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Field Evaluation of Insync Adaptive Traffic Signal Control System in Multiple Environments Using Multiple Approaches

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FIELD EVALUATION OF INSYNC ADAPTIVE TRAFFIC SIGNAL CONTROL SYSTEM IN MULTIPLE ENVIRONMENTS USING MULTIPLE APPROACHES

by

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ABSTRACT

Since the beginning of signalization of intersections, the management of traffic congestion is one of most critical challenges specifically for the city and urbanized area. Almost all the municipal agencies struggle to manage the perplexities associated with traffic congestion or signal control. The Adaptive Traffic Control System (ATCS), an advanced and major technological component of the Intelligent Transportation Systems (ITS) is considered the most dynamic and real-time traffic management technology and has potential to effectively manage rapidly varying traffic flow relative to the current state-of-the-art traffic management practices.

InSync ATCS is deployed in multiple states throughout the US and expanding on a large scale. Although there had been several 'Measure of Effectiveness' studies performed previously, the performance of InSync is not unquestionable especially because the previous studies failed to subject for multiple environments, approaches, and variables. Most studies are accomplished through a single approach using simple/naïve before-after method without any control group/parameter. They also lacked ample statistical analysis, historical, maturation and regression artifacts. An attempt to evaluate the InSync ATCS in varying conditions through multiple approaches was undertaken for the SR-434 and Lake Underhill corridor in Orange County, Florida. A before-after study with an adjacent corridor as control group and volume as a control parameter has been performed where data of multiple variables were collected by three distinct procedures. The average/floating-car method was utilized as a rudimentary data collection process and 'BlueMac' and 'InSync' system database was considered as secondary data sources. Data collected for three times a day for weekdays and weekends before and after the InSync ATCS was deployed.

Results show variation in both performance and scale. It proved ineffective in some of the cases, especially for the left turns, total intersection queue/delay and when the intersection volumes approach capacity. The results are verified through appropriate statistical analysis.

Keywords: Adaptive Traffic Control System (ATCS), Field Evaluation, Before-after Study, Average-car Method, InSync, BlueMAC, Travel Time, Delay.

“Read! In the name of your Lord who created man from a clinging substance” [Al-Quran 96:1-2]

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LIST OF ABBREVIATIONS

ACDSS	Adaptive Decision Support System
ACS	Adaptive Control Software
ATSAC	Automated Traffic Surveillance and Control
ATCS	Adaptive Traffic Control System
FHWA	Federal Highway Administration
ITS	Intelligent Transportation Systems
LA ATCS	Los Angeles Adaptive Traffic Control System
LUH	Lake Underhill
MoE	Measure of Effectiveness
MCO	Orlando International Airport
NMV	Non-motorized Vehicle
O-D	Origin-Destination
OPAC	Optimized Policies for Adaptive Control
RHODES	Real Time Hierarchical Optimized Distributed Effective System
RT-TRACS	Real-Time Traffic-Adaptive-Control System
SCATS	Sydney Coordinated Adaptive Traffic System

SCOOT	Split Cycle Offset Optimization Technique
SPOT	System for Priority and Optimization of Traffic
SR	State Road
TOD	Time of Day
UKTRL	United Kingdom Transport Research Laboratory
UTOPIA	Urban Traffic Optimization by Integrated Automation
WSR	Wilcoxon Signed-Rank

CHAPTER ONE: INTRODUCTION

1.1 Background

The evolution of modern civilization is marked by the invention of the wheel which made the human and goods transportation a reality irrespective of number or size. With the courses of time, technology made it easier, flexible and provided newer dimensions every day. With the advancement of transportation technology and infrastructure, almost every nation is enriched by huge transportation network comprised of thousands of miles of paved roads and highways equipped with numerous types of innovative automobiles. Although the technology of last century exceeds the accomplishments of all previous years, newer challenges are emerging with the massive expansion.

With newer roads and development of automobile industry, the roads became overloaded with motorized and non-motorized vehicle (NMV) and pedestrians. Congestion and crashes started occurring which resulted in the loss of countless hours of operation of the road users and invaluable lives. At this point, the signalization of intersections has brought a revolutionary change in the history of transportation both for saving time and lives. But since the beginning of signalization of intersections, it’s been a challenge for the maintaining agencies to effectively manage and control the traffic in a busy urban arterial having randomly varying flow. Over the years, efforts are made to minimize the travel time and maximize the speed with continuous flow and minimum crashes through the optimization of signal timing.

Researchers and scholars from multidisciplinary areas have been working for years for an innovative alternative to control traffic flow in an effective and responsive manner. The Adaptive Traffic Control System (ATCS/ATC/ATSC/ASCT) which is formerly known as Real-Time Traffic-Adaptive-Control System (RT-TRACS), an advanced and major technological component of the Intelligent Transportation Systems (ITS) is considered as the latest endeavor to provide a dynamic and real-time solution to the traffic congestion problem in the congested intersections.

'InSync' is the commercial brand name of the ATCS developed, manufactured and distributed by Rhythm Engineering (Lenexa, Kansas) which is the most widely-deployed ATCS System in the U.S. [1]. The effectiveness of InSync ATCS has been studied before both in the field through the simple/naïve 'before-after' study using the average/floating car method and virtually through the microsimulation. Most of the previous studies carried out by private/state agencies suggested an improvement in travel time, delay, the number of stops, safety and fuel consumption. But they lack rigor technical and statistical approach as well as failed to subject for multiple circumstances and variables. Also, the simple/naïve before-after analysis does not account for the hidden factors, historical, maturation, randomness, and regression artifacts.

This study addresses some of those issues by combining multiple approaches and variables with ample statistical analysis. A before-after study with a control group and control variable was performed along the Alafaya Trail (SR-434) and Lake Underhill Road Corridors in Orange County, Florida. A control group is where there's no treatment applied compared to the study group. Field data have been collected by the average-car method for the two study corridors along with a control corridor and then combined with the analysis of probe data from 'BlueMAC' (a data collection device developed by Digiwest which collects data based on Bluetooth signal) and

‘InSync’ system database itself. For a considerable number of cases and time period, the before-after data collected, analyzed and compared generically and statistically.

1.2 Objective

The primary study goal of this research is to study and evaluate the InSync ATCS over the traditional Time of Day (TOD) pre-timed algorithm for traffic signal control in the field for varying conditions of time, flow, movement and volume through multiple strategies. An overview of different state-of-the-art signal control systems is also provided. A detailed background study of the Adaptive Control Systems and InSync ATCS specially was performed. The research goal was met through field data collected from multiple sources and results which were obtained through the data analysis and statistical approaches. Attempts were made to combine and compare results with previous case study results. Common cases where InSync ATCS proved effective were identified. The cases where InSync failed to improve the current situation were also recognized and explained in the light of other influencing parameters. Efforts had been made to relate the improvement with different factors such as volume, time of day, movement etc. Limitations of different MoE techniques and special findings were also described. Further studies were advocated to analyze those fields and factors responsible for the failure to perform an unbiased and complete evaluation.

1.3 Thesis Organization

To guide the organizational process of the thesis, a short description here will describe the contents of each chapter. There are six chapters with a number of subchapters in this paper. The first chapter introduces the reader to an overlook of traffic signalization, it's necessity and challenges with an insight of adaptive control systems. This chapter also clarifies the research objective with the required techniques.

Chapter two provides a brief background theory of signal control systems, operations and methods. It also provides essential detail of adaptive control system and InSyc ATCS with historical observation. Furthermore, it includes previous research and case study results as well as findings regarding ATCS and InSync also.

Chapter three focusses on the method used for the study and related description. It summarizes different test techniques and a brief theory of statistical tests along the data collection procedures. Chapter four on the other hand presents the data analysis and results for the three different methods. Chapter five discusses the findings of the study and limitation of each method and analysis. Finally, chapter six concludes the research with future research recommendations.

CHAPTER TWO: THEORY AND LITERATURE REVIEW

2.1 General

This chapter provides a vivid description of distinct types of the state-of-the-art signal control systems and their operations, Adaptive signal control system and InSync ATCS. It provides a brief background of various ATCS developed and practiced throughout the world. Special emphasis is put on the InSync algorithms and functions. Efforts are made to differentiate the InSync ATCS from other ATCSs available in the market. It also highlights previous studies and researches performed previously in the related field. Some of the results of previous studied are also mentioned for the comprehensiveness of the study.

2.2 Signal Control Systems

The design of a true responsive signal control system is one of the most critical and complicated jobs in the field of transportation. This is because of the unpredictable nature of traffic flow and inconsistency and non-uniformity of flow and demand in each intersection. The traffic demand varies with time in a day and day in a week for every approach. The future trend of transportation is also very unpredictable which makes the task more challenging.

Generally, an intersection operates in a free style or controlled by yield/stop sign unless the traffic volume is high enough and there are conflicting movements of traffic which causes congestion and safety problems that warrants the signalization of the intersection. To get an idea of how the signals operate in a signal control system, a brief detail of the system is provided below.

In any signalized intersection, there are three consecutive signals in a cycle- the green to allow traffic to move through the signal, the yellow to allow traffic to stop or pass the intersection safely before red and the red to allow traffic to move in other directions. For a conventional four-legged intersection there are four main directions of traffic- Eastbound, Westbound, Northbound and Southbound. For each main direction, two among the three movements are considered to be controlled by signalization- the left and the through movements, generally the right turns are whether yield or stop controlled. Thus, eight distinct movements which are also called phases under signal control are- North Left (NL), North Through (NT), South Left (SL), South Through (ST), East Left (EL), East Through (ET), West Left (WL) and West Through WT). The movement of pedestrian, bicycle or any non-motorized vehicle are considered a separate or ninth phase which is combined with the green phase of any parallel traffic movement.

Conventionally, two non-conflicting phases are combined together and with the pedestrian/bicycle phase if called. A phase diagram of all traffic and pedestrian movement is shown in Figure 1. The eight traffic movements with numbering from 1 to 8 and four pedestrian/bicycle movements numbered as P2, P4, P6 and P8 are shown in the figure. The most common combination of phases is 1-5, 2-6, 3-7 and 4-8. The pedestrian movements P2 and P6 are combined with the through movements 2-6 and the pedestrian movements P4 and P8 are combined with the through movements 4-8. The pairing and sequence of phases may vary at each intersection depending on the traffic demand in each approach and also based on type of signal control or detector. The group of phases run at the same time is called the ‘Stage’.

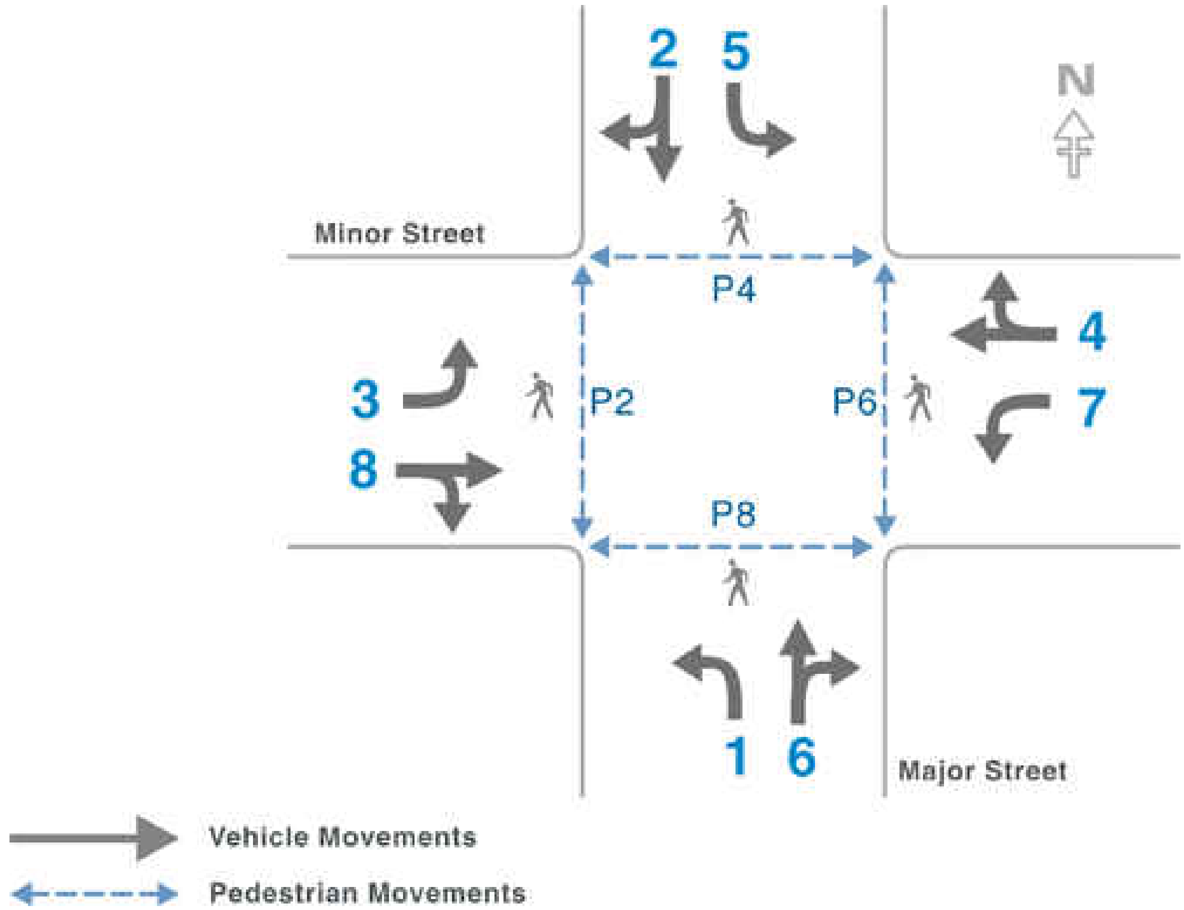


Figure 1: Typical vehicular and pedestrian movements at a four-leg intersection [2]

2.3 Signal Controller and Detectors

The three-main components of a signalized intersection are the sensor or detector, the lights and the controller. Every traffic signal is typically controlled by a controller mounted inside a cabinet located at the corner of the intersections. Normally there are two types of controllers- the local controller and the master/central controller. Depending on the types of operation, the controller might have under-the-pavement or overhead detectors/sensors/cameras to get information about the approaching vehicles. So, the sensors collect the instantaneous data of vehicles and send it to the master/central controller and then it sends the signal to the local controller which implements the signal.

Based on the interconnection between adjacent signals, the controller system might be isolated (free) which operates independently or coordinated which is connected to adjacent intersections. Normally in the urban areas where traffic volume is high, and intersections are placed too closely, the intersections are coordinated especially for the through movement in the major street. The coordinated system forms a green tunnel for the approaching through vehicles to pass a number of intersections at a time.

Detectors can be grouped into three classes: in-pavement detectors, non-intrusive detectors, and detection for non-motorized road users. In-pavement detectors are buried in or under the roadway. Inductive detector loops are the most common type. There are sensors buried in the road to detect the presence of traffic waiting at the light, and thus can reduce the time when a green signal is given to an empty road. The sensor loops typically work in the same fashion as metal detectors.

It is sometimes more advantageous and cost effective to install over-roadway sensors than cutting the road and embedding inductive loops. These technologies include video paved right-of-way; these have the capacity to act as real-time traffic management devices. They also act as multi-lane detectors and collect data types not available from in-roadway sensors.

Non-motorized users are classified as pedestrians, bicyclists, and equestrians or any type of vehicle which is not motorized and requires right of way in addition to the main traffic roadway. Provisions for detecting these users include demand buttons and tuned detectors.

2.4 Signal Operation Types

Signal controller might be set up with different algorithms based on the traffic demand and/or pattern. Depending on the response and dynamics of the signal controller systems, the traffic operations are primarily two types [3]-

1. Pre-timed and
2. Actuated

Pre-timed operation is actually fixed time operation in which the red, yellow, and green indications are timed at fixed intervals. The red, green and yellow timing is calculated based on the previously collected data of traffic flow and demand. In this operation it's assumed that the traffic patterns can be predicted accurately based on time of day (TOD). This predictability can usually only be achieved by controlling the traffic entering the intersection with upstream signals, as in a system. In isolated locations, however, the traffic approaching the intersection arrives randomly, and is not usually predictable enough to make pre-timed operation a good choice. But pre-timed operation does not require traffic detectors at the intersection, and is therefore much cheaper to install. Consequently, pre-timed operation is almost obsolete now and usually used at isolated intersections in rural streets with lower volume of traffic or only when funds do not allow actuated operation.

Actuated or dynamic signals are the most common types of signals available nowadays. Intersections with this form of control consist of actuated traffic controllers and vehicle detectors placed in or on the roadways approaching the intersection. In actuated operation, the control algorithm is primarily concerned with when green intervals terminate. The green time allocation in an actuated signal varies depending on the approaching traffic demand. During actuated operation, a traffic movement is served with a green indication. This green interval lasts for a user-defined minimum amount of time. As long as cars continue to cross the approach detectors frequently enough, the green interval is extended. These extensions continue until the cars thin out sufficiently to allow the signal to gap out, or until the interval reaches the maximum time.

There is a third or sometimes fourth type of traffic operation such as a semi-actuated or pre-timed actuated which are basically the combination of the pre-timed and actuated operation in the same intersection or using some features of these two main types.

2.5 Adaptive Control System

The Adaptive traffic signal control system is the updated or upgraded version of the actuated operation in which traffic signal timing changes, or adapts, based on actual traffic demand. Adaptive signal control technology adjusts the timing of red, yellow and green lights to accommodate changing traffic patterns and ease traffic congestion. By receiving and processing data from strategically placed sensors, the adaptive system can determine which lights should be red and which should be green. The only difference between the actuated and adaptive control system is the actuated system can change the length of red/green, but it cannot alter the phase sequence, but the adaptive system can do both. The later one is also more responsive and real-time which operates in a faster fashion.

The technique used in the adaptive system is very simple. First, traffic sensors or detectors collect the traffic data. Next, traffic data is evaluated, and signal timing improvements are developed. Finally, the controller implements signal timing updates. The process is repeated every few minutes to keep traffic flowing smoothly. The difference between the conventional time of day control system and adaptive system is the later one is more dynamic, responsive and provide real-time solution. The idea of the adaptive system is very popular nowadays and agencies are more likely to replace their old system by the new adaptive systems.

There are multiple types of ATCS available in the market by different vendors such as- the Split Cycle Offset Optimization Technique (SCOOT), Sydney Coordinated Adaptive Traffic System (SCATS), Urban Traffic Optimization by Integrated Automation (UTOPIA)- System for Priority and Optimization of Traffic (SPOT), Real Time Hierarchical Optimized Distributed Effective System (RHODES), Optimized Policies for Adaptive Control (OPAC), Los Angeles ATCS (Also known as ATSAC), Adaptive Control Software (ACS) Lite, InSync etc.

The idea of adaptive control system is not new. The first-generation adaptive control system was first conceived in the early 1960s by a British scholar named *A J Miller* and PLIDENT is the first commercial ATCS which came into action in late 1960s in Glasgow and eventually failed [4]. After a number of attempts, the first successful application of the adaptive online traffic model took place in the early 1970s when SCATS was first deployed in Australia [5]. The second generation of ATCS emerged a few years later when SCOOT was developed by the UK Transport Research Laboratory [6] and until 2012 was the highest deployed ATCS throughout the world [7]. In the early 1980s and later on several advanced third generation strategies have been developed such as the OPAC (1982), PRODYN (1983), SPOT/UTOPIA (1987), BALANCE (1994), RHODES (1990), ACS Lite (1990-2001), LA ATCS (2000) and InSync (2008). Among them, OPAC, RHODES, ACS Lite and LA ATCS/ATSAC are FHWA sponsored projects. InSync is one of the youngest ATCSs in the market, originally founded in 2005 and reported as the most effective ATCS in the USA [8]. There are a lot other ATCSs in the market deployed or currently, under development- some of them are listed in Table 1 along with the developers and distributors name.

Table 1: Adaptive Systems Throughout the World [9]

Older Deployed Systems		Newer Systemss	
System	**Developer/Distributor**	**System**	**Developer/Distributor**
ACS Lite	Siemens, Econolite, PEEK, McCain	QuicTrac	McCain
InSync	Rhythm Engineering, USA	Synchro Green	Trafficware/Naztec, USA
SCATS	Roads and Traffic Authority (RTA) of New South Wales, Australia. TransCore for North America	Centracs Adaptive	Econolite, version of ACS Lite
SCOOT	UK, Siemens is a distributor for North America	Adaptive Decision Support System (ACDSS)	KLD developed for NYCDOT, USA
RHODES	University of Arizona & Gardner Systems, Siemens	NWS VOYAGE	Northwest Signal, USA
OPAC	Telvent (Farradyne) & UMASS, Schneider Electric/Telvent, USA	PTV BALANCE	VISSIM, Germany
LA ATCS	McTrans developed for Los Angeles, USA	SPOT/UTOPIA	FIAT Research Centre, ITAL TEL and MIZAR Automation, Italy

2.6 InSync ATCS

The InSync adaptive traffic control system, developed by Rhythm Engineering is an intelligent transportation system that enables traffic signals to adapt to actual traffic demand.

InSync is one of the youngest ATCSs in the market, originally founded in 2005. As of November 2015, InSync is operational in 2,300 traffic signals in 31 states and 160 municipalities in the U.S [10].

Three basic operational objectives of the adaptive signal controller are- dynamic allocation of green time, automatic adjustment to control parameters, and fast revision of signal plans [11]. InSync a plug-and-play system that works with the existing traffic control cabinets and controllers achieves those objectives through two main hardware components- Internet Protocol (IP) video cameras and a processor which are sometimes referred to as 'the eyes' and 'the brain' of the system, respectively [12]. The number of vehicles and how long the vehicles have been waiting (delay) is determined by the mounted video cameras. The processor, a state machine located in the traffic controller cabinet at the intersection, based on the second-by-second camera detection calls up the traffic signal state that best serves actual demand while coordinating its decision with other intersections.

So, InSync performs at two levels of signal optimization- Local Optimization and Global Optimization to yield the best control and coordination. Locally, it uses integrated digital sensors to know the exact number of cars demanding service at an intersection and the duration for which they have been waiting. Based on these queue and delay data, approaches are given phasing priority. The dynamic phasing, dynamic sequencing, and dynamic green splits enable the traffic signals to use the green time efficiently. In global, InSync creates progression along an entire corridor by using 'green tunnels' where platoons of vehicles gather and are then released through the corridor. By coordinating with each other, the signals anticipate the green tunnel's arrival, so vehicles pass through without slowing down or stopping. The green tunnels' duration, period and frequency can vary to best support traffic conditions.

If any intersection detects a notable change in demand, the adaptive traffic management system can make a global decision to add more/less time between scheduled movements to best serve all phases. Between green tunnels, the local optimization serves the side streets and left turns. Moreover, if any issues arise in any intersection, the InSync web interface allows users to troubleshoot intersections, reboot cameras or turn on emergency mode, without having to travel to the cabinet [13]. A brief description of the system is provided here, *Chandra et al.* elaborated the logics, working techniques, and algorithms of InSync in the US patents [14] which are recommended for further learning.

2.7 Previous Studies

Numerous studies have been performed in the past for isolated and combined evaluation of different ATCSs and InSync especially. *Sims et al*. first studied the philosophy and benefits of SCAT system in 1980 at Sydney [5] and then *Hu et al.* performed a field evaluation of SCATS in Las Vegas [15]. SCOOT is first evaluated by *Hunt et al*. in 1981 in Glasglow, UK [6]. *Gartner et al.* first evaluated the performance of OPAC in 1991 in USA [16] and then again in 2001 [17]. *Friedrich B.* provided an overview and short history of the nineteenth-century adaptive control systems [4]. The architecture, algorithms, and effectiveness of RHODES are analyzed and found effective by *Mirchandani et al.* [18]. An overview and performance evaluation of ACS Lite is accomplished by *Shelby et al*. [19]. *So et al*. accomplished a field evaluation of Synchro-Green

Adaptive Signal System [20]. *Shelby S.* performed a novel simulation study focused on real-time computational capabilities of adaptive-control algorithms used in OPAC, PRODYN, ALLONS-D, and COP, the intersection control algorithm of RHODES [21]. *Zhao et al.* provided an overview of the usage of adaptive signal control system in the USA where, the functions and features of SCOOT, SCATS, OPAC, RHODES, and ACS Lite are reviewed [22]. *Studer et al.* combined various features and case study results of SCOOT, SCATS, InSync and UTOPIA where the performance of InSync is found to outperform others [12]. HDR Engineering Inc. performed two consecutive surveys over the cost, maintenance, and reliability of popular adaptive traffic control technologies in the US and their operational benefits in 2009 [23] and 2010[8] respectively where InSync is found to be the best performing among other ATCSs.

For InSync ATCS, most of the field evaluation studies are performed by private or commercial institution or state departments whether using the floating/average-vehicle method or using the virtual environment of simulation. *Stevanovic et al.* evaluated InSync in microsimulation environment for Volusia County, FL using VISSIM model and showed a varying improvement of 2-20% over the traditional TOD control system [24]. *Hu et al.* performed field evaluations of InSync using private-sector probe data from the vendor 'INRIX' and stated a 16-25% increase in performance [25]. All other MOE studies are accomplished by the public or private authorities and their reports showed a varying percentage of improvement ranging from -87% to 90% averaging to 15-20% improvement for corridor travel time, delay and number of stops [26] but side street delay is reported to be increased significantly [27].

CHAPTER- THREE: METHODOLOGY

3.1 General

This chapter provides some necessary descriptions and theoretical background of the methods used for the research as well as the statistical analysis used in the study. It also provides the detailed information about the method utilized for the study which includes the method and procedure of data collection, theory, calculation, statistical theory and analysis etc. The results obtained from the raw data analysis are also represented in both tabular and graphical forms.

3.2 Test Vehicle Techniques

Since the early nineteenth century, the test vehicle technique has been used for travel time data collection. This technique involves the use of a data collection vehicle within which an observer records cumulative travel time at predefined checkpoints along a travel route. This information is then converted to travel time, speed, and delay for each segment along the survey route. The average number of stops for the specific route and the vehicle counts can also be achieved for this method.

There are several different methods for performing this type of data collection, depending upon the instrumentation used in the vehicle and the driving instructions given to the driver. Since these vehicles are instrumented and then sent into the field for travel time data collection, they are sometimes referred to as “active” test vehicles. Conversely, “passive” ITS probe vehicles are vehicles that are already in the traffic stream for purposes other than data collection.

Generally, there are three levels of instrumentation used to measure travel time with a test vehicle. Firstly, manually recording elapsed time at predefined checkpoints using a passenger in the test vehicle. Secondly, determining travel time along a corridor based upon speed and distance information provided by an electronic Distance Measuring Instrument (DMI) connected to the transmission of the test vehicle; and thirdly, using Global Positioning System (GPS) to determine test vehicle position and speed by using signals from the Department of Defense (DOD) system of earth-orbiting satellites.

Historically, the manual method has been the most commonly used travel time data collection technique. This method requires a driver and a passenger to be in the test vehicle. The driver operates the test vehicle while the passenger records time information at predefined checkpoints. Technology has automated the manual method with the use of an electronic DMI. The DMI is connected to a portable computer in the test vehicle and receives pulses at given intervals from the transmission of the vehicle. Distance and speed information are then determined from these pulses. GPS has become the most recent technology to be used for travel time data collection. A GPS receiver is connected to a portable computer and collects the latitude and longitude information that enables tracking of the test vehicle.

Since the driver of the test vehicle is a member of the data collection team, driving styles and behavior can be controlled to match desired driving behavior. The following are three common test vehicle driving styles:

- Average car - test vehicle travels according to the driver's judgement of the average speed of the traffic stream;

- Floating car - driver “floats” with the traffic by attempting to safely pass as many vehicles as pass the test vehicle; and
- Maximum car - test vehicle is driven at the posted speed limit unless impeded by actual traffic conditions or safety considerations.

The floating car driving style is the most commonly referenced. In practice, however, drivers are likely to adopt a hybrid of the floating car and average car because of the inherent difficulties of keeping track of passed and passing vehicles in high traffic volume conditions [28].

3.3 Methodology

A naïve/simple before-after study is the most widespread practice for the Measure of Effectiveness (MoE) study for any traffic control system. But the naïve study is failed to account for many hidden factors which may affect the results. That’s the reason why the naïve study is not recommended for safety studies. Although the MOE studies are not solely based on safety analysis, the naïve study can also be unconsidered based on the same principle as safety studies. And MOE study also considers safety analysis to evaluate the system. So, for all MOE study a before-after study with control group is recommended.

To make sure that no hidden factors affecting the result, a before-after study with a control group and a control parameter has been accomplished as a primary method to achieve the research objective. In this study, the MoE of InSync ATCS has been tested in the field in the Waterford Lakes area for two intersecting corridors- the 1.92 miles Alafaya Trail (SR-434) corridor having 9 intersections and the 2.16 miles Lake Underhill (LUH) Road corridor having 7 intersections in East Orange County, Florida. Provided that the study corridors are the stage-III implementation of InSync ATCS for Orange County by the Orange County Public Works Department.

Originally installed several months earlier, the InSync ATCS was turned on to its full functionality on April 14th, 2017. One of the reasons behind the upgrade of the existing time of day (TOD) pre-timed traffic control system is to manage the heavy traffic using the Waterford Lakes Mall, and the Expressway SR-408 to commute to Downtown Orlando and Orlando International Airport (MCO) for which these corridors are being used as entry and exit route. Also, high volume of traffic from the rapidly growing University of Central Florida (UCF) community affects these corridors. An adjacent 2.35 miles' corridor of Alafaya Trail (SR-434) having 7 intersections is also studied as a control group to get more realistic and unbiased results over the simple/naïve before-after study. The control corridor selected is just the next intersection after the study corridor. The traffic of the control corridor is also affected by UCF and traffic from Oviedo area. Table 2 provides brief description of the study and control corridors whereas Figure 2 and 3 shows the map of corridors and intersections studied.

Table 2: Study and control corridors description

Corridor Type	Corridor Name	Length (Miles)	No. of Intersections Studied	Influencing Traffic
Study	Alafaya Trail (SR-434)	1.92	9	Waterford Lakes Mall, Expressway SR-408, University of Central Florida
	Lake Underhill Road	2.16	7	University of Central Florida, Waterford Lakes Mall, Expressway SR-408
Control	Alafaya Trail (SR-434)	2.35	7	University of Central Florida, Oviedo Area

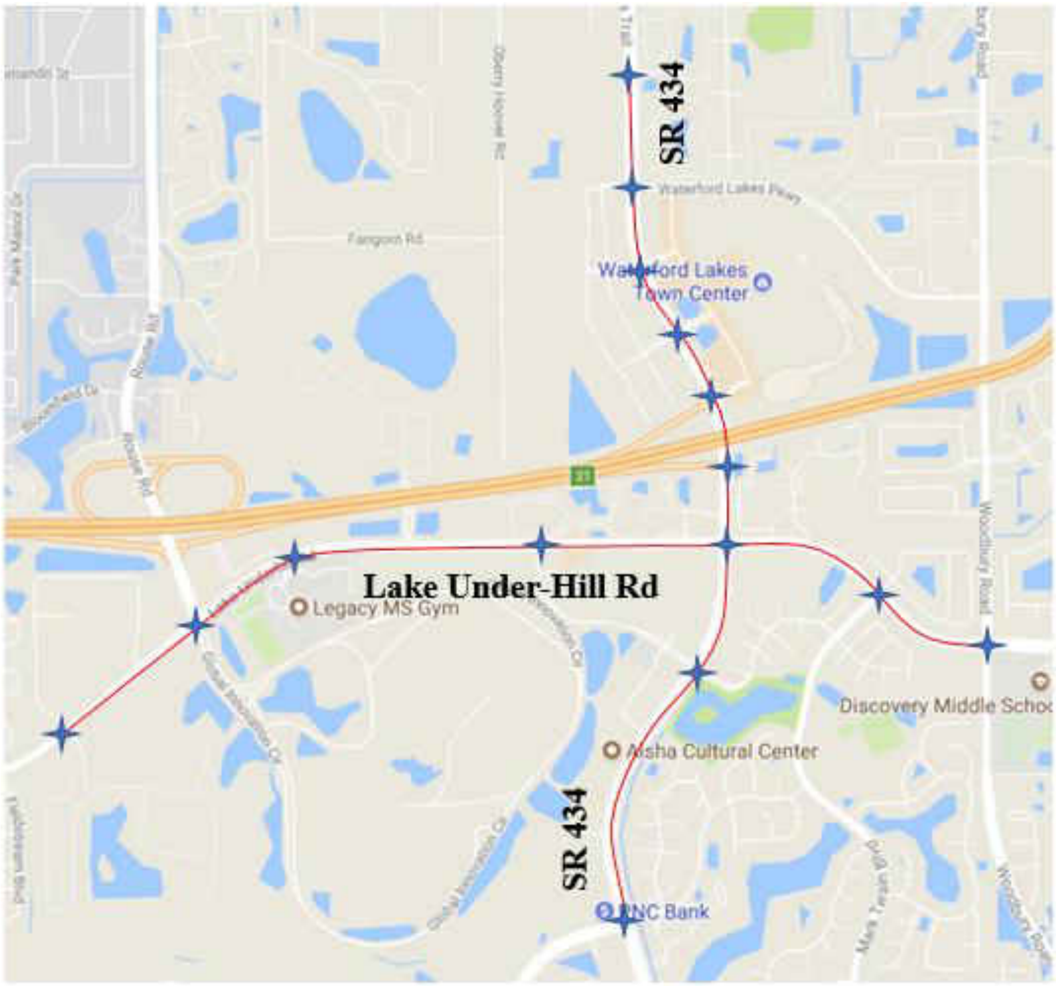


Figure 2: Study Corridors and Intersections

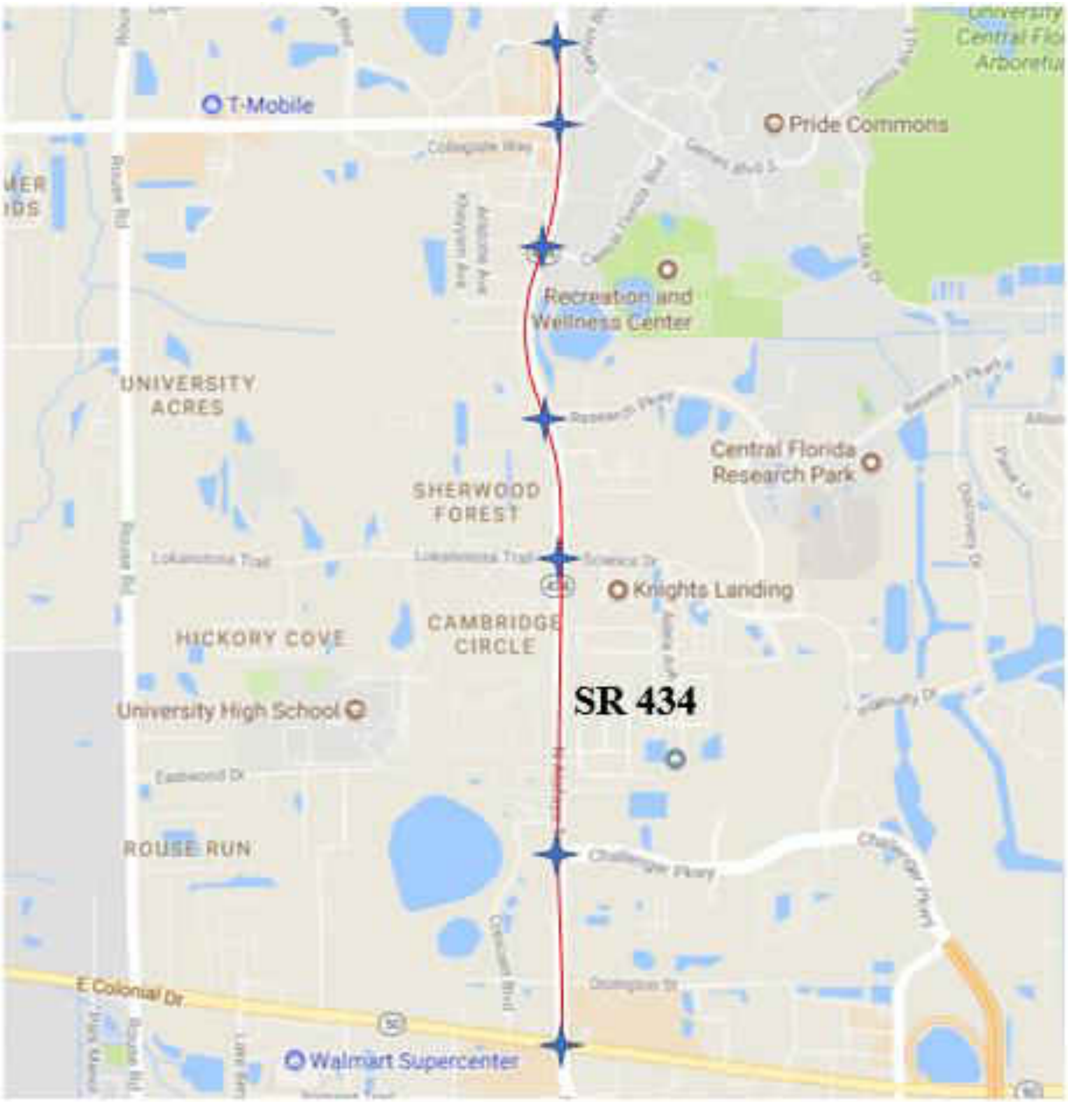


Figure 3: Control Corridors and Intersections

Three different approaches have been taken into account to evaluate the performance of InSync ATCS in the respective corridors. Firstly, field data of travel time, delay and the number of stops have been collected through the average-vehicle method. Also, the volume/vehicle count is counted from the recorded video for each run. Secondly, travel time and speed data are collected from the private vendor 'BlueMAC' database. A total of eight Origin-Destinations are analyzed.

The locations with BlueMAC devices and studied O-Ds (circled) are shown in Figure 4. The third approach involves the analysis of total intersection delay and queue length for each movement as well as the approach volume counts data from InSync database itself. Two intersections are analyzed with the InSync data (Figure 5). The BlueMAC and InSync data were collected from their respective web interface with the assistance of Orange County Public Works Department.

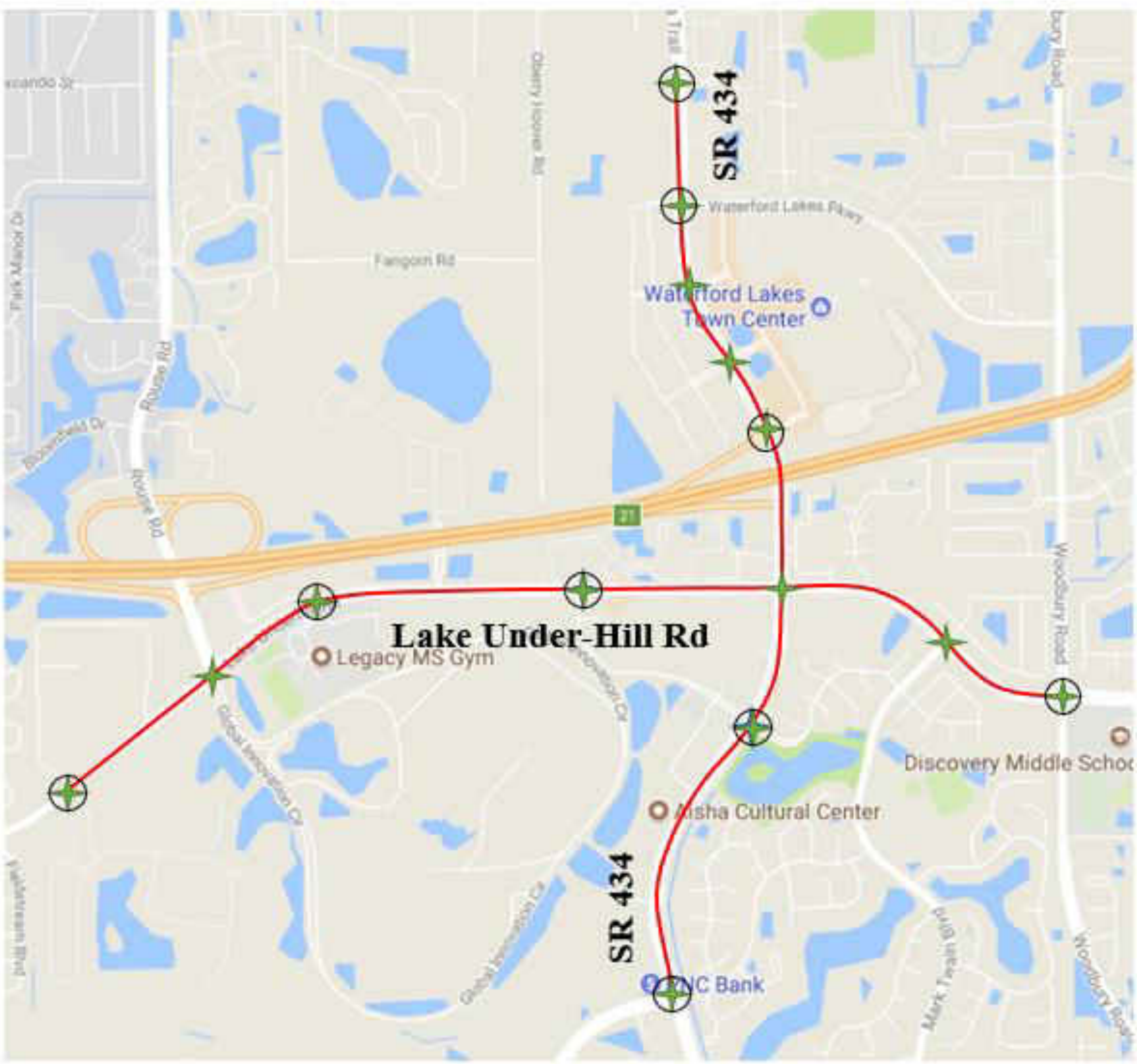


Figure 4: Locations showing BlueMAC devices and studied O-D (circled)

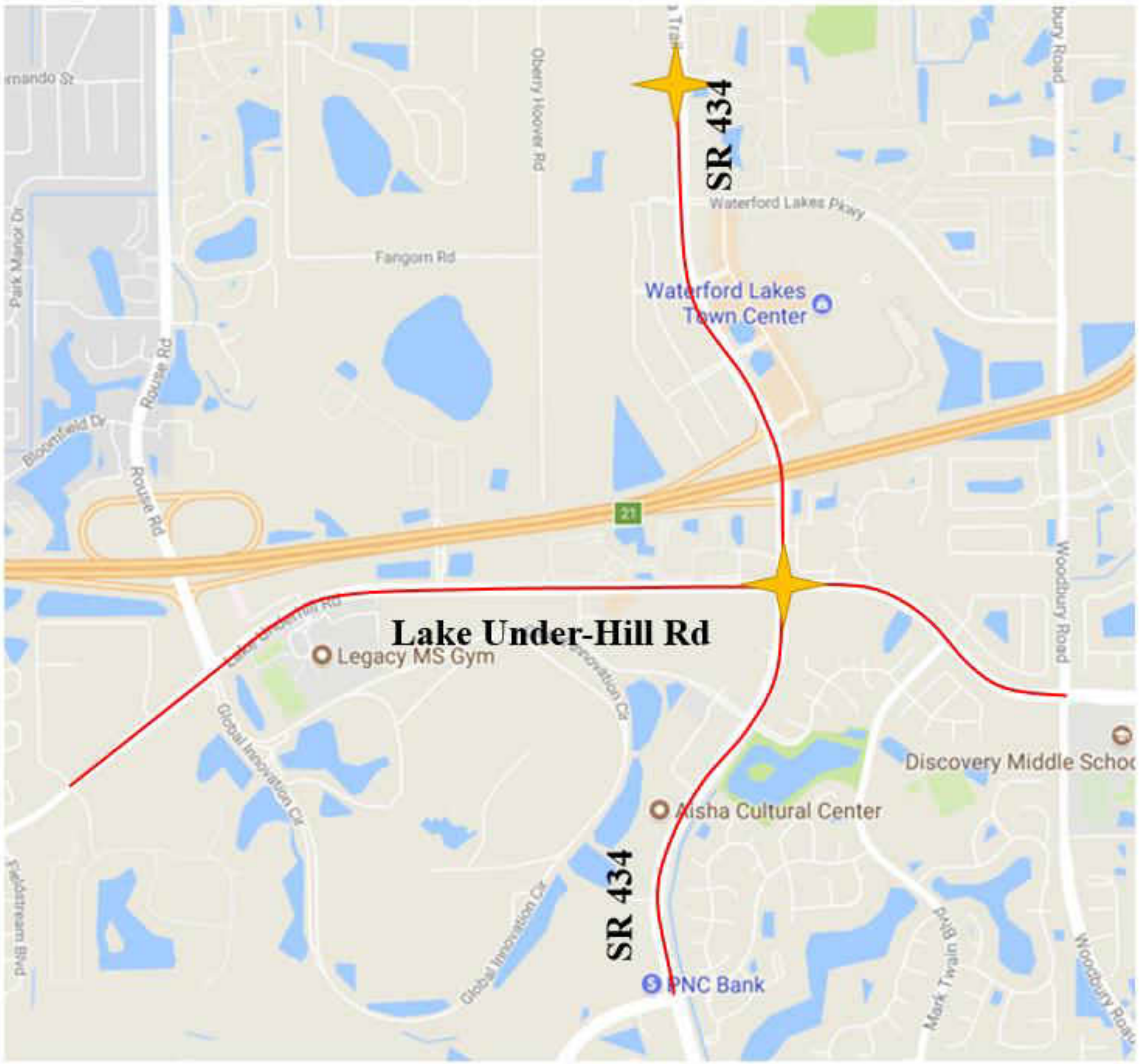


Figure 5: Intersections analyzed with InSync Data

3.4 Data Collection

For each of the above-mentioned three methods, data have been collected for weekdays and weekends and for three peak periods- morning, afternoon, and evening for each corridor and each direction. The data collection date, time and period for each method is shown in Table 3 and

4. Furthermore, the volume is counted as a control parameter to confirm any effect of volume change to the operations.

Table 3: Data Collection Date, Time and Period for Average-Vehicle Method

Method	**Group**	**Data Collection Period**		**Day of Week**	**Time of Day**	**Time**
		Before	**After**			
Average-Vehicle	Study	March 28th to April 1st, 2017	April 18th to April 22nd, 2017	Weekday	Morning	8.30 am
					Afternoon	1.00 pm
					Evening	6.00 pm
				Weekend	Morning	9.30 am
					Afternoon	12.30 pm
					Evening	5.30 pm
	Control	April 11th to April 15th, 2017	April 25th to April 29th, 2017	Weekday	Morning	9.00 am
					Afternoon	1.00 pm
					Evening	6.00 pm
				Weekend	Morning	10.15 am
					Afternoon	1.00 pm
					Evening	6.30 pm

Table 4: Data Collection Date, Time and Period for BlueMAC and InSync

Method	Group	Data Collection Period: Before	Data Collection Period: After	Day of Week	Time of Day	Time
BlueMAC	Study	January 2nd, 2017 to April 9th, 2017	April 15th, 2017 to June 16th, 2017	Weekday	Morning	8.00-10.00 am
					Afternoon	12.00-2.00 pm
					Evening	5.00-7.00 pm
				Weekend	Morning	9.00-11.00 am
					Afternoon	12.00-2.00 pm
					Evening	6.00-8.00 pm
InSync	Study	March 5th, 2017 to April 2nd, 2017	April 15th, 2017 to April 30th, 2017	Weekday	Morning	8.00-10.00 am
					Afternoon	12.00-2.00 pm
					Evening	5.00-7.00 pm
				Weekend	Morning	9.00-11.00 am
					Afternoon	12.00-2.00 pm
					Evening	6.00-8.00 pm

3.5 Statistical Analysis

Two statistical tests were performed to provide enough evidence in favor of the results obtained. A parametric two sample paired t-test (also known as students t-test) is performed for the large sample size where the distribution of the data is considered standard normal. And the

Wilcoxon Signed-Rank test (which is considered as the non-parametric version of the students t-test) is performed for the small sample size where the underlying assumption is that the distribution of the data in not standard normal. A brief detail of these two-statistical method is provided in the following sections.

3.5.1 T-Test

The t-test also called student's t-test is the most commonly applied statistical hypothesis test which is mainly used to compare two averages (means) if they are different from each other. The t-test also tells how significant the differences are. In other words, it lets to know if the differences could have happened by chance. The underlying assumption for the students t-test is that it assumes the dataset comes from or follows a standard normal distribution or a student's t-distribution. Although the normal distribution and student's t-distribution have almost the same shape (bell curve), t-distribution is more applicable for a sample of data or a small size of sample rather than the entire population. Figure 6 shows the graphical representation of a normal distribution and t-distribution. It's observed that with a higher degree of freedom the t-distribution approaches the normal distribution. That means if the sample size approaches the population both distribution will be the same.

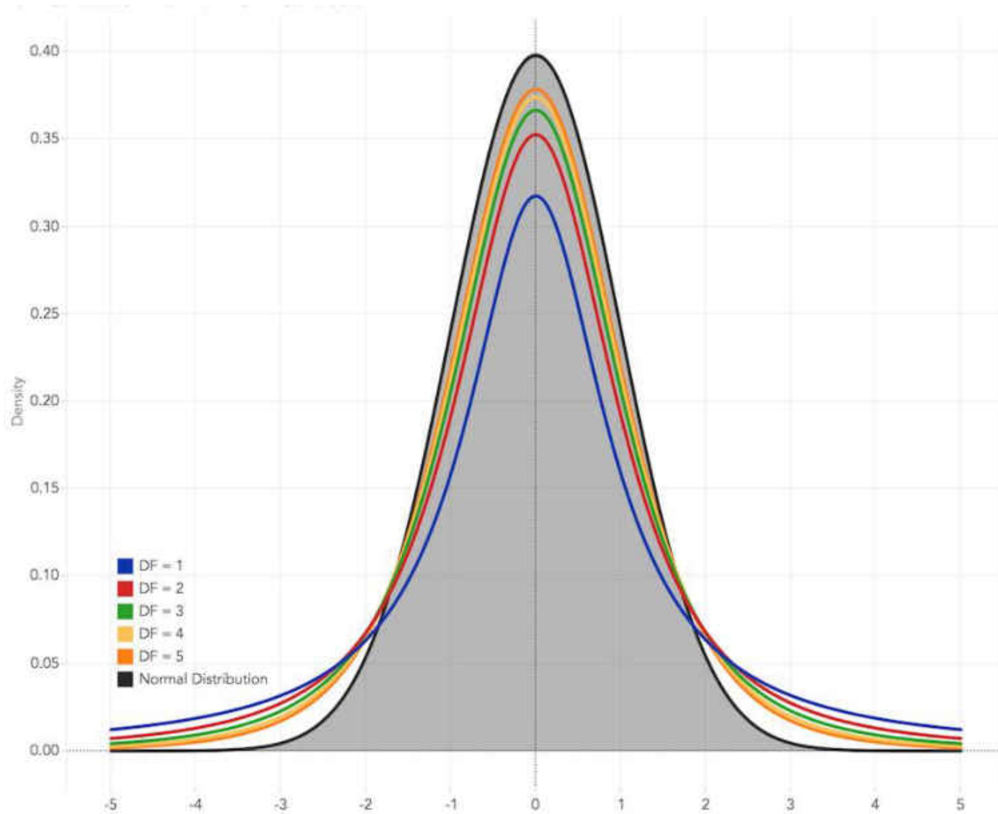


Figure 6: Normal vs t-distribution [29]

Based on the number of sample studied, the t-test is mainly of two types- one sample and two sample. The one sample t-test compares the mean with a designated/standard value and the two-sample t-test compares the mean of two distinct samples. Based on the characteristics of the sample data, the two-sample t-test is again classified into two types- unpaired and paired. Unpaired means there's no relation between the two sets of data to be compared, they are totally independent of each other or they receive different treatment in different environment. The paired data are related, connected or have the same treatment in the same environment just at a different period of time. The paired data could be two types- equal variance and unequal variance. For this study the same treatment is provided to the same sample in a different time period. So, the paired t-test with unequal variance best fits the data which is also called Welch's t-test.

In the students t-test, the t-statistic is calculated and compared with the critical t-value from the chart. The critical t-value depends on the level of significance and degrees of freedom. The comparison between the calculated and critical t-value provides evidence whether to reject or accept the null or alternative hypothesis. Normally, the null hypothesis infers that there’s no significant difference between the two sets of data at the assumed level of significance and the vice versa for the alternative hypothesis. Decision can also be made based on p-value. The formula for determining the t-value is-

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

where, $\bar{X}_1$, s_1^2 and N_1 are the first sample mean, population variance and sample size, respectively. The degrees of freedom associated with this variance estimate is approximated using the equation-

$$\nu \approx \frac{\left(\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2} \right)^2}{\frac{s_1^4}{N_1^2 \nu_1} + \frac{s_2^4}{N_2^2 \nu_2}}$$

Where $v_1 = N_1 - 1$, the degrees of freedom associated with the first variance estimate. Table 17 in Appendix A shows the critical t-value for different degrees of freedom and level of significance.

3.5.2 Wilcoxon Signed-Rank (WSR) Test

In any event, when the data within two correlated samples fail to meet one or another of the assumptions of the t-test, an appropriate non-parametric alternative can often be found in the Wilcoxon Signed-Rank Test. The Wilcoxon signed-rank test is a non-parametric statistical hypothesis test used when comparing two related samples, matched samples, or repeated measurements on a single sample to assess whether their population mean ranks differ. This test is a very handy tool for a sample of smaller size where the underlying distribution doesn't follow standard normal distribution or unknown. The underlying assumptions of the Wilcoxon Signed-Rank test are-

- Data paired and comes from the same population.
- Each pair is chosen randomly and independently.
- The data are measured on at least an interval scale when, as is usual, within-pair differences are calculated to perform the test.

The test procedure involves the calculation of the difference between two paired values and their ranks. First, the difference between the values of each pair is calculated and the sign of the difference is checked. If the value of the difference of any pair is zero, they are excluded. The absolute difference of each pair is then ordered in an ascending manner from smallest to largest value. They are then assigned a rank with the smallest as 1 and so on. Ties receive a rank equal to the average of the ranks they span. Finally, the test statistic W is calculated using the formula-

$$W = \sum_{i=1}^{N_r} [\operatorname{sgn}(x_{2,i} - x_{1,i}) \cdot R_i],$$

Where, N_r is total number of remaining pair after excluding the pairs with zero difference. sgn($x_{2,i}- x_{1.i}$) is the sign of the difference in i-th pair. R_i is the rank of the absolute difference in i-th pair.

The z-score is another test statistic which can also be obtained by using the formula-

$$z = \frac{W}{\sigma_W}, \sigma_W = \sqrt{\frac{N_r(N_r+1)(2N_r+1)}{6}}.$$

The calculated W statistic and z-score is compared with the critical values shown in Table 18 and 19 in Appendix A. Based on the relative comparison between the calculated and critical value, the null or alternative hypothesis is accepted. Generally, if the critical value is greater than the calculated value the alternative is accepted, and the null hypothesis is rejected.

CHAPTER- FOUR: DATA ANALYSIS AND RESULTS

4.1 General

Data have been collected and analyzed using three different methods- the average-vehicle method, the BlueMAC probe data, and the InSync probe data as mentioned earlier. In this chapter, the summary of data analysis and results are represented in both tabular and graphical form. The results are also discussed separately in the following sections for the three distinct approaches.

4.2 First Approach: Average-Vehicle Technique

The average-vehicle (also known as the floating-car or maximum car method depending on the driving technique) method is the simplest and most widely used modus operandi for the speed/travel time study in the field for the conventional before-after study. In the average vehicle method, the driver of the test vehicle tries to drive at the average velocity of the traffic stream without hampering or altering the flow of traffic.

Travel time and delay are two principal measures of effectiveness which can be calculated by the average-vehicle technique. The travel time is directly connected to the speed and the number of stops in the corridor can also be measured by the average-vehicle method which is also another significant parameter for traffic performance study. Data can be collected either manually by a driver and a passenger/observer/collector or automatically by a driver with an equipped car.

For this study, the manual process was utilized with a driver who kept constant throughout the study and an observer who recorded the data through audio-video recording. For consistency, attempts were taken to keep the car in the same lane (leftmost) for all the runs throughout the study without affecting the flow. The test vehicle was also kept constant for the whole period of study which traveled according to the driver's judgment of the average speed of the traffic stream.

The volume counts were obtained as a surplus of the video recording system which is considered as a control parameter to depict any effect of the volume change to the operation of InSync. For example, if the volume is increased significantly in the after period it's less likely to be improved greatly. Data of study and control corridors were collected for weekdays and weekends for three peak periods for each direction and approach. The three peak periods are- the morning peak, the afternoon peak and the evening peak. A control group was selected which has similar characteristics as the study group where there is no change in infrastructure for the before and after period.

Data have been collected for Tuesday and Wednesday for the weekdays and Saturday for weekend. The date, start time and period of data collection are summarized earlier in Table 3. The start time of data collection varies based on the presence of traffic for weekdays and weekend and also for the control and study group. The timing was selected based on the typical recurring congestion in the study area for maximum flow although a few cases captured the normal or minimal flows. Only thru movements were considered, and no left-right turn or side street movements were included for the average-vehicle method.

Figure 28 in Appendix B represents the data collection worksheet used for the manual data collection procedure. Figure 29 in Appendix B consequently depicts the travel time field worksheet which was used to do the hand calculation for travel time and delay. This form can be used by the passenger or data collector in the test car and could be filled instantly while running in the field. Alternatively, they can be filled after the run if the test run is audio-video recorded with necessary commentary. Or both procedures can be combined and utilized for precise data.

A minimum of two test runs of through movement were taken at first for each case and based on the running speed, minimum required sample size was calculated using the following equation-

$$R = \frac{\sum A}{N - 1}$$

Where,

R = average range in running speed

$\sum A$ = sum of calculated speed differences

N = number of completed test runs.

A 95% confidence level and a range of ±2 mph permitted error for running speed were selected. Based on the value of R, confidence interval and permitted error, the minimum number of required run was calculated from the chart provided in the Manual of Transportation Engineering Studies by *H. Douglas Robertson* [31]. There were total 120 runs taken for the two study groups and 60 runs for the control group totaling to 180 runs and almost 500 miles of travel.

The data consisted of over 150GB audio-video records. Among them, a three were excluded due to data inconsistency. A total of 22 cases studied for the two-corridor study group and 12 cases for the single-corridor control group. The cases are varied depending on the time of the day, day of the week, corridor and movement/approach. Average of all runs for each case in the before period was compared to the after period.

Table 5 lists the cases and summarizes the percent improvement of average travel time, delay, speed and number of stops along with the change in volume for each 22 cases of the two study corridors. The percent improvement for travel time ranges between -69% to 42%, for delay -611% to 86%, for speed -41% to 74%, for number of stops -133% to 70% and for volume -27% to 52%. The maximum and minimum values are highlighted in the table. For the travel time and speed, InSync was found to provide better results in 15 out of 22 cases, for delay 14 out of 22, and for number of stops, only 9 cases have improved. 14 among the total 22 cases, there was an increase in volume. So, the InSync system improved mostly the performance in reducing travel time and delay. The cases where the system deteriorated the performance was mostly during the evening and afternoon periods when the intersections were operating near capacity with heavy conflicting movements. So, InSync might not be effective with higher traffic volume. The improvement by time of day is discussed later.

Table 6 lists the cases and summarizes the percent improvement of average travel time, delay, speed and number of stops along with the change in volume for each 12 cases of the control corridor. The percent improvement for travel time ranges between -29% to 31%, for delay -248% to 53%, for speed -23% to 45%, for number of stops -17% to 40%. The percent increase for the volume ranges between -34% to 41%. The maximum and minimum values are highlighted in the table. The travel time improved in 8 out of 12 cases, for speed 9 out of 12 cases, for delay 7 out of 12, and for number of stops, 6 cases out of 12 have improved.

Table 5: Percent Improvement for Each 22 Cases of Study Corridors (Average-Car)

Corridor	Direction	Day of Week	Time of Day	% Improvement				% Change
				Travel Time	Delay	Speed	No. of Stop	Volume
SR-434 (Alafaya Trail)	NB	Weekday	Morning	(16.1)*	(36.9)	(13.9)	**(133.0)**	**52.3**
			Afternoon	8.2	25.1	8.9	(49.7)	4.5
			Evening	(16.8)	(34.1)	(14.4)	(100.0)	(17.3)
		Weekend	Morning	39.5	**86.4**	65.3	70.0	23.1
			Afternoon	19.3	45.4	24.0	(16.7)	8.1
			Evening	15.4	31.0	18.2	(28.8)	(3.6)
	SB	Weekday	Morning	**41.9**	69.9	72.2	22.3	12.7
			Afternoon	33.3	63.6	49.9	(7.3)	(22.4)
			Evening	**(69.0)**	(157.9)	**(40.8)**	(45.2)	15.3
		Weekend	Morning	36.6	80.6	57.8	59.1	29.5
			Afternoon	36.5	30.0	57.5	63.6	1.8
			Evening	24.0	57.4	31.5	0.0	8.0
Lake Under Hill Road	EB	Weekday	Morning	32.5	56.9	48.1	**70.0**	15.2
			Afternoon	42.5	73.7	**74.0**	66.7	(17.4)
			Evening	0.7	(1.6)	0.7	24.9	(10.9)
		Weekend	Afternoon	2.3	7.1	2.3	0.0	(14.5)
			Evening	10.5	14.3	11.7	0.0	**(27.1)**
	WB	Weekday	Morning	14.6	35.0	17.1	35.6	50.5
			Afternoon	(7.3)	**(611.5)**	(6.8)	(33.3)	36.4
			Evening	(27.9)	(134.3)	(21.8)	30.0	10.4
		Weekend	Afternoon	(14.8)	(31.8)	(12.9)	0.0	(5.8)
			Evening	(25.0)	(463.0)	(20.0)	(50.0)	1.6

*Negative values are shown in parentheses which indicate deterioration in performance

Table 6: Percent Improvement for Each 12 Cases of Control Corridor (Average-Car)

Corridor	Direction	Day of Week	Time of Day	% Improvement				% Change
				Travel Time	Delay	Speed	No. of Stop	Volume
SR-434 (Alafaya Trail)	NB	Weekday	Morning	**(28.71)**	**(248.28)**	**(22.59)**	(33.33)	(0.87)
			Afternoon	0.79	46.25	0.32	0.00	(1.95)
			Evening	8.16	(13.04)	8.99	20.00	**41.14**
		Weekend	Morning	18.82	31.61	23.35	33.33	(7.40)
			Afternoon	(6.57)	(21.97)	(6.17)	0.00	32.10
			Evening	9.98	35.92	10.69	**40.00**	2.03
	SB	Weekday	Morning	21.54	32.16	41.76	23.71	(26.03)
			Afternoon	15.14	7.49	9.96	0.00	(1.95)
			Evening	**31.14**	**52.52**	**45.21**	33.33	**(33.85)**
		Weekend	Morning	(2.58)	(2.59)	0.73	0.00	41.14
			Afternoon	15.34	50.91	17.74	14.29	12.60
			Evening	(9.11)	(15.38)	(7.18)	**(16.50)**	(7.40)

The overall percent improvements irrespective of the cases for the travel time, delay, speed and number of stop for the two study corridors with relation to the time of the day are graphically visualized in Figure 7, 8, 9 and 10 respectively. It's obvious from the figures that InSync mostly improved the condition at the AM/morning period. For mid-day/afternoon, the improvement was very low or negative. For the evening period, the improvements were mostly negative that means InSync deteriorated the situation at the evening period greatly. Figure 11 shows the volume change by the time of day and it's observed that for the mid-day and evening, the volume change is negative meaning that the volume reduced at the after period rather than increasing. So, although the volume was reduced at the after period, the InSync system failed to improve the performance rather deteriorated it.

The overall percent improvements of travel time, delay, speed and number of stop for the control corridor with relation to the time of day are graphically visualized in Figure 12, 13, 14 and 15 respectively. Figure 18 shows the volume change by the time of day. From the figures, It's observed that unlike the study corridor, the control corridor doesn't follow any specific rather varying trend of change although the volume at the after period is increased for all the three times of the day on an average with the mid-day as a maximum.

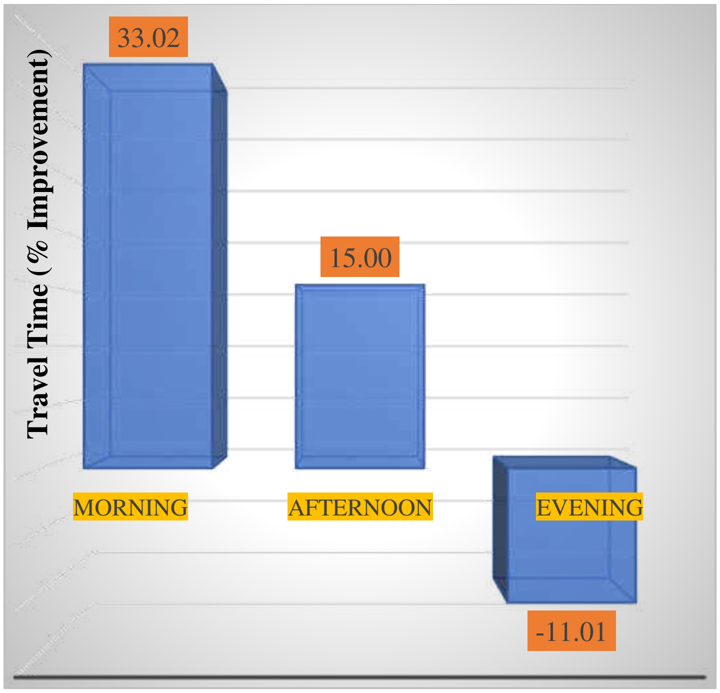


Figure 7: Percent improvement in Travel Time by time of day (Study Group, Average-car)

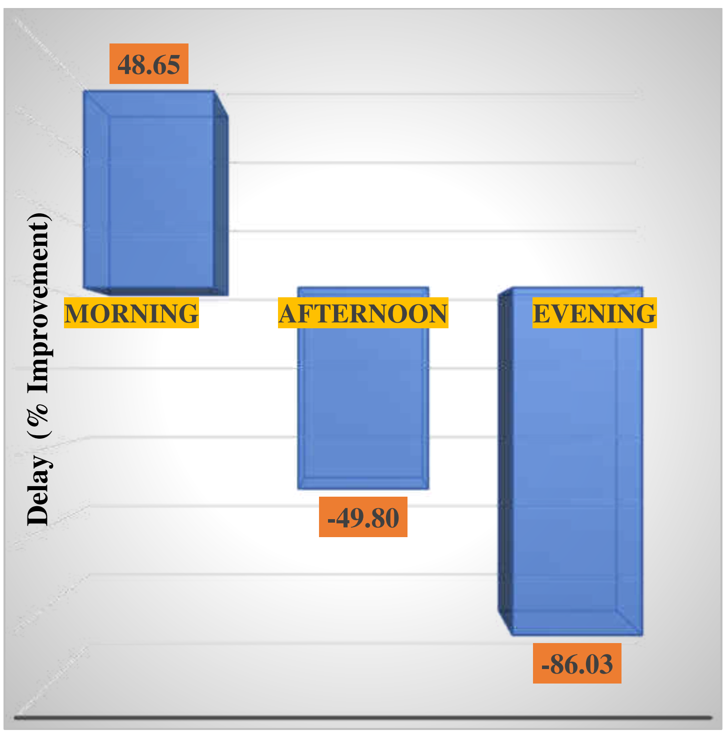


Figure 8: Percent improvement in Delay by time of day (Study Group, Average-car)

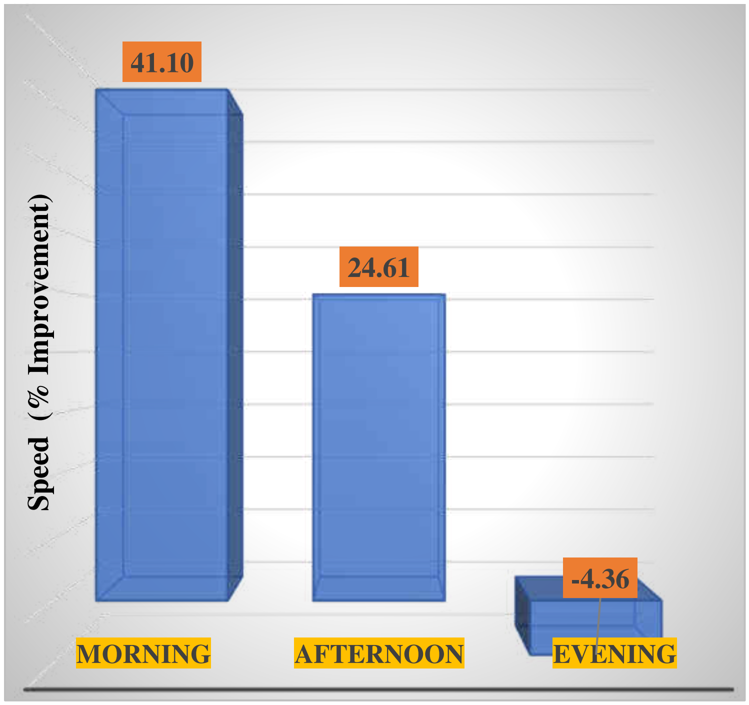


Figure 9: Percent improvement in Speed by time of day (Study Group, Average-car)

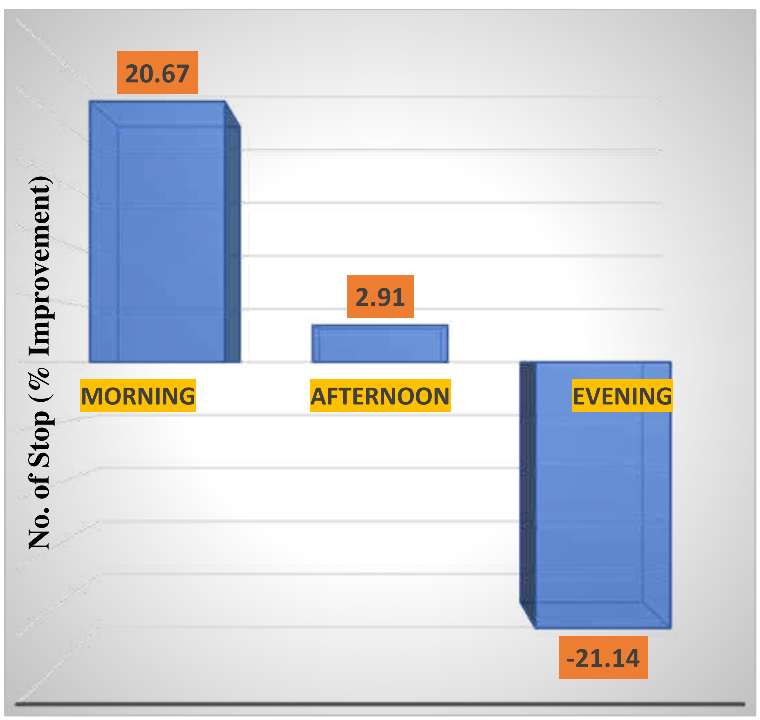


Figure 10: Percent improvement in No. of Stop by time of day (Study Group, Average-car)

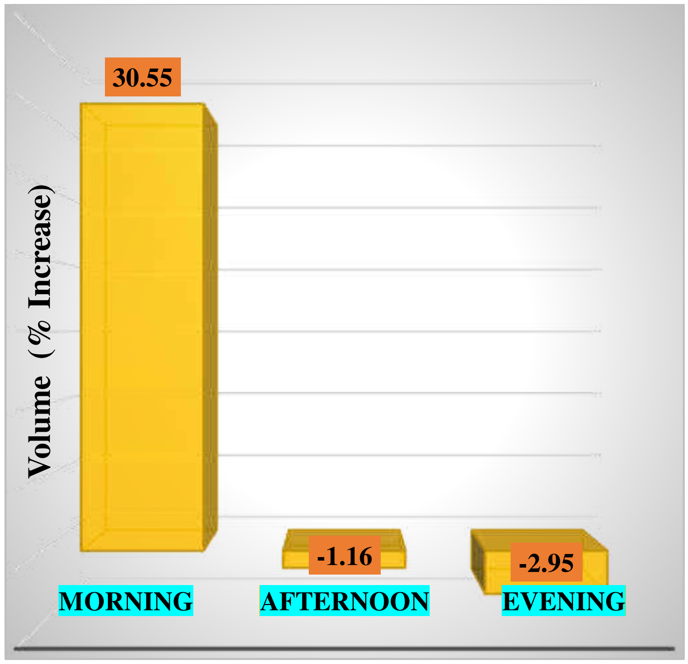


Figure 11: Percent increase in Volume by time of day (Study Group, Average-car)

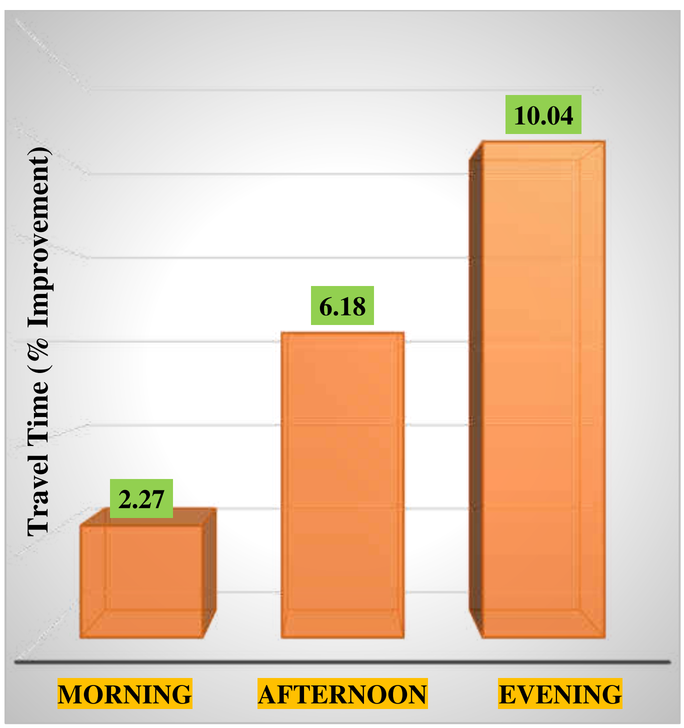


Figure 12: Percent improvement in Travel Time by time of day (Control Group, Average-car)

Figure 13: Percent improvement in Delay by time of day (Control Group, Average-car)

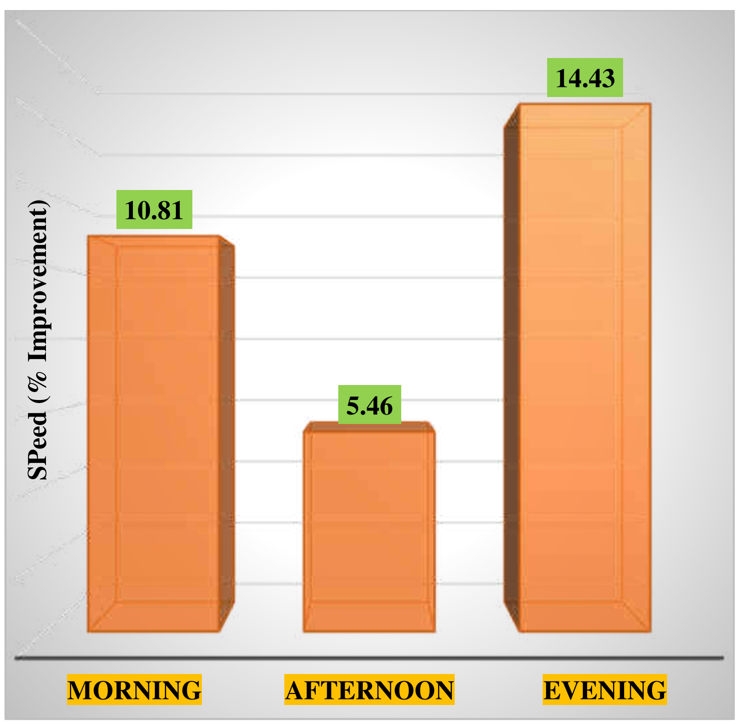


Figure 14: Percent improvement in Speed by time of day (Control Group, Average-car)

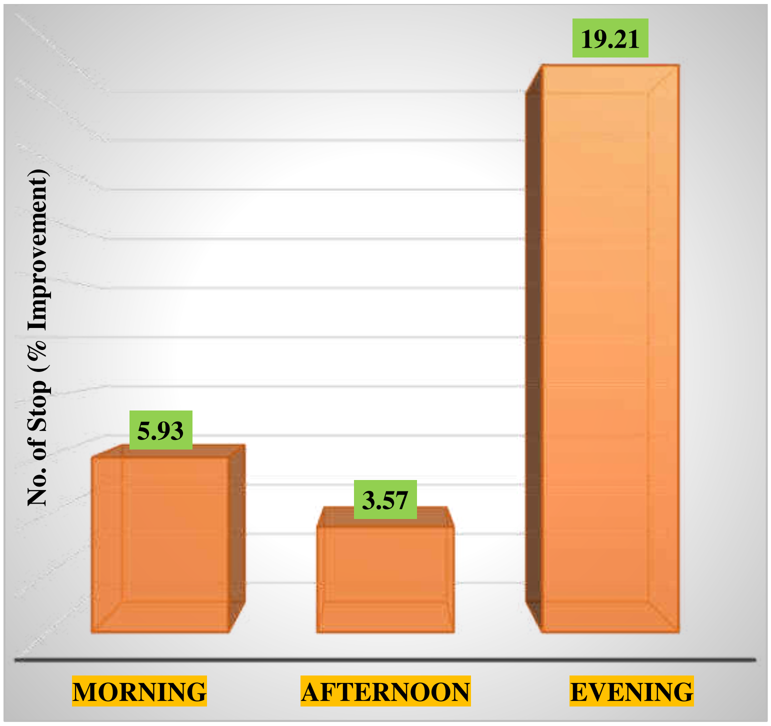


Figure 15: Percent improvement in No. of Stop by time of day (Control Group, Average-car)

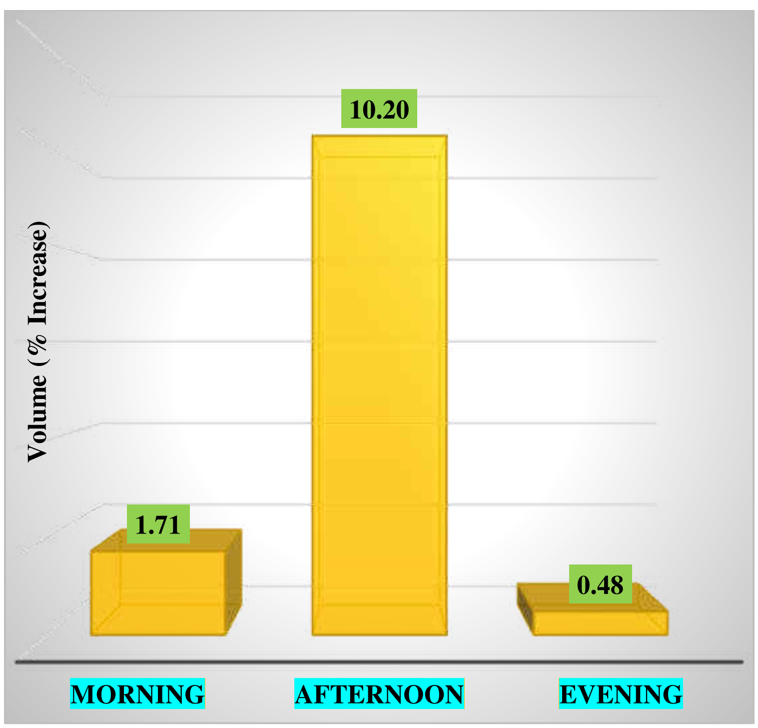


Figure 16: Percent increase in Volume by time of day (Control Group, Average-car)

The overall average percent improvement for travel time, delay, speed and number of stops were found to be 10.3%, 15.8%, 14.6%, and 12.4% respectively with an average of 5.5% volume increase for the study group. The overall percent improvement of the control corridor is 8.7%, 18.4%, 7.2%, and 12.5 % for travel time, delay, speed and number of stops respectively with an average of 1.9% volume increase (as shown in Table 7). The non-parametric Wilcoxon Signed-Rank (WSR) test was performed to subject for a significant difference in the before and after period using the JMP Pro 13 software [33] and an online Wilcoxon Signed-Rank test calculator [34]. There's no statistical difference found at the 95% confidence interval for any of the parameters studied for any of the corridors. Although not recommended in WSR test, but with a 90% confidence interval, a significant difference was found in travel time and speed for the study corridors and number of stops for the control corridor which indicated a significant improvement in both study and control corridor. The summary of average percent improvement and statistical results for both study and control group are represented in Table 7. As from table 10 it's observed that the p value is not less than 0.05 meaning the change is not statistically significant at 95% confidence interval.

The overall mean travel time, delay, speed, number of stops and volume for before and after period for the study and control corridors are depicted in Figure 17, 18, 19, 20 and 21 respectively and it's found that the control corridor has almost equal overall percentage of improvement and in some cases more improved than the study corridors without any prior treatment with an average volume increase of 2% than the control group which ascertains the potential effect of historical, maturation (trends over time), regression (tendency to regress to the mean), randomness artifacts or any other factors rather than the effect of InSync only. There might be a small effect of InSync as the volume increase in the study corridors was slightly higher than that of the control corridor.

To study the validity of the claim of uncertainty and to confirm whether there's significant effect of InSync ATCS over the performance improvement of signal control system on the respective corridors, two further approaches have been adopted utilizing the private vendor probe data from BlueMAC and historical data provided by InSync itself which are discussed in the following chapters.

Table 7: Average Improvement and Statistical Results (Average-Car)

Parameters	Group	Before (Avg.)	After (Avg.)	% Improve	W-statistic	z-score	p-value
Travel Time (min)	**Study**	5.35	4.8	10.31	72	-1.78561	**0.0731**
	Control	5.81	5.31	8.7	20	-1.4905	0.1514
Delay (min)	**Study**	2.01	1.69	15.83	85	-1.3473	0.1894
	Control	2.12	1.73	18.41	24	-1.1767	0.2661
Speed (mph)	**Study**	23.55	26.99	14.58	70	-1.8343	**0.0650**
	Control	26	27.87	7.18	19	-1.5689	0.1294
No. of Stop	**Study**	2.48	2.17	12.37	59	-1.1541	0.3999
	Control	2.67	2.33	12.5	4	-1.9604	**0.0625**
Volume (vehicle/day)	**Study**	2776.59	2928.73	5.48	94	-1.0551	0.3021
	Control	3235.42	3296.42	1.89	31.5	-0.5883	0.6825

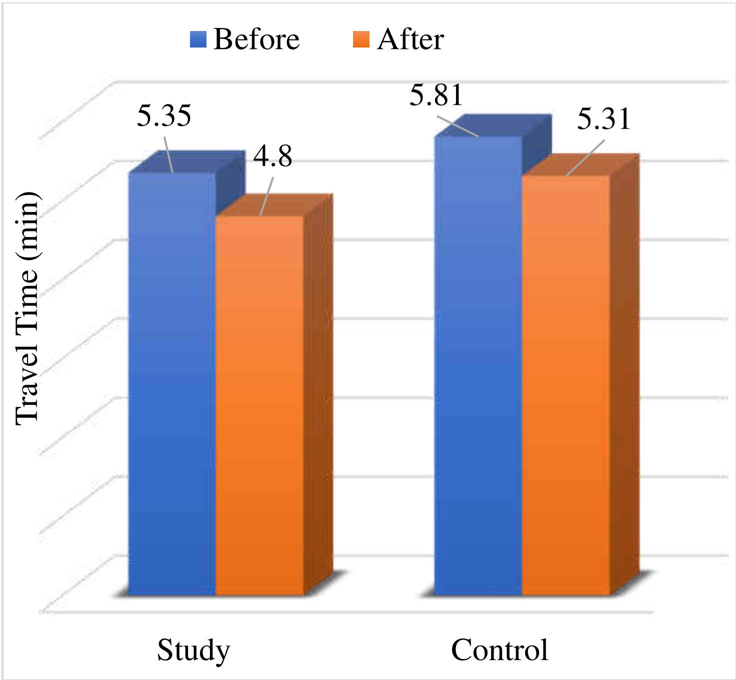


Figure 17: Mean Travel Time in Before and After Period for Study and Control Corridors (Average-Car)

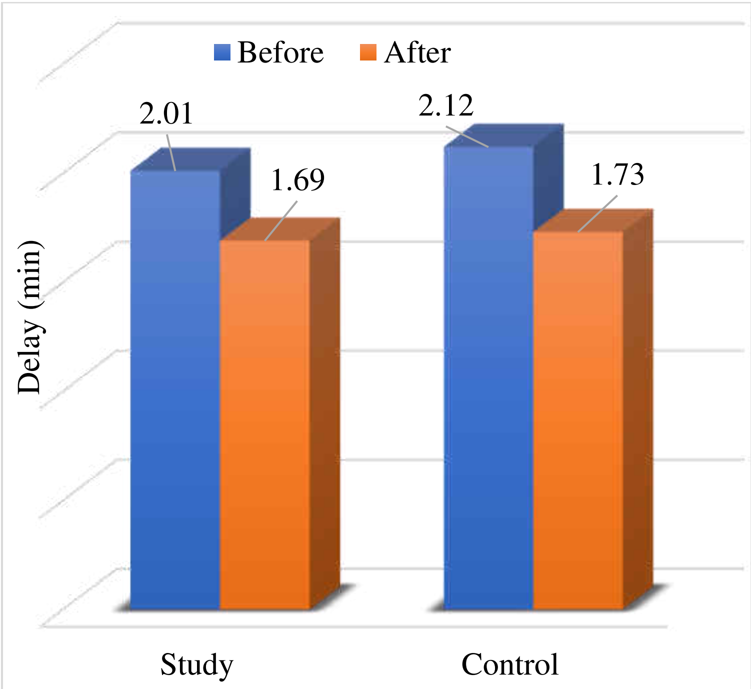


Figure 18: Mean Delay in Before and After Period for Study and Control Corridors (Average-Car)

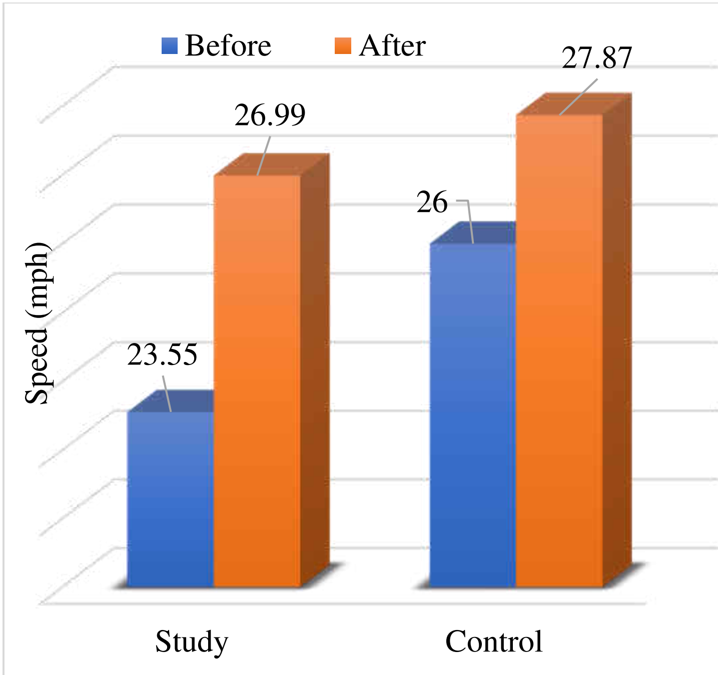


Figure 19: Mean Travel Speed in Before and After Period for Both Study and Control Corridors (Average-Car)

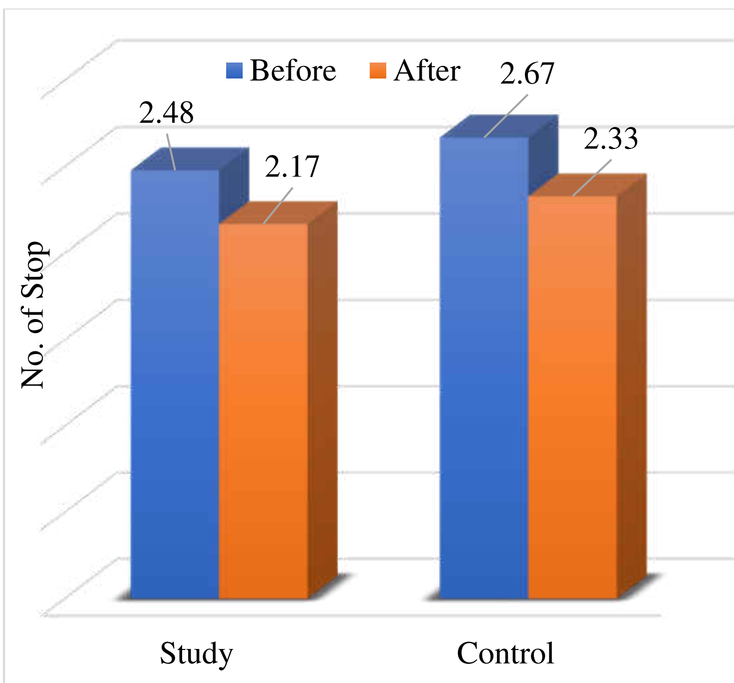


Figure 20: Average No. of Stop in Before and After Period for Both Study and Control Corridors (Average-Car)

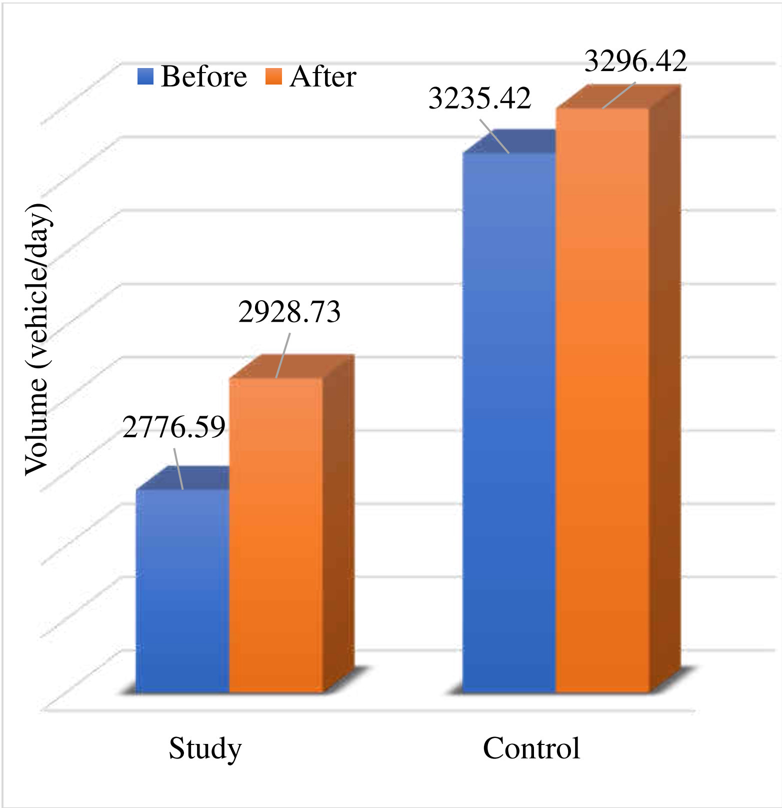


Figure 21: Average Volume in Before and After Period for Both Study and Control Corridors (Average-Car)

4.3 Second Approach: BlueMAC Probe Data

Media Access Control (MAC) readers represent the latest advances in the world of real-time transportation data collection and monitoring in the field, and BlueMAC developed by a computer and IT firm- Digiwest LLC (Portland, Oregon) is considered as the most comprehensive data collection device and software suite utilizing this technology [35]. By collecting and time-stamping anonymous MAC addresses from passing vehicles and wireless devices and then matching these addresses across a network of devices, BlueMAC can provide data of travel times, average speeds, origin-destination etc. Data is accessible in real-time through the cloud and rendered into customizable, user-friendly reports by BlueMAC's high-end software.

Like the average-car method, data have been collected for both weekdays and weekends, for three times a day for a period of three months before and after (Table 4). Data collected through the web User Interface (UI) of BlueMAC through the server of Orange County Public Works Department. The travel time and speed data were available from BlueMAC database which are screened out from enormous outliers to befit for analysis using Microsoft Excel Spreadsheet and JMP Pro 13. There was a total of 54 cases studied in a total of ten distinguished origin-destination pairs for the two study corridors. Among the ten origin-destination pair, five were consisted of through movements only, four included left turns, and one included the right turns. Table 8 provides the distribution of cases for O-D and movements. The cases are differentiated by the time of day, day of week, movements and origin-destination. The origin and destination were selected both along the corridors and interchanging between them through left or right turns. So, unlike the average-vehicle method, BlueMAC covers turning movements in excess of the trough movement.

The summary of the travel time and speed for all the cases in before and after period is delineated in Table 9 and 10. Table 9 shows the results for all through movements along the single corridor among two whereas Table 10 shows the results for turning travel along the two corridors. In table 9 right turns are highlighted, the rest includes left turns.

From Table 9 and 10, It's found that in 15 out of 54 cases the performance deteriorated for travel time and 16 out of 54 for speed. The percent improvement ranges from -39% to 35% for the travel time and -33% to 57 % for average speed. The maximum and minimum values are highlighted in Table 9 and 10. The cases where InSync failed to provide any improvement were mainly those included left turns mostly and a few right turns also. For the through movements InSync improved for almost all the cases. Also, InSync mainly provided better results for the morning or AM period. For afternoon and evening the improvement was very negligible or negative. Table 11 shows the percent improvement by the time of day (TOD) and the movements. Figure 22 and 23 represents graphically the percent improvement of travel time and speed by the movement whereas Figure 24 and 25 delineates the percent improvement of travel time and speed by the time of day (TOD). From the table and figures, it's obvious that InSync improved the performance for morning period and through movements mainly.

Table 8: Distribution of Cases Studied (BlueMAC)

No. of O-D	Movement Includes	No. of Cases
5	Through	37
4	Left Turn	21
1	Right Turn	6
Total = 10		Total = 54

Table 9: Travel Time and Speed Summary for Through Travel (BlueMAC)

Corridor (Origin-Destination)	Day of Week	Time of Day	Avg. Travel Time (sec)			Avg. Speed (mph)		
			Before	After	% Improve	Before	After	% Improve
SR-434 (Curry Ford Road-Ashton Manor Way)	Weekday	Morning	287.79	234.71	18.44	24.64	30.77	24.88
		Afternoon	319.31	275.71	13.65	22.71	26.06	14.75
		Evening	326.76	296.95	9.12	22.41	24.62	9.86
	Weekend	Morning	273.64	258.09	5.68	26.06	27.92	7.14
		Afternoon	336.17	287.04	14.61	21.51	25.01	16.27
		Evening	311.00	271.48	12.71	23.01	26.95	17.12
SR-434 (Ashton Manor Way-Curry Ford Road)	Weekday	Morning	272.18	202.15	25.73	28.41	35.80	26.01
		Afternoon	347.55	226.08	**34.95**	21.21	33.27	**56.86**
		Evening	329.91	285.57	13.44	24.42	27.68	13.35
	Weekend	Morning	317.67	224.29	29.40	25.05	32.81	30.98
		Afternoon	332.25	250.12	24.72	21.56	29.52	36.92
		Evening	302.5	216.63	28.39	24.56	33.71	37.26
SR-434 (Waterford Lake Pkwy to Huckleberry Finn)	Weekday	Morning	175.5	164.87	6.06	25.68	27.29	6.27
		Afternoon	235.75	181.11	23.18	18.8	24.85	32.18
		Evening	219.6	237.76	(8.27)	20.02	19.55	(2.35)
	Weekend	Morning	195.83	164.98	15.75	21.67	27.46	26.72
		Afternoon	247.47	180.65	27.00	18.76	25.31	34.91
		Evening	210.33	175.76	16.44	22.3	25.28	13.36
LUH (Legacy PI-Woodbury Road)	Weekday	Morning	344.07	341.70	0.69	25.75	24.04	(6.64)
		Afternoon	359.58	294.70	18.04	23.25	27.88	19.91
		Evening	401.43	356.00	11.32	20.28	24.15	19.08
	Weekend	Morning	355.71	282.50	20.58	24.48	27.70	13.15
		Afternoon	335.43	267.37	20.29	23.57	30.94	31.27
		Evening	398.60	286.63	28.09	20.26	27.73	36.87
LUH (Woodbury Road-Legacy PI)	Weekday	Morning	305.25	279.33	8.49	25.97	28.70	10.51
		Afternoon	355.14	296.57	16.49	25.01	26.66	6.60
		Evening	376.00	292.33	22.25	20.80	29.38	41.25

Table 10: Travel Time and Speed Summary for Turning Travel (BlueMAC)

Corridor (Origin-Destination)	Day of Week	Time of Day	Avg. Travel Time (sec)			Avg. Speed (mph)		
			Before	After	% Improve	Before	After	% Improve
Mixed (ALA_ Huckleberry Finn to LUH_ Huckleberry Finn)	Weekday	Morning	88.48	102.64	(16.00)	21.08	19.02	(9.77)
		Afternoon	102.66	113.2	(10.27)	18.23	17.05	(6.47)
		Evening	116.84	129.1	(10.49)	16.53	15.14	(8.41)
	Weekend	Morning	80.06	98.21	(22.67)	22.61	19.86	(12.16)
		Afternoon	111.85	121.58	(8.70)	17.87	16.07	(10.07)
		Evening	104.55	112.52	(7.62)	18.61	17.5	(5.96)
Mixed (LUH_ Huckleberry Finn to ALA_SR 408 WB)	Weekday	Morning	167.64	162.89	2.83	15.58	16.2	3.98
		Afternoon	170.04	163.51	3.84	14.87	15.53	4.44
		Evening	166.94	198.29	(18.78)	15.08	12.6	(16.45)
	Weekend	Morning	145.02	158.8	(9.50)	16.9	15.69	(7.16)
		Afternoon	181.34	188.56	(3.98)	13.98	13.36	(4.43)
		Evening	171.21	166.11	2.98	14.2	14.94	5.21
Mixed (LUH_ Huckleberry Finn to ALA_ Waterford Lakes Pkwy)	Weekday	Morning	265.17	221.29	16.55	18.12	18.91	4.36
		Afternoon	278	229.72	17.37	15.02	18.33	22.04
		Evening	196.15	272.9	**(39.13)**	22.78	15.28	**(32.92)**
	Weekend	Morning	255.33	232.97	8.76	16.35	17.67	8.07
		Afternoon	256.5	278.72	(8.66)	15.93	15.17	(4.77)
		Evening	248	244.95	1.23	16.52	16.59	0.42
Mixed (LUH_ Legacy MS- to ALA_ Curry Ford Road)	Weekday	Morning	210.81	206.31	2.13	30.88	29.92	(3.11)
		Afternoon	211.13	219.46	(3.95)	28.93	28.60	(1.14)
		Evening	286.49	245.03	14.47	21.93	25.24	15.09
	Weekend	Morning	185.80	172.17	7.34	31.90	34.49	8.12
		Afternoon	237.15	232.77	1.85	27.38	28.17	2.89
		Evening	188.15	198.96	(5.75)	31.58	32.68	3.48
Mixed (ALA_ Curry Ford to LUH_ Legacy MS)	Weekday	Morning	325.68	275.45	15.42	20.73	23.19	11.87
		Afternoon	270.18	245.37	9.18	24.45	25.88	5.85
		Evening	296.40	328.86	(10.95)	20.93	19.77	(5.54)

Table 11: Percent Improvement by Time of Day and Movement (BlueMAC)

Variable	Particular	Avg. Travel Time (sec)			Avg. Speed (mph)		
		Before	After	% Improve	Before	After	% Improve
Time of Day	Morning	191.55	181.19	5.41	21.57	21.66	0.41
	Afternoon	202.09	199.21	1.43	19.63	19.80	0.85
	Evening	197.19	210.75	-6.87	19.80	18.86	-4.73
Movement	Through	306.39	253.00	17.42	23.04	27.82	20.72
	Left Turn	190.38	192.65	-1.19	17.92	17.32	-3.35
	Right Turn	219.92	212.45	3.40	28.77	29.85	3.77

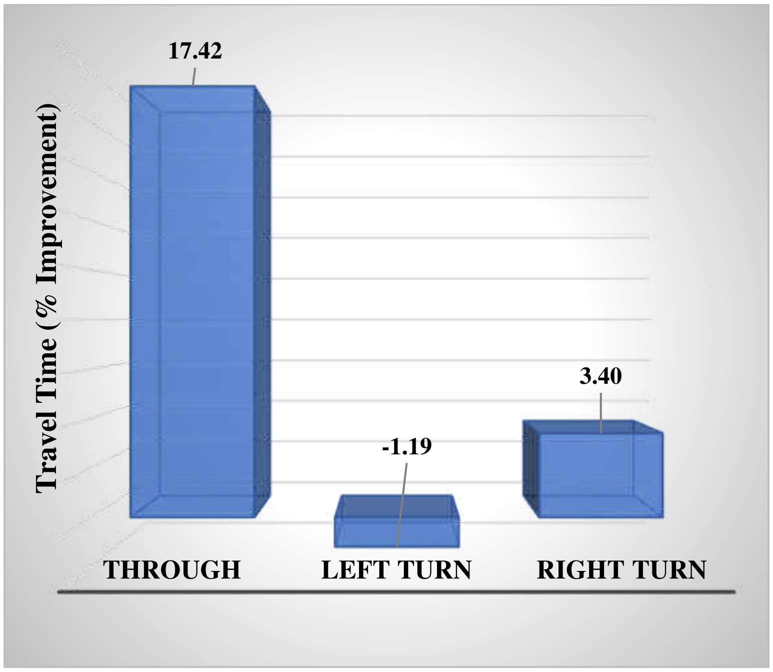


Figure 22: Percent improvement in Travel Time by Movement (BlueMAC)

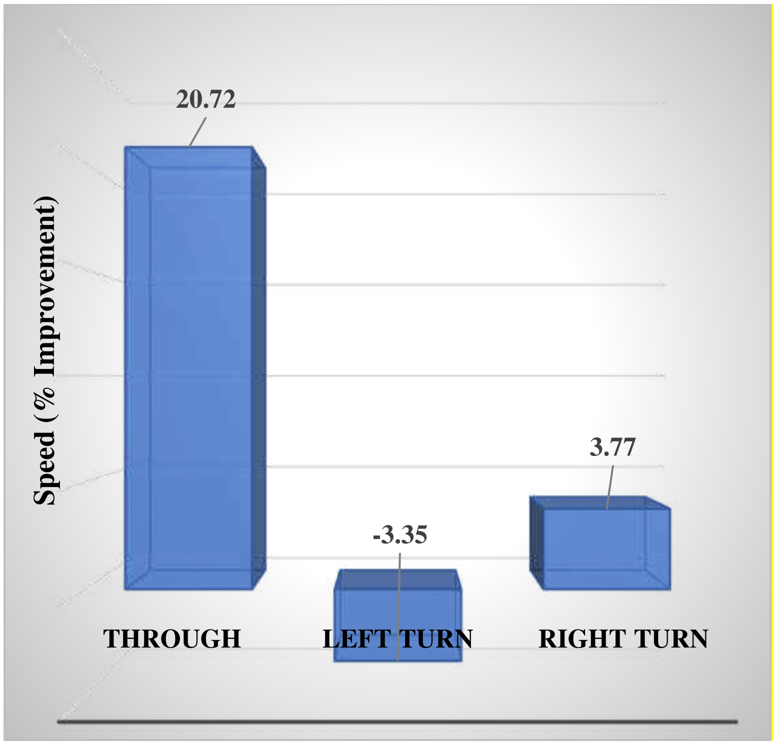


Figure 23: Percent improvement in Speed by Movement (BlueMAC)

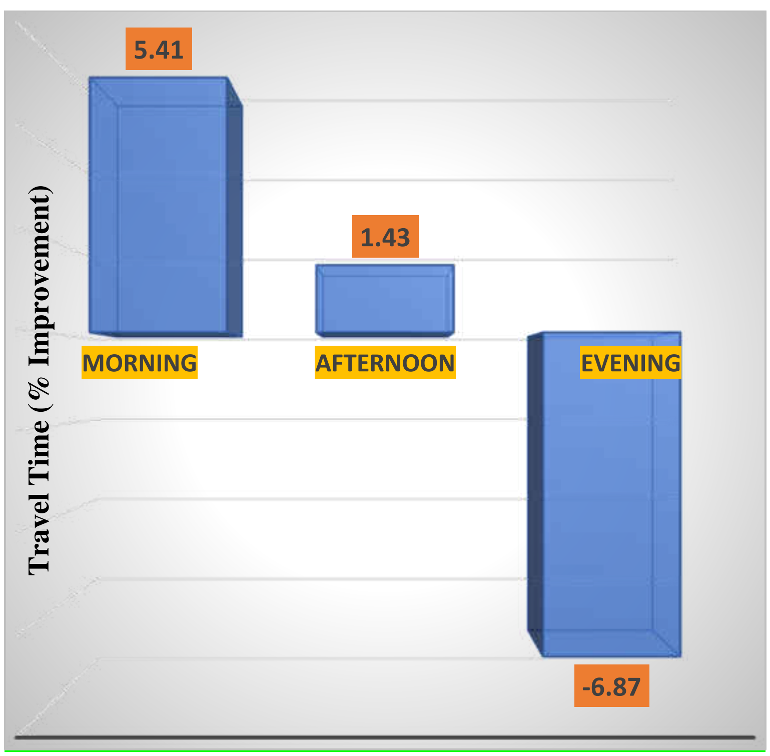


Figure 24: Percent improvement in Travel Time by TOD (BlueMAC)

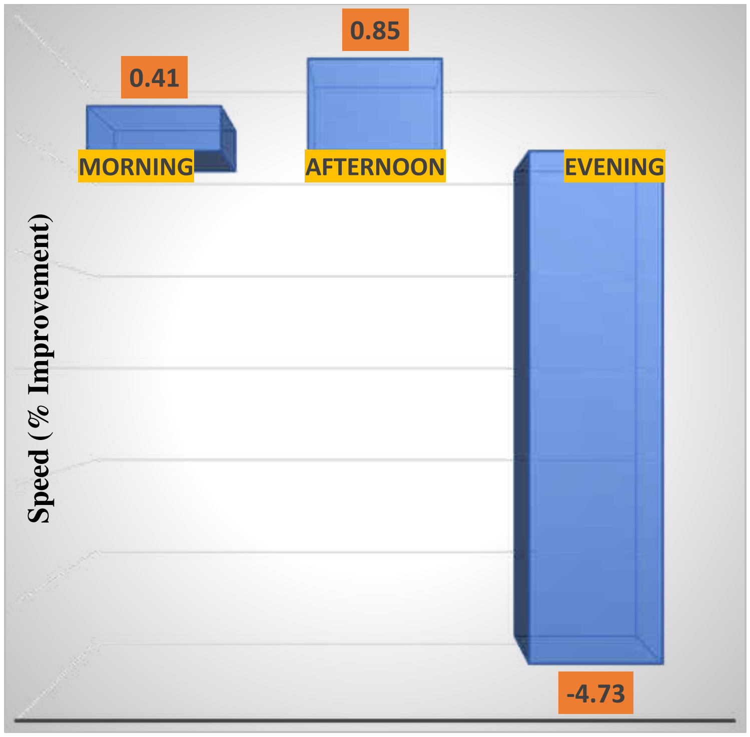


Figure 25: Percent improvement in Speed by TOD (BlueMAC)

The final summary along with the statistical results are shown in Table 12. The overall average percent improvement in both travel time and speed is 10% approximately. Both the non-parametric WSR test and parametric t-test were performed to get significant results. The sample size is large enough in this case to assume standard normal distribution. The statistical tests are performed using the JMP Pro 13 software and online test calculator. The WSR test was performed using the same online calculator as the average-car method. The t-test was performed using a different online interface than the WSR test [36].

The statistical test (WSR and t-test) results provide very promising evidence for significant changes in the after period as the p-value is significantly very small. So, the performance of the system significantly reduced travel time and increased speed although it's not 100% confirmed that these improvements are solely attributed to InSync ATCS as there were no adjacent control corridor/intersections available which are equipped with BlueMAC or other data collection device for analysis to address the effect of other factors. Also, BlueMAC doesn't provide any indication of delay, number of stops and volume change. There might still be a chance that the improvements were because of other hidden factors or parameters. Also, the side street movements are not also considered for this method. The historical and maturation effect is counteracted through the analysis of long time series. A third approach was also conducted to account for further potential flaws in the evaluation process which is discussed in the following sections.

Table 12: Final summary with Statistical Results (BlueMAC)

Statistical Test		Avg. Travel Time (sec)			Avg. Speed (mph)		
		Before	After	% Improve	Before	After	% Improve
	Average	251.67	225.03	10.59	21.69	23.96	10.48
WSR test	W-statistic	282			283		
	z-score	-3.965			-3.9564		
	p-value	<0.0001			<0.0001		
T-test	t-ratio	4.8697			4.5290		
	p-value	<0.0001			<0.0001		

4.4 Third Approach: InSync Data

Although InSync provides an array of intersection delay and queue length data, researchers are less likely to use InSync data because of several reasons, the main reason may be that the InSync is not considered as a data collection system. The other reasons are separately discussed in chapter five. For this study the InSync data was considered after a thorough understanding for analysis to confirm the findings in the two other methods.

InSync database provides two types of data- the Turning Movement Counts (TMC) data which includes vehicle counts per phase and lane for every 15 minutes and the history data which provides the details of each movement with the time, duration, queue and wait time for each phase. The InSync database also provides vehicles count which helped to verify the volume counts obtained through the average-car method. The total wait time and queue length for an intersection for each movement (green) was calculated from the raw history data provided by InSync using JMP Pro 13. Queue logged in the history report is defined by InSync as the largest number of vehicles seen in a phase at the time logged in the history log. Wait time similarly refers to the wait time in seconds of the first car that was detected on the phase at the time logged. The History report logs an entry every time the light status changes.

Data collected for the same circumstances (as described at Table 4) as previous methods for two weeks before and the after period. There were total 90 different cases studied for two intersections and ten distinct movements, among them 2 cases are omitted due to insufficient data. Among them, 30 cases are studied for one of the intersections having one major road with a minor side street and 48 cases are studied for the other intersection having both major roads with high volume. The cases are distinguished from each other based on the time of day, day of week, intersection and movement.

The total queue builds at the intersection and wait time of all vehicles for all approaches/directions at the intersection for every single/paired movement (green) was calculated for the study period and the average was compared. Among 88 cases, only 21 cases show an improvement for queue length and 41 cases for wait time as shown in Table 16 and 17. The percent improvement ranges from -114% to 23% for the queue length and -194% to 72% for the wait time. The maximum and minimum values are highlighted in Table 13 and 14. The cases where the performance improved at the intersection as well as along the corridor are mostly at the intersection with a minor side street and with lower traffic volumes (Table 14). Table 15 separately shows the percent improvement for the two intersections.

Table 13: Summary of Percent Improvement in Intersection having both way major (InSync)

Inter-section	**Move-ment**	**Para-meter**	**% Improvement**					
			Weekday			**Weekend**		
			Morning	**Afternoon**	**Evening**	**Morning**	**Afternoon**	**Evening**
SR-434 and Lake Underhill Road (Both Major)	NT	Queue	(83.03)	(98.25)	N/A	(51.25)	N/A	(48.99)
		Delay	25.33	22.75	N/A	10.54	N/A	21.67
	ST	Queue	(82.65)	(82.12)	(113.40)	(47.02)	**(114.06)**	(60.24)
		Delay	(5.22)	13.30	(77.47)	5.08	(26.74)	4.36
	ET	Queue	(50.52)	(65.89)	(92.63)	3.64	(82.84)	(6.13)
		Delay	(88.89)	(77.94)	(149.18)	(57.56)	(184.62)	(84.05)
	WT	Queue	(44.07)	(68.18)	(99.98)	(8.44)	(82.72)	(16.93)
		Delay	22.15	18.56	(16.65)	9.87	(3.91)	7.23
	ST/NT	Queue	(91.90)	(94.89)	(94.30)	(44.75)	(91.31)	(100.30)
		Delay	(11.91)	(1.15)	(40.91)	(6.72)	(28.54)	(14.35)
	WT/ET	Queue	(41.67)	(62.67)	(66.84)	10.24	(52.99)	(14.13)
		Delay	(14.65)	(26.44)	(29.77)	(14.99)	(9.62)	(28.12)
	SL/ST	Queue	(59.20)	(75.92)	(106.91)	(16.13)	(84.17)	(50.40)
		Delay	2.01	5.98	(62.85)	8.63	(30.54)	(5.56)
	NL/NT	Queue	(82.06)	(104.02)	N/A	(28.36)	N/A	(76.46)
		Delay	1.86	(15.44)	N/A	(1.59)	N/A	(14.39)
	EL/ET	Queue	(51.81)	(62.87)	(81.27)	(2.83)	(81.85)	(29.13)
		Delay	(83.02)	(67.51)	(191.34)	(87.04)	(156.16)	(109.68)
	WL/WT	Queue	(40.95)	(81.89)	(79.10)	(13.16)	(78.88)	(38.04)
		Delay	13.32	0.74	9.89	28.69	18.74	23.69

Table 14: Summary of Percent Improvement in Intersection having Major and Minor (InSync)

Inter-section	Move-ment	Para-meter	% Improvement					
			Weekday			Weekend		
			Morning	**Afternoon**	**Evening**	**Morning**	**Afternoon**	**Evening**
SR-434 and Ashton Manor Way (Major and minor)	NT	Queue	12.20	11.85	7.43	1.14	(7.64)	(4.65)
		Delay	**72.42**	73.59	68.90	54.01	76.55	74.11
	ST	Queue	7.41	15.82	11.49	7.47	(0.20)	(4.17)
		Delay	(51.92)	(65.47)	(81.22)	(99.75)	**(193.92)**	(84.99)
	ST/NT	Queue	(19.71)	0.78	(7.78)	4.87	(3.74)	6.97
		Delay	(12.59)	(1.01)	7.58	(43.02)	(19.43)	7.00
	WT/ET	Queue	14.97	**22.71**	10.00	12.47	(2.70)	20.35
		Delay	40.71	37.03	22.05	12.52	13.66	49.87
	NL/NT	Queue	9.39	(2.13)	5.98	8.40	(1.65)	(6.45)
		Delay	49.96	58.50	34.81	35.07	41.93	49.27

Table 15: Overall Percent Improvement for Two Intersections (InSync)

Intersection	% Improvement	
	Queue	**Delay**
SR-434 and Lake Underhill Rd (Both way Major)	-62.55	-25.41
SR-434 and Ashton Manor Way (Major and Minor)	4.36	7.54

Figure 26 and 27 depicts the relationship between the overall percent improvement for all the movements as a whole with the time of the day for the queue length and the delay/wait time respectively. From the figure it's clear that the InSync system deteriorated the performance for the afternoon and evening mostly. It provides better results for the morning period.

The overall average percent improvement and statistical test results are shown in Table 16. The non-parametric WSR test and parametric t-test was performed as the sample size was large enough to assume their standard normal distribution. As like as the previous methods the JMP Pro 13 software and the online web interface were used to calculate the test statistics. The online calculator is same as the previous methods. The overall average percent improvement is -44% and -11% for total intersection queue length and wait time per movement respectively (Table 16).

The statistical results also show a very momentous change in the queue length as shown in Table 16. The two-sample paired t-test was performed along with the WSR test as the sample size was large enough to assume a standard normal distribution. The results indicate that the queue length is significantly increased in the after period at a 95% confidence-interval. The wait time was also increased although the statistical significance is not very high (significant at a 90% confidence-interval).

Combining these results with other methods, it's found that the total intersection queue/wait time per movement was increased although total corridor delay for through movement decreased notably. So, this is plausible that the queue/wait time for the side streets increased in a large scale resulting in the total queue/delay to be increased. Most of the deterioration occurred at the intersection with heavy conflicting movements in both approaches.

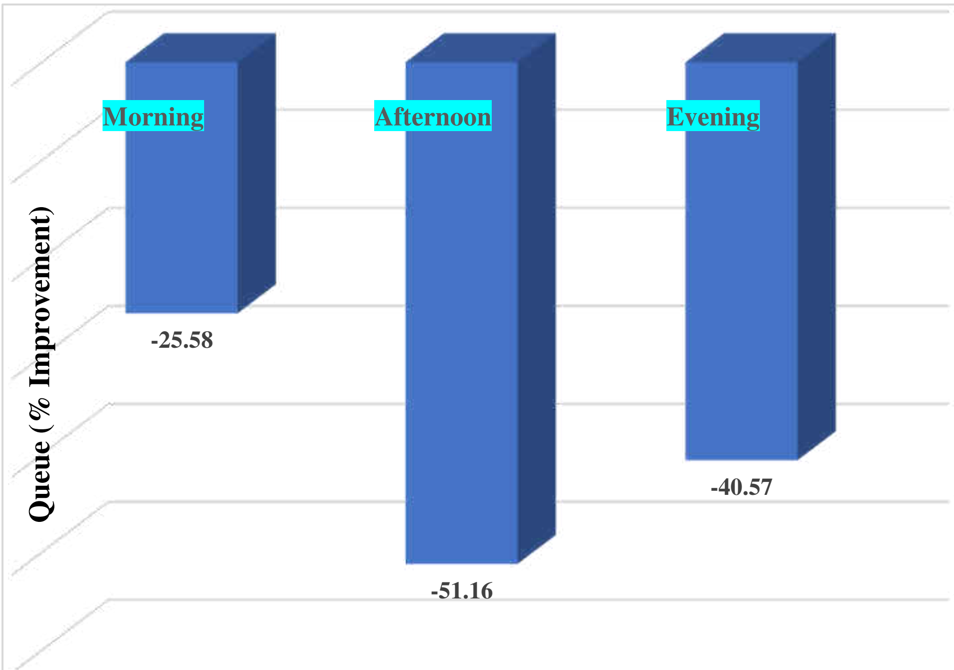


Figure 26: Percent Improvement of Queue by Time of Day (InSync)

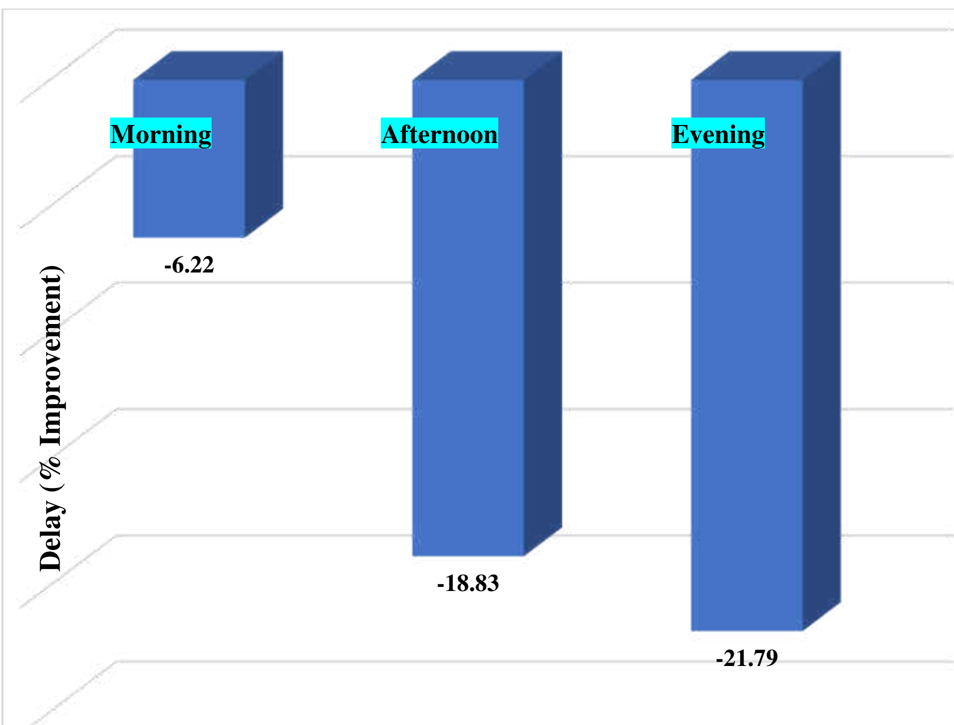


Figure 27: Percent Improvement of Delay by Time of Day (InSync)

Table 16: Summary and Statistical Test Results (InSync)

Para-meter	**Before**	**After**	**% Improve**	**Wilcoxon Signed Rank Test**			**Paired t-test**	
				W-statistic	**z-score**	**p-value**	**t-ratio**	**p-value**
Queue	33.72	48.67	-44%	509	-6.0291	< 0.0001	5.7188	< 0.0001
Delay	232.31	256.94	-11%	1725	-0.9695	0.3352	1.7527	**0.0832**

CHAPTER- FIVE: FINDINGS AND LIMITATIONS

5.1 General

The findings of the study through the data analysis and statistical tests are summarized and explained in this chapter. The limitations and shortcomings of both the test method or the system and the study proceedings are also discussed elaborately.

5.2 Findings

From the average-car method, the InSync ATCS was found to decrease the overall corridor travel time, corridor delay and number of stops for through movements although statistically not very significant. The cases where InSync improved mostly were in the morning period when the volume was less. The control group also showed an improvement of equivalent scale with an increase in volume of less percentage than the study corridors. So, the effectiveness of InSync ATCS is plausible but not verified precisely through the average-car method. And the performance of InSync is also evaluated for through movements using the average-vehicle method only which doesn't provide evidence for other movements and side streets. So, the bottom line is- InSync might improve the performance for through movements at non-peak period along the corridors having InSync.

From the analysis of data obtained from the BlueMAC, it's clear that InSync significantly reduced travel time and increased speed significantly. But the improvements are again attributed mainly to through movements and morning period. InSync deteriorated the performance for afternoon and/or evening as well as for turning movements even for right turn also. The rates of improvement were comparable to the average-vehicle method, but the absence of control group and side street movements made it plausible that there might be other factors acting. The cases where InSync proved effective are all through movements. So, in accordance with the average-vehicle it could be inferred that the InSync improved the performance for through movements at morning period along the corridors having InSync.

From the InSync data analysis, it’s found that InSync significantly increased the total queue length developed at intersections especially for the heavy left turning traffic. Although statistically not very significant, it also increased the total wait time at intersections by over 11%. Intersections having major roads in both approaches with heavy conflicting movements are likely to be deteriorated more than intersections with a minor side street and low traffic volumes. InSync also proved less effective for the afternoon and evening period as similar fashion as other methods.

Based on the three approaches, it could be concluded that the InSync ATCS might effectively reduce the corridor travel time and delay but eventually it can increase the queue and wait time at intersections for traffic turning onto the side streets and for intersections as a whole. Furthermore, the results also showed that it’s not effective especially when the corridor volumes approach capacity levels especially in the evening and/or afternoon period and its performance deteriorates at intersections with heavy conflicting major turning movements.

5.3 Limitations

There were several limitations and shortcomings of the study and methods associated with the study. Some of the limitations were attributed to the time and equipment constraints, some were attributable to the particular method and system. The limitations are listed below associated with the three approaches used for the study.

5.3.1 Average Vehicle Method

The average vehicle method is the most commonly used method to evaluate any signal control system. Yet it has some limitations to yield perfect results. The limitations are classified into two groups- Method Specific and Study Specific. Method specific limitations are concerned with the method itself as a whole and study specific limitations are concerned with this study only. They are listed below-

Method Specific:

- Traffic patterns and behaviors of driving changes from time to time and driver to driver. So, it's really hard to depict the real scenario of the roadway through a short time or momentary data collection. The average car or floating car method provides a limited perspective of the true condition through the instantaneous data.
- The average-vehicle or floating vehicle method requires a very high level of significance and accuracy and thus requires a large number of runs which is very cumbersome, time

consuming and tedious for a big project like the studied one. So, cost and time constraints prohibit large sample sizes.

- There might be some hidden/unforeseen factors which might affect the data and results. For example, if there's an event of crash or roadwork in an adjacent corridor to the study corridor which results in a road/lane closure, it affects directly to the study corridor but the surveyor/data collector might not be aware of it totally.
- The driver of the test vehicle and the test vehicle itself should be kept constant for the whole period of the study which is burdensome if the data collected for a long period of time.
- Greater potential for human error (potential for marking wrong checkpoints or inaccurate times). Potential data entry errors (e.g., recording travel time errors in the field and transcription errors from field sheet to electronic format).
- Any malfunction of the device for the automated data collection process or any car breakdown might result in a loss of the whole set of the data for the respective setup.

Study Specific

- In this study, only through corridor movements are considered. No side street side or turning movement is analyzed due to time and resource constraint for this method but they are considered for the other two techniques.

- A 95% confidence level and a range of ±2 mph permitted error for running speed were selected for this study. A 99% confidence and ±1 mph permitted error is expected for better results.
- One of the data collection set ups experienced a car break down which is completed with another car with a different driver.

5.3.2 BlueMAC

BlueMAC is a popular data collection device because of its simplicity and straight forwardness in data extraction. Besides the raw data, it provides summary of data as well as their graphical representation. Despite those advantages it has some shortcomings too. They are-

- The BlueMAC device uses the Bluetooth signal embedded in the car or any external device in the car and their availability is very limited as people are less likely to keep their Bluetooth connectivity open.
- The BlueMAC device cannot detect the enormous outliers in the dataset and provides the result based on all the signals it detects. The outliers are mainly data from the vehicle who left the corridor or road section before arriving the next device/sensor or the vehicle who stopped for a long time and then came back between two adjacent detectors/devices. It also experiences merging and mixing of data from one vehicle to the other.
- Only the travel time and speed data are available. And anomalies in travel time and speed data were observed. As an example, for the same corridor- travel time is increased but the speed is also observed increased although the change should be the vice versa for the same corridor as the travel length is kept constant.

- No data of delay, queue or vehicles count is available.
- A total of ten pairs out of sixteen pairs of O-D are selected for this study which seemed to be adequate, but study of all O-D pairs might provide better results. The O-D pairs which were omitted are similar in pattern and mostly comprised of two adjacent intersections, the analysis of them won't provide much indication of intersection delay.

5.3.3 InSync

InSync probe data are quite unfamiliar for the evaluation study as there are some disadvantages associated with it. They are-

- The data itself are very complicated and disorganized. It doesn't provide direct information, data or summary of data of interest.
- InSync only stores data for past one-month.
- InSync only provides data of queue and intersection delay for each movement for each cycle/phase. Also provide vehicles count for each phase for each lane. Finding the total queue and volume is very tedious and cumbersome.
- InSync has its own convention, algorithm and definition for the parameters which might not comply with the traditional practice.
- No data of travel time or speed.
- Volume can be counted through a very complicated and painstaking calculation from the raw data. No direct information.

- A total of two intersections and ten movements are considered for this study. Study of all the intersections and movements might provide better results. The intersections which were omitted are similar in pattern and provided almost equivalent results.

CHAPTER-SIX: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

InSync ATCS, the most widely deployed ATCS in the US and considered a promising technology to solve and manage arterial congestion problem and provide real-time control over all the traffic challenges- was evaluated in this study in a holistic manner. In line with previous studies, the effectiveness of this technology was tested for two corridors in Orange County, Florida using three different approaches. The findings show mixed results consisting of improvement in corridor travel time and delay for through movement but deterioration in total intersection queue length and wait time mainly for the left turn movement and side street delays. vehicles waiting for the opposing through traffic favored by InSync. It's plausible that the deterioration of certain measures counteracts the improvement of others resulting in a benefit to cost ratio of unity (benefit equals the cost). Further research is suggested to find the efficiency of InSync in varying conditions using multiple methods. A time series before-after study with control groups and parameters for a series of intersecting corridors and intersections could be a more realistic and nonpartisan way to evaluate InSync. Special emphasis should be put on the analysis of side street delay and wait time for turning vehicles in future studies. The benefit-cost ratio should be determined taking the side street and total intersection delay into account.

6.2 Future Recommendations

Efforts have been made to make this study reliable, precise and unbiased. But it has some limitations in data collection and other resources. Depending on the observation of the study, several recommendations for future study are suggested below.

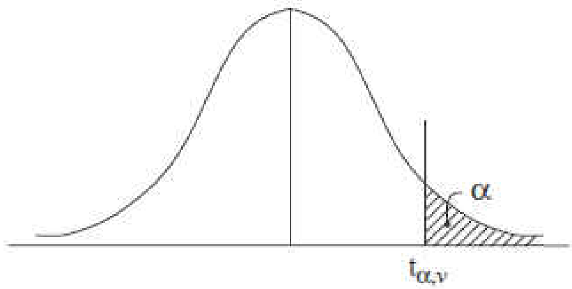
- Although there had been numerous studies performed already, no single study provides adequate evidence for the effectiveness of InSync. So, more extensive and in-depth research should be performed.
- Despite its shortcomings, the average-car method could be adopted with a very high level of confidence and very low level of error i.e. increasing the total number of runs.
- Beside the through movement, turning and side street movements should also be included for every method and technique.
- BlueMAC probe data could be used and might be a reliable source of data but it must be screened out from the numerous outliers.
- It's better not to use the InSync data as itself is not data collecting system but can also be used after understanding the data, algorithms and definitions precisely.
- Any other data collection software such as Vantage Velocity or INRIX may be used to verify the results obtained from other methods. Microsimulation can also be used along with the field data to confirm the results.
- Large dataset should be obtained to get better statistical results.

- The safety, fuel consumption and emission/pollution analysis should also be combined to the evaluation study.
- A benefit to cost analysis should be provided to justify the use of InSync.
- Focus should be given to invent a new method to evaluate such technologies.
- A time series analysis could be a good way to evaluate the effectiveness of InSync.
- InSync should be compared with other ATCS available in the market.

APPENDIX A

Statistical Value (Critical) Charts

Table 17: Critical t-value chart [30]



VALUES OF $t_{\alpha,\nu}$

ν	α: 0.25	0.20	0.15	0.10	0.05	0.025	0.01	0.005	ν
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	1
2	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	2
3	0.765	0.978	1.350	1.638	2.353	3.182	4.541	5.841	3
4	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	4
5	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5
6	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	6
7	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	7
8	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	8
9	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	9
10	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	10
11	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	11
12	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	12
13	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	13
14	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	14
15	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	15
16	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	16
17	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	17
18	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	18
19	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	19
20	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	20
21	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	21
22	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	22
23	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	23
24	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	24
25	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	25
26	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	26
27	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	27
28	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	28
29	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	29
30	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	30
∞	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	∞

Table 18: Quantiles of the Wilcoxon Signed-Rank Test Statistic [30]

	$W_{0.005}$	$W_{0.01}$	$W_{0.025}$	$W_{0.05}$	$W_{0.10}$	$W_{0.20}$	$W_{0.30}$	$W_{0.40}$	$W_{0.50}$	$\frac{n(n+1)}{2}$
$n = 4$	0	0	0	0	1	3	3	4	5	10
5	0	0	0	1	3	4	5	6	7.5	15
6	0	0	1	3	4	6	8	9	10.5	21
7	0	1	3	4	6	9	11	12	14	28
8	1	2	4	6	9	12	14	16	18	36
9	2	4	6	9	11	15	18	20	22.5	45
10	4	6	9	11	15	19	22	25	27.5	55
11	6	8	11	14	18	23	27	30	33	66
12	8	10	14	18	22	28	32	36	39	78
13	10	13	18	22	27	33	38	42	45.5	91
14	13	16	22	26	32	39	44	48	52.5	105
15	16	20	26	31	37	45	51	55	60	120
16	20	24	30	36	43	51	58	63	68	136
17	24	28	35	42	49	58	65	71	76.5	153
18	28	33	41	48	56	66	73	80	85.5	171
19	33	38	47	54	63	74	82	89	95	190
20	38	44	53	61	70	83	91	98	105	210
21	44	50	59	68	78	91	100	108	115.5	231
22	49	56	67	76	87	100	110	119	126.5	253
23	55	63	74	84	95	110	120	130	138	276
24	62	70	82	92	105	120	131	141	150	300
25	69	77	90	101	114	131	143	153	162.5	325
26	76	85	99	111	125	142	155	165	175.5	351
27	84	94	108	120	135	154	167	178	189	378
28	92	102	117	131	146	166	180	192	203	406
29	101	111	127	141	158	178	193	206	217.5	435
30	110	121	138	152	170	191	207	220	232.5	465
31	119	131	148	164	182	205	221	235	248	496
32	129	141	160	176	195	219	236	250	264	528
33	139	152	171	188	208	233	251	266	280.5	561
34	149	163	183	201	222	248	266	282	297.5	595

Table 19: Standard z-score table [30]

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-3.9	.00005	.00005	.00004	.00004	.00004	.00004	.00004	.00004	.00003	.00003
-3.8	.00007	.00007	.00007	.00006	.00006	.00006	.00006	.00005	.00005	.00005
-3.7	.00011	.00010	.00010	.00010	.00009	.00009	.00008	.00008	.00008	.00008
-3.6	.00016	.00015	.00015	.00014	.00014	.00013	.00013	.00012	.00012	.00011
-3.5	.00023	.00022	.00022	.00021	.00020	.00019	.00019	.00018	.00017	.00017
-3.4	.00034	.00032	.00031	.00030	.00029	.00028	.00027	.00026	.00025	.00024
-3.3	.00048	.00047	.00045	.00043	.00042	.00040	.00039	.00038	.00036	.00035
-3.2	.00069	.00066	.00064	.00062	.00060	.00058	.00056	.00054	.00052	.00050
-3.1	.00097	.00094	.00090	.00087	.00084	.00082	.00079	.00076	.00074	.00071
-3.0	.00135	.00131	.00126	.00122	.00118	.00114	.00111	.00107	.00104	.00100
-2.9	.00187	.00181	.00175	.00169	.00164	.00159	.00154	.00149	.00144	.00139
-2.8	.00256	.00248	.00240	.00233	.00226	.00219	.00212	.00205	.00199	.00193
-2.7	.00347	.00336	.00326	.00317	.00307	.00298	.00289	.00280	.00272	.00264
-2.6	.00466	.00453	.00440	.00427	.00415	.00402	.00391	.00379	.00368	.00357
-2.5	.00621	.00604	.00587	.00570	.00554	.00539	.00523	.00508	.00494	.00480
-2.4	.00820	.00798	.00776	.00755	.00734	.00714	.00695	.00676	.00657	.00639
-2.3	.01072	.01044	.01017	.00990	.00964	.00939	.00914	.00889	.00866	.00842
-2.2	.01390	.01355	.01321	.01287	.01255	.01222	.01191	.01160	.01130	.01101
-2.1	.01786	.01743	.01700	.01659	.01618	.01578	.01539	.01500	.01463	.01426
-2.0	.02275	.02222	.02169	.02118	.02068	.02018	.01970	.01923	.01876	.01831
-1.9	.02872	.02807	.02743	.02680	.02619	.02559	.02500	.02442	.02385	.02330
-1.8	.03593	.03515	.03438	.03362	.03288	.03216	.03144	.03074	.03005	.02938
-1.7	.04457	.04363	.04272	.04182	.04093	.04006	.03920	.03836	.03754	.03673
-1.6	.05480	.05370	.05262	.05155	.05050	.04947	.04846	.04746	.04648	.04551
-1.5	.06681	.06552	.06426	.06301	.06178	.06057	.05938	.05821	.05705	.05592
-1.4	.08076	.07927	.07780	.07636	.07493	.07353	.07215	.07078	.06944	.06811
-1.3	.09680	.09510	.09342	.09176	.09012	.08851	.08691	.08534	.08379	.08226
-1.2	.11507	.11314	.11123	.10935	.10749	.10565	.10383	.10204	.10027	.09853
-1.1	.13567	.13350	.13136	.12924	.12714	.12507	.12302	.12100	.11900	.11702
-1.0	.15866	.15625	.15386	.15151	.14917	.14686	.14457	.14231	.14007	.13786
-0.9	.18406	.18141	.17879	.17619	.17361	.17106	.16853	.16602	.16354	.16109
-0.8	.21186	.20897	.20611	.20327	.20045	.19766	.19489	.19215	.18943	.18673
-0.7	.24196	.23885	.23576	.23270	.22965	.22663	.22363	.22065	.21770	.21476
-0.6	.27425	.27093	.26763	.26435	.26109	.25785	.25463	.25143	.24825	.24510
-0.5	.30854	.30503	.30153	.29806	.29460	.29116	.28774	.28434	.28096	.27760
-0.4	.34458	.34090	.33724	.33360	.32997	.32636	.32276	.31918	.31561	.31207
-0.3	.38209	.37828	.37448	.37070	.36693	.36317	.35942	.35569	.35197	.34827
-0.2	.42074	.41683	.41294	.40905	.40517	.40129	.39743	.39358	.38974	.38591
-0.1	.46017	.45620	.45224	.44828	.44433	.44038	.43644	.43251	.42858	.42465
-0.0	.50000	.49601	.49202	.48803	.48405	.48006	.47608	.47210	.46812	.46414

APPENDIX B

Average Vehicle Method Field and Work Data Sheet

TRAVEL-TIME AND DELAY STUDY
AVERAGE VEHICLE METHOD
FIELD SHEET

DATE ________ WEATHER ______________ TRIP NO. ______________

ROUTE ______________ DIRECTION ______________________________

TRIP STARTED AT __________ AT ______________________ (LOCATION) ______________ (MILEAGE)

TRIP ENDED AT __________ AT ______________________ (LOCATION) ______________ (MILEAGE)

CONTROL POINTS		STOPS OR SLOWS		
LOCATION	TIME	LOCATION	Delay (seconds)	

TRIP LENGTH TRIP TIME TRAVEL SPEED

RUNNING TIME STOPPED TIME RUNNING SPEED

SYMBOLS OF DELAY CAUSE: S-TRAFFIC SIGNALS SS-STOP SIGN LT-LEFT TURNS
PK-PARKED CARS DP-DOUBLE PARKING T-GENERAL
PED-PEDESTRIANS BP-BUS PASSENGERS LOADING OR UNLOADING

COMMENTS ______________________________ RECORDER ______________

Figure 28: Travel-Time And Delay Study Average Vehicle Method Field Sheet [31]

TRAVEL TIME FIELD WORKSHEET

Arterial____________________ Date__________

Driver______________ Recorder____________ Direction__________

SIGNAL LOCATION	DISTANCE (MI)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)

S – Signal (lower box)
LT – Left Turn (upper box)
P – Pedestrian (upper box)
PK – Parking (upper box)
4W – 4-Way Stop (upper box)

Figure 29: Travel Time Field Worksheet [32]

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