

- *Beginning*: PPt´s are fixed and sequential.
- *End*: either floating force-off or fixed force-off can be selected.
- *PPer Duration*: Minimum.

Considerations about the Mode 2 (M2)

The example used will be based on the coord phase dwelling in Don’t Walk. As soon as the controller decides to release, it brings up only the vehicle clearance time (5 sec) before servicing the demanding phase. Therefore, since the controller does not have to time the FDW, the PPer´s can close later within the cycle in this mode. Since the coord phases rest in DON’T WALK, it can be said this is less pedestrian friendly mode. Like in Mode 1, in Mode 2 the PPer of a non-coord phase closes when the controller is still able to service that phase for its minimum time and the subsequent phases for their programmed split time (20 sec.). Figure 4-5 illustrates mode 2 on traffic saturation case. The cycle is the same as that of Mode 1, shown in Figure 4-2.

As opposed to those in mode 1, the PPer´s in mode 2 do not overlap each other, they occur sequentially. When compared to Mode 1, mode 2 reduces early return to the green, because the PPer’s occur later, allowing the non-coord phases 4+8 and 1+5 to be serviced later within the cycle. As shown in Figure 4-6, a disadvantage of this mode is that a vehicle on the side street could wait longer to be serviced while the unused green might be running on the main street. See that despite the constant calls on phases 1+5 starting at t=40 sec, the controller does not decide to release until 1+5 PPer opens at t=75 sec, when the controller then brings up the vehicle clearance and starts serving phases 1+5 at t=80sec.

In this mode, because of its PPer’s configuration, the floating- and fixed force off

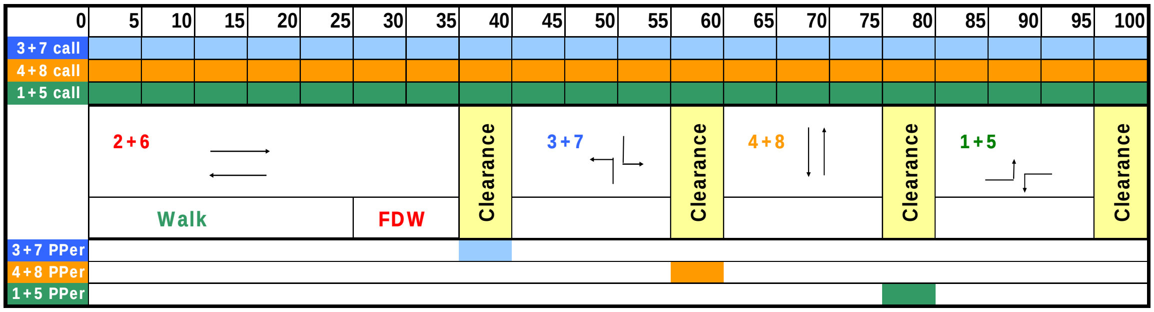

Figure 4-5: Mode 2. Constant calls on all phases.

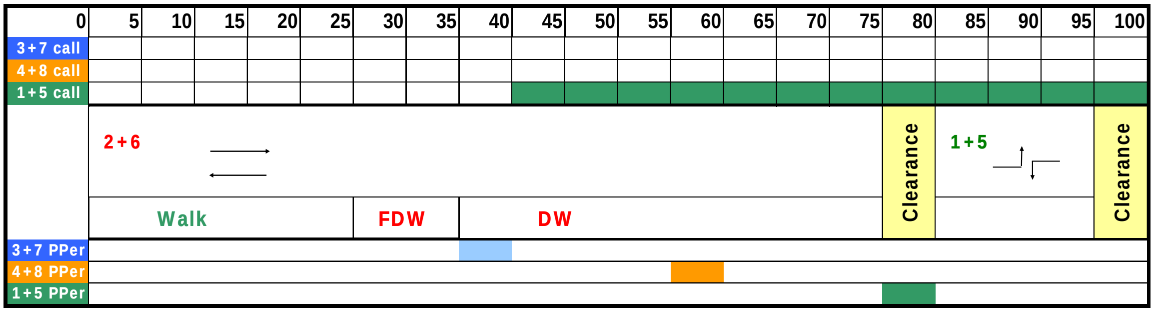

Figure 4-6: Mode 2. Constant calls on phases 1+5 starting at 40 seconds.

points are coincident: t=60 sec (phases 3+7), t=80 sec (phases 4+8), and t=100 sec (phases 1+5). In other words, regardless of the force-off type, the non-coord phases cannot run longer than their programmed split time (20 sec).

4.3 MODE 3 (M3): SIMULTANEOUS FIXES PPt MODE WITH SHORT PPer'S. COORD RESTING IN WALK.

Coord Phases:

- *Beginning* floating.
- *End*: non-actuated.
- *Pedestrian*: Rest (dwell) in Walk.

Non-Coord Phases:

- *Beginning*: PPt´s are fixed and simultaneous.
- *End*: either floating force-off or fixed force-off can be selected
- *PPer Duration*: Minimum:

Considerations about the Mode 3 (M3)

The only difference between this mode and mode 1 is that the PPer's in this are short. Figure 4-7 shows how this mode operates for saturated traffic conditions. The significant disadvantage of this mode is that if any call is placed after the PPer´s close, which occurs at t-30 sec, this call cannot be serviced until next cycle. This condition is illustrated in Figure 4-8 where call on phases 1+5 are placed at t=40, when 1+5 PPer had already been closed. Therefore, these phases have to wait until next cycle to be serviced even though there would be available time to service them in the current cycle.

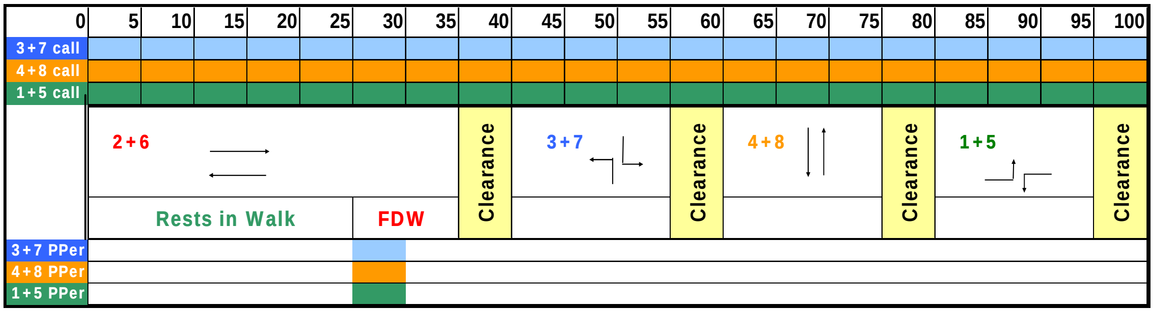

Figure 4-7: Constant calls on all phases.

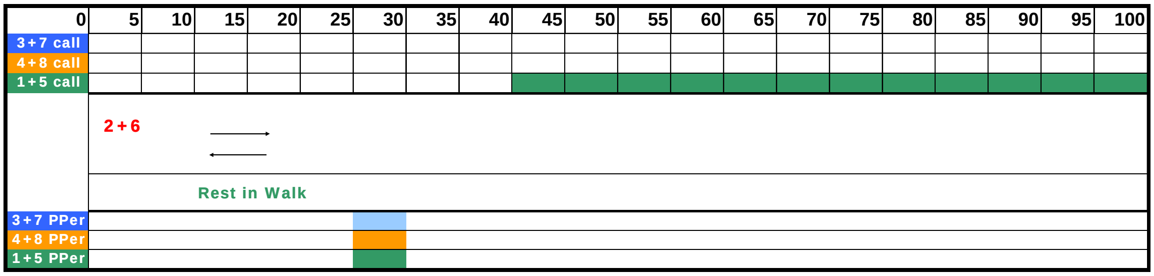

Figure 4-8: Mode 3. Constant calls on phases 1+5 starting at 40 seconds.

5. SIMULATION

In order to observe the difference among the three coordination modes, hardware-in-the-loop simulations were conducted. The HITL system consisted of a desktop computer running the VISSIM 3.70 simulation model, a NIATT CID II, and an Eagle EPAC 300 traffic controller. These three components were shown in the Figure 2-1, which illustrated the HITL traffic simulation concept in chapter 2.

Three coordinated intersections were simulated: the middle one coordinated-actuated and the other two fixed time. The purpose of the two fixed time intersections was to form platoons on the main street (see Figure 5-1). All intersections were controlled by the same controller in order to provide perfect synchronization among the three coordinated intersections by accurately maintaining the desired offsets. The controller used in this experiment provides control up to 16 phases distributed in 4 rings (4 phases per ring). Eight phases in two rings were assigned to the coordinated-actuated intersection and two phases in a single ring for each of the fixed time ones. The Table 5-1 summarizes the three coordinated intersections control characteristics.

5.1 SCENARIOS OF STUDY

The simulations were conducted in three different traffic configurations: scenarios I, II, and III, with the following characteristics:

- Scenario I: non-coord phases with v/c ratio equal to 0.50;
- Scenario II: non-coord phases with v/c ratio equal to 0.12.

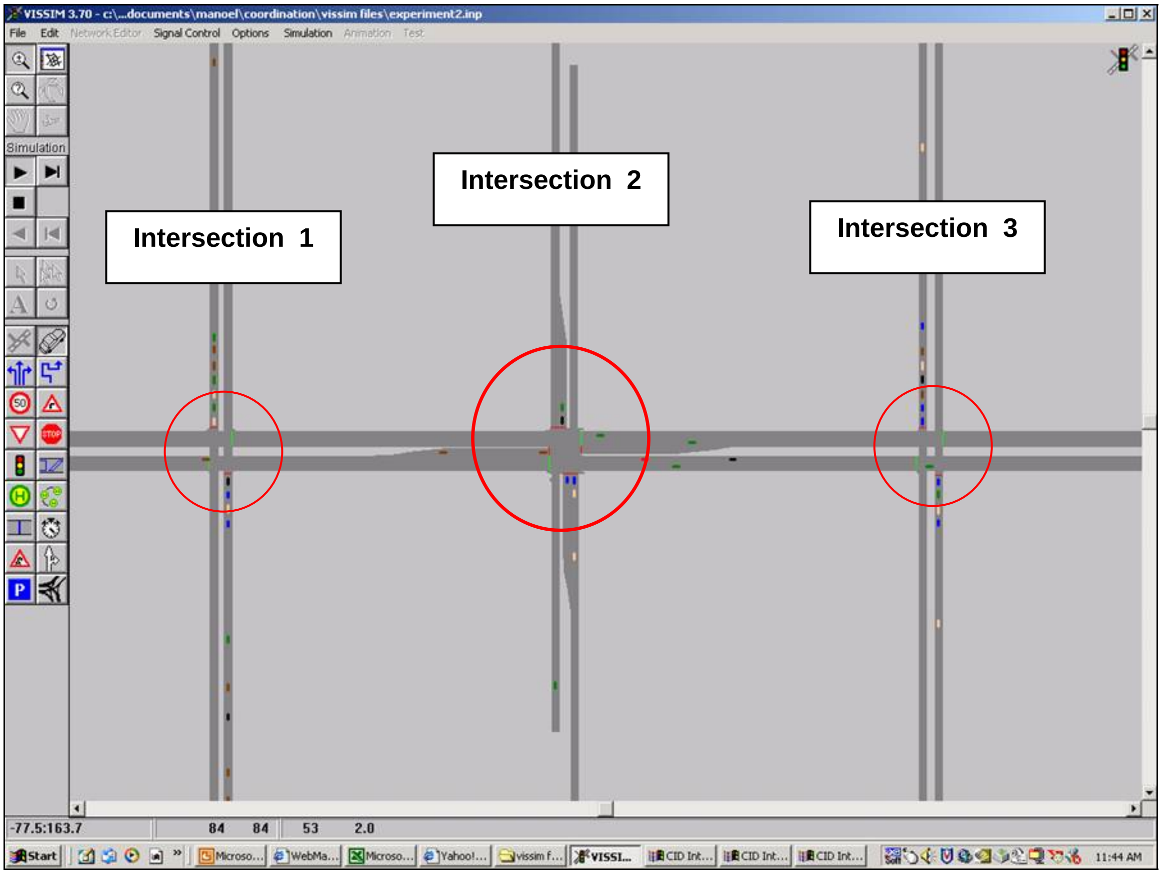

Figure 5-1: Simulated Intersections

Table 5-1: Actuated-coordinated Intersection Characteristics

Control type		**Intersection1**	**Intersection2**	**Interesection3**
		Fixed time	Actuated-coordinated	Fixed time
Cycle Length (sec)		100	100	100
Offsets		0	+13	0
Controller phases	**Coord.**	10 (50 sec)	2+6 (max 40sec)	12 (50 sec)
	Non-coord.	9 (50 sec)	Dual phases: 3+7 (max 20 sec), 4+8 (max 20 sec) 1+5 (max 20 sec)	11 (50 sec)
Vehicle clearance time (sec)		3.5 of yellow + 1.5 of all read for all phases	3.5 of yellow + 1.5 of all read for all phases	3.5 of yellow + 1.5 of all read for all phases

- Scenario III: non-coord phases 3+7 and 4+8 with extremely low v/c ratio of 0.03 and phases 1+5 with v/c ratio equal to 0,20. The traffic on phases 1+5 was set up to arrive at the end of the cycle by making most traffic on these phases come from the non-coord movements (side streets) of intersections 1 and 3 by controlling the origins and destinations of traffic. Because of the offsets of the three intersections, traffic coming form those movements arrived at the end of the cycle in intersection 2.

The coordination modes presented in chapter 4, (M1, M2, and M3) were simulated for each scenario I, II, and III. M1 and M3 were used in this experiment with floating force-off. In this study, especially for scenarios II and III, it would not make any difference if fixed force-off had been selected because the traffic volumes are low, and the phases are usually gaped out rather than forced-off.

5.2 MEASURE OF EFFECTIVENESS AND SAMPLE SIZES

The measure of effectiveness (MOE) used in this experiment was the average 15-minute control delay (D) per vehicle in seconds for each phase of the coordinated-actuated intersection.

Each sample had 30 observations. Each observation was obtained from a 45-minute simulation. The actual data were taken from the middle 15 minutes of the simulation. The first 15 minutes were used to allow the system to reach equilibrium and the last 15 minutes to make sure there where no queues at the end of the 15-miunte period used for the experiments.

For a better understanding of the experiment, Table 5-2 summarizes the experiment for one scenario. Figure 5-2 shows the 90 simulations that were ran for each

Table 5-2: Experiment summary table for each scenario

Type of Study	Experimental
Response Variable	Average 15-minute control delay (D) per vehicle in seconds for each phase.
Factor	Coordination Mode
Factor Levels (L)	Coord. Mode 1 (M1) Coord Mode 2 (M2) Coord Mode 3 (M3)
Sample Sizes	M1:30 M2: 30 M3: 30

scenario, which results a total of 270 simulations of 45 minutes each.

The research hypothesis is that for low traffic volumes, there are differences in the average vehicle delay (MOE) means for non-coordinated phases when different coordination modes (M1, M2, and M3) are implemented.

5.3 SETTING THE TRAFFIC VOLUMES FOR EACH SCENARIO

As described earlier, scenarios I, II, and III differ from each other only on the v/c ratios used. Since volumes, not v/c ratios, can be inserted on the VISSIM software, the Highway Capacity Software (HCS) 2000 was used to calculate the traffic volumes associated with the v/c ratios desired. Ultimately, the volumes were imputed in VISSIM.

5.4 DATA COLLECTION

In order to better replicate the stochastic behavior inherent to real traffic, every observation in this study had its unique seed number. Nine blocks (M1, M2, and M3 for each scenario I, II, and III) of 30 simulation runs were collected. Each block was collected using the multi-run feature provided by the simulation model.

5.5 RESULTS

The data on table 5-3 indicates that there are no big differences in delay among the coordination modes in scenario I, which had been expected because in moderate-high traffic demand, non-coord calls are regularly placed in all phases in every cycle and once the controller releases to service phases 3+7, all subsequent phases are normally serviced regardless of their PPer's.

Difference among modes 1, 2, and 3 are more likely to occur in lower traffic volume situation, especially where phases 3+7 and/or 4+8 might be skipped. Therefore, differences in scenario III are larger. For instance, table 5-3 shows that for phase 5, M3 is 53% higher than M2. For phase 1, this difference is 44%. That might have occurred because in scenario III the traffic was set up to arrive at the end of the cycle, therefore many 1+5 calls were placed after the short 5-second PPer's closed in M3, having to be serviced in the next cycle. For the same reason, M1 performed worse than M2 because

Table 5-3: Average 15-minute delay per vehicle for each phase (sec)

Scenario	Modes	N	Phase							
			1	2	3	4	5	6	7	8
1	M1	30	86.3	6.9	43.6	56.1	95.0	6.6	44.1	60.2
	M2	30	78.6	6.9	44.9	50.8	75.7	7.1	43.5	52.9
	M3	30	82.2	7.3	42.0	54.8	78.2	6.9	43.5	53.9
2	M1	30	58.0	6.8	47.3	48.4	56.2	6.5	43.3	45.6
	M2	30	52.4	6.4	42.8	43.1	57.2	7.0	43.3	45.5
	M3	30	45.0	6.4	45.3	45.6	56.4	7.2	49.4	42.9
3	M1	30	48.0	2.9	57.1	46.1	46.5	2.9	32.9	41.0
	M2	30	40.0	1.7	43.3	43.7	35.7	1.6	31.4	44.2
	M3	30	57.6	2.9	57.3	54.0	54.5	3.1	36.7	42.7

1+5 PPer in M1 closes earlier than in M2. That is the reason for which M2 presented the best performance in Scenario III for phases 1 and 5.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

In this study, a set of terms and definitions for coordinated-actuated operation parameters was proposed including permissive point, permissive period, and force-off point. Based on the terminology proposed, three coordination modes were presented and compared regarding their non-coord movements. The modes differ from each other by their permissive period configurations.

For moderately-high traffic volumes, the three modes performed similarly because non-coord calls are regularly placed in all phases, including the first non-coord phase, in every cycle and once the controller releases to service phases 3+7, all subsequent phases are normally serviced regardless of their PPer's configuration.

For extremely low volumes on the non-coord phases, apparent differences among the modes were found for phases 1 and 5. Mode 2, whose PPer's closes later in the cycle, appeared to present the best performance for phases 1 and 5. Mode 3 appeared to present the worst performance because its 1+5 PPer had already been closed when most 1+5 calls were placed.

6.2 CONCLUSIONS

The proposed terminology and definitions make it easier for traffic engineers to understand and discuss the issues related to coordinated-actuated traffic signal operation.

It was concluded that the coordination mode affects the performance of the intersection in low traffic demand periods. Mode 3 should be avoided because the controller will not release if calls are placed shortly after the end of the coord phase, which makes cars on the non-coord phases unnecessarily wait until the next cycle to be serviced. In this sense mode 1 and mode 2 are a better option. If mode 1 is selected, non-coord phases can be serviced earlier in the cycle and extra time to the coord phase will be assigned to the beginning of the next coord phase, which favors an early return to the green. On the other hand, if the mode 2 is chosen, non-coord phases will be serviced later in the cycle and therefore extra time to the coord phase will be assigned to the end of the current coord phase.

The final conclusion is that each coordinated intersection might provide better arterial performance based on the coordination mode used. In other words, the PPer's for each individual intersection should be set up according to the arrival patterns.

6.3 RECOMMENDATIONS

The author acknowledges that there are many possible ways of setting permissive periods, permissive points, and force-off points other than those set for the three coordination modes presented in this research. More detailed and comprehensive studies involving different cycle lengths, phase timings, and traffic volumes should be conducted in order to assess the differences among the modes.

Right turn on red (RTR) movements were purposefully not allowed in the simulation. In low traffic configurations, RTR could considerably decrease the vehicle delay on phases 4 and 8 in such a way that possible differences among the modes would not have been as noticeable. Permissive left turns on phases 1 and 5 were not used for the same reason. Further research could be done to evaluate different coordination modes when those features are considered.

Since this study dealt with unsaturated traffic conditions, the effect of different force-off types (fixed and floating) on the performance could not be evaluated. Future research could be done in that area.

The author recommends the collection of fairly large samples of data in traffic studies. Arithmetic means are very sensitive to outliers, especially in small samples, which can lead researchers to derive wrong conclusions. In regular traffic simulations, where no HITL is implemented, there is no reason to collect small samples as the simulations can run much faster than in real time. Besides, with the *mutli-run* feature provided by VISSIM 3.70, simulations can be run without the researcher being present to manually stop and start the simulation runs when needed.

In this study, each observation was randomly generated from a different seed number (independent samples). Probably simulating samples with the same set of seed numbers (paired samples) would be recommended because in this case the variation in the MOE due to traffic variation would be eliminated. In other words, paired samples would isolate the effect of the control features from the effects of variation in the traffic demand, which would not be possible in field studies.

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VITA

Manoel Castro-Neto was born in 1979, in Fortaleza, Brazil, where he received a Bachelor's degree in Civil Engineering from the Universidade Federal do Ceará in 2003. In 2000, he was awarded a scholarship to attend one year of his undergraduate program at the Technical University of Berlin, Germany. After he received his Bachelor's degree, he worked for an advance urban traffic control center in his hometown.

In August of 2003, Manoel started his Masters's degree in Civil Engineering (Transportation) at the University of Tennessee. In 2004, he received the Tennessee Section ITE 2004 Student Paper Award (first place). In the same year, he also received the Tennessee Section ITE 2004 Student Scholarship. In 2005, Manoel received the ITE William H. Temple Student Challenge scholarship.